# A Decision Support System (DSS) to Select the most Sustainable Alternative to Deal with Buildings with Unacceptable Conditions

by

Hisham Sherif

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Construction Engineering and Management

Department of Civil and Environmental Engineering
University of Alberta

# Abstract

The gradual development of the construction sector is worsening environmental deterioration and causing an unsustainable rise in resource use, further complicating the industry's long-term issues. An important facet of this matter is the present strategy for handling antiquated structures, frequently distinguished by demanding upkeep needs. This thesis focuses on the urgent requirement for a novel decision-making framework that can simplify renovating or replacing buildings, consequently improving sustainability and efficiency in the construction industry. Implementing a Decision Support System (DSS) that utilizes (MCDM) approaches is a significant development in this field. This system enables a decision-making process based on scientific principles, resulting in time and cost savings and reduced environmental emissions. The DSS model presented here utilizes (MCDM) to include user preferences in identifying the most effective approach for dealing with elderly buildings that require extensive maintenance. The study examines four options: Major Renovation, Minor Renovation, Building Relocation, and Building Replacement. It utilizes a comprehensive evaluation framework that incorporates the three established aspects of sustainability - Economic, Environmental, and Social - along with a crucial fourth aspect, Technical Sustainability. This comprehensive method greatly improves the project work environment by incorporating varied perspectives from all major stakeholders (including owners, designers, and constructors) into the decision-making process. A hybrid MCDM technique was designed to put this model into operation. The method combines the Analytical Hierarchy Process (AHP), decision matrix, and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) within a Fuzzy environment. This novel fusion was utilized to construct and assess numerous sub-criteria identified after an extensive literature review and meetings with

industry experts. A former educational facility was utilized as a case study to verify the effectiveness and dependability of the produced Decision Support System (DSS). The validation process uncovered substantial disparities in the ultimate ordering of options, which can be attributed to the diverse weights allocated to each sub-criterion according to expert opinions. The DSS developed in this study is designed to be versatile, allowing it to be used in several construction industry sectors. This tool represents a significant advancement in promoting sustainable construction methods by improving the objectivity and consistency of the decision-making process. By using it, the construction sector may make more knowledgeable and environmentally friendly decisions about the maintenance of ancient structures, aiding the sector's progress toward sustainability.

# Preface

This thesis is an original work by Hisham Sherif under the supervision of Dr. Yasser Mohamed, Professor of the Department of Civil and Environmental Engineering, Faculty of Engineering, University of Alberta. & Dr. Ahmed Hammad, Professors of the Department of Civil and Environmental Engineering, Faculty of Engineering, University of Alberta.

# Acknowledgment

The journey through my MSc program has been exciting and so much rewarding. With several challenges and failures along the way in the last few years, it would not have been possible to complete it without the help and support of many people. Therefore, all the appreciation and gratitude to these wonderful individuals, as well as the great University of Alberta with its administration, facilities and generous funding, made my graduate studies an outstanding experience.

I would like to thank my supervisors, Dr. Yasser Mohamed and Dr. Ahmed Hammad, for the support, guidance, advice, suggestions, funding, opportunities and patience. Since I joined the Program, they have always been there for me, guiding me through many steps with not only their rich and great professional research expertise but also a wonderful life experience. With their help, I managed to overcome several challenges.

I would like to thank my dear friends and lab mates:. Thank you, guys, for all the wonderful times in the lab and out, your advice and chumminess when things got rough. I couldn’t have wished for better company in the lab.  Thanks for a beloved time spent together in the lab and in other social settings.

I further had the opportunity to collaborate with great industrial expertise throughout the research. Special thanks to Kenneth Cantor, Adam Cantor, Royden Mills, Tony Hodge and Lara McClelland. I also want to thank my dear friends Mohammad Rezaul Karim and Mohammad Masfiqul for their great support.

Finally, to my wonderful family, my father, Dr. Mohamed Soliman, my sweet mother, my lovely wife Mariam, my daughter Reem and my brothers Amro and Osama, thank you for your endless encouragement and support and for keeping me level-headed and motivated. Love you, my sweet family.

# Table of Contents

# List of Tables

# List of Figures

# List of Abbreviations

| | |
|---|---|
| AHP | Analytic Hierarchy Process |
| DBB | Design Bid Build |
| DM | Decision-maker |
| DSS | Decision Support System |
| FAHP | Fuzzy Analytic Hierarchy Process |
| GHG | Greenhouse Gas |
| IPD | Integrated Project Delivery |
| ISO | International Organization for Standards |
| LCA | Life Cycle Assessment |
| LEED | Leadership in Energy and Environmental Design |
| MADM | Multi-attribute Decision-making |
| MCDM | Multi-criteria Decision-making |
| MODM | Multi-objective Decision-making |
| PDM | Project Delivery Method |
| PROMETHEE | Preference Ranking Organization Method for Enrichment Evaluation |
| TOPSIS | Technique for Order Performance by Similarity to Ideal Solution |
| VIKOR | VIekriterijumsko KOmpromisno Rangiranje |

# Chapter I

# Introduction

## 1.1. Background

To address the 21st-century global sustainability issues, the surroundingenvironment is crucial. Renovation and retrofitting become more important as the building ages to increase sustainability. Yet building owners and decision-makers may find it challenging to select the most sustainable alternative for new projects, particularly when maintenance expenses soar intolerably high levels. By including a variety of sustainability criteria and directing building owners and decision-makers to the best choice for their specific needs, Decision Support Systems (DSS) combine quantitative data like environmental impact and costs with qualitative inputs like stakeholder preferences and social impacts to help make sustainable decisions. This holistic approach combines rational analysis with emotional and contextual insights to make sustainable economic and environmental decisions. DSS helps construction firms find resilient and equitable solutions by exploring scenarios and understanding decision implications, A Decision Support System (DSS) may be very helpful in this case. Figure1.1. shows that the building sector has a substantial influence on both energy consumption and emissions, with residential buildings being the primary contributors in both areas. Although the construction industry consumes a smaller amount of energy compared to non-residential buildings, it contributes an equal amount of emissions. This data highlights the necessity of implementing specific energy efficiency and emission reduction strategies in the building sector to accomplish broader environmental sustainability objectives.

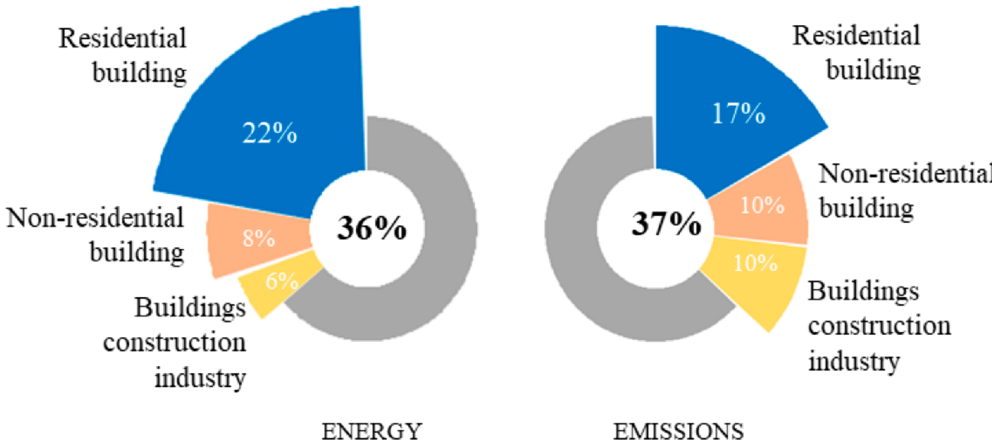


**Figure 1.1. Share of global energy and energy-related CO2 emissions attributable to buildings and construction ("Tracking Progress | Globalabc," n.d.).**

Sustainable development was defined as "the use of resources and the environment to meet present demands while not impairing the capacity of future generations to meet their own needs" (Y. Zhong and Wu 2015). The goal of sustainable construction is to maximize benefits while minimizing Adverse effects. To achieve this, the three pillars of sustainability, economic, social, and environmental, must all be balanced in a project (Farzanehrafat, Akbar Nezhad, and Ghoddousi 2015). The United Nations' 2005 Global Conference on Social Development adopted these sustainability pillars. The biophysical environment influences the economic and social harmony of a community. While it is crucial, the economy is not everything; the environment affects everything, including social order and equality. The core tenet of sustainability is that all social actors, from the individual to the global community, must be considered when making decisions to advance both the present and the welfare of future generations (Sakalasooriya 2021).

Sustainable building is a comprehensive process that fosters harmony between nature, people, and the built environment by designing communities that are comfortable for people and encourage economic equality. It incorporates sustainable development concepts across the entire building life cycle, including planning the construction, mining for raw materials, producing construction materials, using those materials, destroying them, and managing waste. (Yılmaz and Bakış 2015). In addition to promoting environmental benefits for society, sustainability is anticipated to result in a win-win situation where competitive market gains and financial benefits for construction enterprises are pursued (Shen et al. 2010).

## 1.2. Problem Statement

Selecting the best sustainable solution for old buildings with unsustainable construction systems is a challenging decision that considers a variety of aspects and criteria, including social equality, environmental effect, and economic viability. Arriving at an informed and rational conclusion can be challenging because of the many variables and the potential compromises that may need to be made. As a result, a decision support system is required to help owners, architects, and builders assess the sustainability of various repair or destruction options for ancient buildings. A thorough grasp of the essential variables and standards that affect sustainable decision-making in building construction is necessary to develop such a system. However, most of the previous research in this area focused on three pillars of sustainable construction.

While some researchers have emphasized the importance of the technical pillar in assessing the sustainability of civil infrastructure, there is a lack of comprehensive studies that integrate the technical pillar with economic, social, and environmental factors to analyze sustainability. Therefore, there is still an opportunity to examine and contrast their performance in terms of sustainability by integrating technical factors with other widely utilized sustainability principles in the IPD (Integrated Project Delivery) framework.

In the case of traditional project delivery methods, contractors and manufacturers participate in the project after the completion of the project's design phase. Traditional construction procedures sometimes lead to higher costs due to rework caused by miscoordination, quality problems, inefficient project delivery timelines, sub-par performance, and customer unhappiness with the final product. In contrast, Integrated Project

Delivery (IPD) is more significant in advancing sustainability by involving all stakeholders from the project's inception. The approach is more sustainable as it aims to enhance the outcomes of the triple constraint (money, time, and quality) by aligning the project team's goals and implementing a system of shared risk and reward.

## 1.3. Research Objectives

### 1.3.1. Evaluation and Integration of Stakeholder Opinions

The primary goal is to methodically collect and consider the various viewpoints and preferences of all parties engaged in the project. This entails involving a range of stakeholders to make sure that their goals and points of view are fully recognized and considered during the decision-making process.

### 1.3.2. Evaluation of Sustainability Alternatives

Assessing the sustainability of various building alternatives is the focus of the second objective. In addition to environmental sustainability, this also takes social and economic factors into account. Criteria including energy efficiency, cost-effectiveness, preservation of historical value, and social impact would be used to evaluate different options, including renovation, adaptive reuse, and full redevelopment. Creating a strong framework capable of methodically evaluating these options in relation to the established sustainability standards is the aim.

### 1.3.3. Development of a Decision Support System (DSS)

The creation of a thorough Decision Support System (DSS) that incorporates the assessment of stakeholder opinions and the analysis of sustainability alternatives is the third goal. Stakeholders should be able to enter data into this DSS and receive concise, useful recommendations. It should process the acquired data and provide the best possible answers by utilizing sophisticated analytical techniques and tools like multi-criteria decision analysis (MCDA). The system's goal is to make future building decision-making more transparent, knowledgeable, and focused on reaching a consensus.

## 1.4. Research Methodology

### 1.4.1. Research Deliverables and Activities

a. Explain and study each option from the options addressing the benefits and drawbacks.

b. Thoroughly assess each option's sustainability, considering technical, economic, social, and environmental aspects. Develop sub-criteria for all aspects of sustainable building primarily by thoroughly examining existing literature. Validate and finalize these criteria by obtaining feedback from professionals in industry and academia.

c. Development of a decision matrix and using Fuzzy AHP to assign weightage of criteria and TOPSIS in the ranking process.

d. The decision support model will be developed utilizing (MCDM) methodologies to assist in selecting the best sustainable solution for an ancient structure with significant maintenance needs.

This study was carried out as shown in Figure 1.2, which depicts the stages of the research methodology, with details on each step summarized below:

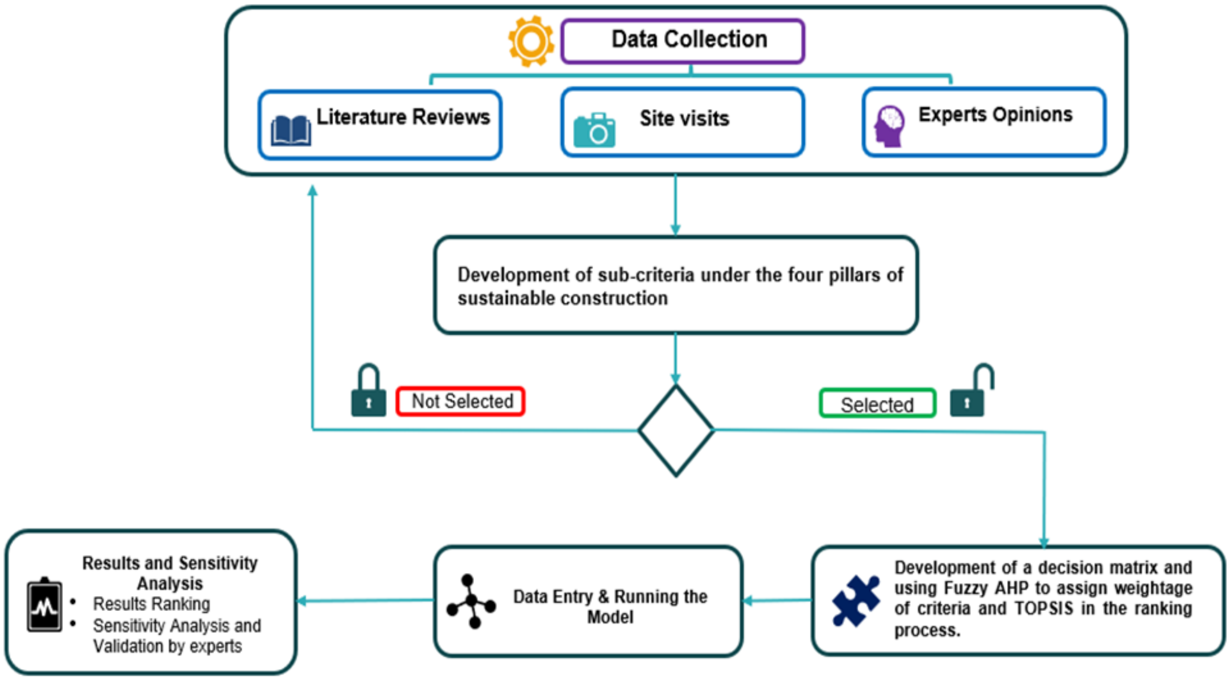


**Figure 1.2. Research Methodology**

The full approach used in the research study to evaluate sustainability criteria in construction projects is described in this paper. Each methodology's steps are intended to progressively polish and support the study findings. These steps include gathering data through literature reviews, site visits, and expert opinions; developing sub-criteria under the four sustainability pillars; reviewing by industry experts; developing a decision matrix; applying FUZZY AHP and TOPSIS; cleaning and entering the data; performing a sensitivity analysis of the results; ranking; and expert validation. This exacting methodology guarantees a methodical and trustworthy approach to the study process.

### 1.4.2. Data Collection

The initial step entails gathering information from various sources. This involves completing in-depth literature reviews to compile the most recent information on sustainability requirements for construction projects. Site visits are also made to have a firsthand understanding of procedures and difficulties that exist in the actual world. Expert comments are sought through organized interviews and questionnaires to supplement the research results.

### 1.4.3. Development of Sub-Criteria

In the second stage, key sub-criteria under each of the four pillars of sustainability, economic, environmental, social, and technical, are identified through analysis of the acquired data. Developing sub-criteria representing various factors within these pillars creates a thorough evaluation framework.

### 1.4.4. Expert Review

The third stage entails a rigorous evaluation of the created sub-criteria by professionals in the field. Their opinions are solicited to confirm the suitability and relevance of the chosen sub-criteria. Experts are contacted to ensure that no important criteria are missed, and that the framework considers practical factors.

### 1.4.5. Decision Matrix and Weightage Assignment

The fourth stage involves creating a decision matrix to arrange and assess the sub-criteria. The FUZZY Analytic Hierarchy Process (AHP) is used to allocate weight to each criterion and sub-criterion while considering the inherent uncertainties and imprecisions in sustainability assessment. The technique used to rank alternatives is known as TOPSIS, which stands for Technique for Order of Preference by Similarity to Ideal Solution.

### 1.4.6. Data Cleaning, Entry, and Model Testing

Data cleansing is performed during the fifth stage to guarantee precision and uniformity. The decision model is constructed using the gathered data and then assessed using real data from construction projects. This phase aims to validate the functionality and suitability of the framework.

#### 1.4.7. Results and Sensitivity Analysis and Ranking

Following the testing of the model, a sensitivity analysis is conducted to evaluate the dependability of the results and the impact of modifications to the criteria weights and data inputs. The study's findings are used to assess construction projects based on their sustainability performance.

#### 1.4.8. Expert Validation

The last step is to validate the study results with professionals from the industry. Expert comments are sought to evaluate the validity and applicability of the sustainability criteria, weightings, and rankings produced from the research. Their knowledge offers vital confirmation and practical relevance. Through a systematic progression of these five stages, the research methodology guarantees a thorough and dependable evaluation of sustainability requirements in construction projects. The framework incorporates qualitative and quantitative data, expert views, and sensitivity assessments to provide a comprehensive method for assessing the sustainability performance of construction projects. The meticulous approach employed in this research study increases the trustworthiness and real-world applicability of the findings.

### 1.5. Expected Contribution

#### 1.5.1. Academic Contribution

The academic contributions of this research are:

a. Combining literature review, expert opinion, and industry practices to identify the factors impacting the selection process.

b. Integrating technical aspects with the commonly used three pillars (economic, social, and environmental) of sustainability to assess the sustainability aspects of the chosen alternative

c. Two different MCDM methods (Fuzzy TOPSIS) are applied to handle qualitative and quantitative data in a similar situation, rank alternatives, and compare the results. Use the Fuzzy AHP technique with trapezoidal membership functions to provide maximum values and more realistic results. Utilization of Fuzzy logic in all cases to minimize subjectivity, add rationality, and improve fairness in the decision-making process.

d. The integration of quantitative and qualitative data in a decision support system (DSS) improves its capacity to accurately measure and calculate data, resulting in more authentic outcomes. Quantitative data offers measurable and unbiased metrics for accurate analysis, whereas qualitative data captures subjective perspectives such as stakeholder preferences and social impacts. This integration facilitates a harmonious perspective, enabling the DSS to evaluate quantitative measurements alongside subtle variables, guaranteeing pragmatic and contextually informed suggestions. Consequently, the DSS provides more precise, authentic, and practical insights for making sustainable decisions.

### 1.5.2. Industrial Contribution

The industrial contributions of this research are:

a. Developing a decision matrix for assigning a weightage of criteria, specifically once the numbers of evaluation criteria are quite large.

b. The objective is to create a Decision Support System (DSS) that will aid decision-makers in selecting evaluation criteria and assigning relative weight to those criteria. This will be achieved using qualitative and quantitative methodologies inside an Integrated Project Delivery (IPD) framework. The goal is to identify the most sustainable alternative.

d. By integrating quantitative metrics like energy consumption and qualitative inputs like stakeholder preferences, the DSS reduces bias and subjectivity in decision-making, while reflecting the users preferences in scientific way.

## 1.6. Thesis Organization

This thesis is unfolded in six chapters. The contents of different chapters are summarized below:

- Chapter One, **Introduction**: This chapter begins with the topic's background and then discusses the problem statement, objectives of the study, research methodology, and expected outcomes, as well as outlines the structure of the thesis.

- Chapter Two, **Literature Review**: It reviews pertinent earlier research and journal articles to determine the research gap and establish this work's foundation.

- Chapter Three, **Methodology**: It discusses methodologies, assumptions, etc., used in the calculation, data analysis, and development of the DSS.

- Chapter Four, **Application and Case Study**: This chapter applies the methodologies explained in Chapter Three. The Microsoft Excel templates and DSS are utilized here with the case study data to obtain the desired outputs.

- Chapter Five **Validation and Verification**: This chapter verifies and validates calculations and the DSS.

- Chapter Six **Conclusions and Recommendations**: Conclusions, limitations, and recommendations for future works are discussed in this chapter.

## Chapter II

# Literature Review

## 2.1. Introduction

This literature review aims to summarize the previous work that has been done for selecting the most sustainable solution for buildings with unsustainable construction systems, while trying to find the best method to help considering all stakeholders opinions in the process.

It is well known that with unsustainable construction systems, costs account for a significant portion of a building's total life cycle cost (Yip, Fan, and Chiang 2014) Therefore, when the decision maker comes across a building with a highly unsustainable construction system, it is important to find the most sustainable way to rehabilitate it. Sustainability in building redevelopment refers to using resources and energy with minimum Adverse impacts on the environment while satisfying the needs of future generations. We propose a sustainable method for deciding on redeveloping buildings with unbearable maintenance costs.

There are many redevelopment solutions for a building with unsustainable construction systems. Therefore, it is difficult for a decision-maker to compare different redevelopment alternatives. This is where multi-criteria evaluation is very useful. It is based on assigning a set of values to a list of criteria. Each criterion value is a function of the attribute values of the considered alternative. A criteria value represents the performance of the alternative concerning a criterion (Bohanec 2022) A better solution will have a higher performance value.

The proposed decision support system (DSS) will present a list of redevelopment alternatives along with their performance values for a decision maker. In this way, the decision-maker will be able to compare different alternatives and select the most appropriate solution according to his.

## 2.2. The Importance and Meaning of Sustainability

Sustainability refers to preserving natural systems' ability to support and improve the standard of social systems (Sev 2009) Climate change, a result of global warming, is one of the main worldwide challenges the general populace must face. This is mostly a result of the ozone layer being destroyed by carbon emissions from human activities like manufacturing and construction. Other factors include quick industrialization, globalization and cooperation, inventive practices to better satisfy clients and users of products, and technological advancements in dealing with aspects of human endeavor; factors contributing to excessive urbanization and emigration to developed countries include war, political instability, population growth, and increased resource consumption to meet the demands of the growing population (Yılmaz and Bakış 2015).

According to some academics, social-ecological systems are complex systems that include human societies, economic systems, ecosystems, and their interconnections. Additionally, there have been arguments urging academics to consider both human communities and natural resources and how human actions have changed through time (Olsson, Folke, and Berkes 2004) Construction is increasingly paying greater attention to sustainable development because of the increasing resource limits, the engagement of more stakeholders, and the need to balance the demands of environmental, economic, and social goals(Sev 2009).

Due to its energy-intensive operations, high GHG emissions, and low productivity, the construction industry is viewed by many as an unsustainable sector (Finkel 1997). In contrast to focusing on sustainability, an examination of the literature on construction project management, sustainability, and sustainability in construction project management demonstrates a disjointed progression of categories and concepts. These concepts concern specific financial and traditional project success factors (Silvius and Schipper 2014). The fundamental idea of sustainable development calls for the careful use of natural resources, improved social advancement that considers the needs of everyone, higher economic growth levels, lower unemployment rates, and proper environmental protection (Zabihi, Habib, and Mirsaeedie 2013).

(J. Liu, Liu, and Wang 2020a) Compared sustainability to a three-legged stool as shown in Figure 2.1, with ecology, society, and economy as each leg. Since the community, ecology, and economy are all inextricably intertwined, it stands to reason that any leg missing from the "sustainable stool" will lead to instability in all three (Y. Liu et al. 2014). The assessment of sustainability must include both individual and group efforts to maintain the environment, as well as economic growth and societal requirements (J. Liu, Liu, and Wang 2020b).(Elkington 1998) broadened the idea of sustainability in the corporate world and created the triple-bottom-line principles. The social, environmental, and financial performance pillars offer a framework aligned with sustainable development objectives. Like other single criteria techniques, the triple bottom line idea places equal emphasis on the economic value of development and the environmental and social aspects (Elkington 1998).

Sustainability should be considered during the planning and construction phases and during the renovation and demolition phases. Renovation and deconstruction are linked to environmental sustainability since construction materials have a finite lifespan. Recycling and reusing the materials collected during demolition decreases the need for new materials and resources (Petzek, Toduţi, and Băncilă 2016). As a result, the built environment and the construction sector may benefit greatly from the circular economy. Intelligent urban design that maximizes the utilization of land and transportation systems is the basis of circularity.

When used in construction, operation, and deconstruction, the circular economy idea might significantly optimize the environment, society, and the economy. Deconstruction, reuse, and reassembly of construction materials should be considered from the start when planning and developing zero-energy buildings, installing greywater recycling systems in buildings, and any other sustainability-related technologies (Iyer-Raniga et al. 2020).

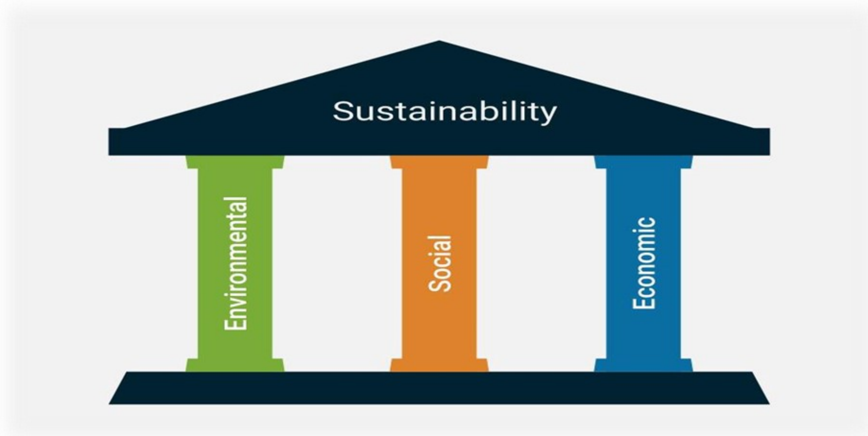


**Figure 2.1. The Sustainability Pillars ("Re-Thinking Sustainability in 2021" 2021)**

### 2.2.1. Technical Sustainability

Technical performance as the fourth pillar of infrastructure sustainability theory and was explained by (Levitt 2007) and showed how technical design and the other three pillars have relevant linkages; in his work, the researcher made the case that technical performance should be specifically included as a pillar of infrastructure sustainability theory and proposed four pillars (environmental, technical, economic, and social) as the crucial analytic components of sustainability theory for civil infrastructure. In addition, several industry insiders and academic researchers remarked that the technological pillar is a crucial component of sustainable construction besides the economic, social, and environmental pillars. In the case of sustainable construction, they also voiced their concern about integrating the technical pillar with the current system. Table 2.1 lists the technical sub-criteria discovered through the literature review and used to evaluate the sustainability of various building projects.

**Table 2. 1. List of Technical Sub-criteria Applied in the Sustainability Evaluation.**

| Criteria | Sub-criteria | Reference |
|---|---|---|
| **Technical** | Building Addition Lifespan | (Choi and Kim 2023) |
| | Building lifetime | (Rodrigues et al. 2018) |
| | Project Duration | (Saghatforoush, Trigunarsyah, and Too 2012) |

| | | |
|---|---|---|
| | How easy is it to construct | (F. W. H. Wong et al. 2006) |
| | The capability of saving energy | (Papadopoulos, Theodosiou, and Karatzas 2002) |
| | Current Building Condition | (Liao, Ren, and Li 2023) |
| | Durability from the surrounding environment | (Biseniece et al. 2017) |
| | Moving and relocating difficulty | (X. Zhong and Chen 2017) |
| | Variance Between current and Future Energy Use Index (EUI) | (X. Zhong and Chen 2017) |
| | horizontal load Resistance | (Branco and Araújo 2010) |

### 2.2.2. Economic Sustainability

The main financial benefits of applying sustainable principles are enhanced building performance and durability, reducing maintenance and operating expenses throughout a construction project (Roufechaei, Hassan Abu Bakar, and Tabassi 2014). To achieve economic sustainability, the construction sector must switch from non-renewable resources to renewable ones, from producing waste to reusing and recycling it, from first costs to life cycle costs, and from full-cost accounting (Y. Zhong and Wu 2015). For economic sustainability, the construction sector must consider housing affordability, building life cycle costs, renovation and development costs, business enhancement, legal compliance, profitability, and risk management (Bennett and James 1999). In addition to environmental life cycle analysis, life cycle cost analysis measures all costs incurred throughout a product system's financial reimbursement by one or more parties participating in the product life cycle (Finkbeiner et al. 2010).

The cost of owning an item across its entire life cycle from acquisition to uselessness, while it satisfies its performance obligations. Construction expenses, maintenance costs, operational costs, occupancy costs, end-of-life costs, and non-construction expenditures are all included in life cycle costs (Kehily, McAuley, and Hore 2012). Economic analysis often incorporates time by using life cycle costing techniques, which in their full form cover expenses from resource extraction to the reuse phase (Kaminsky 2015). Table 2.2 provides a set of economic sub-criteria discovered through the literature review and used to evaluate the sustainability of various construction projects.

**Table 2. 2. List of Economic Sub-criteria Applied in the Sustainability Evaluation.**

| Criteria | Sub-criteria | Reference |
|---|---|---|
| | New Construction Cost | (Baloi and Price 2003; Holm and Schaufelberger 2021; Lowe, Emsley, and Harding 2006) |
| | Initial construction cost | (Rehm and Ade 2013; Rosenfeld 2014) |
| | Maintenance Liability | (Doloi 2012; Farahani, Wallbaum, and Dalenbäck 2020; Le et al. 2018; Zavadskas, Kaklauskas, and Raslanas 2004) |
| | Return on Investment (ROI) | (Ferreira and Moro 2011; Siller, Kost, and Imboden 2007) |
| | Demolition cost | (Y. C. Wong, Al-Obaidi, and Mahyuddin 2018) |

### 2.2.3. Social Sustainability

The goal of social sustainability in construction is to raise the standard of living for people (Hill and Bowen 1997). The emphasis was turned towards constructing social sustainability assessment frameworks and, as a result, generating a trustworthy set of indicators on which the evaluation or implementation may be pursued. (Farzanehrafat, Akbar Nezhad, and Ghoddousi 2015) Stated that during the full life cycle of a construction project, there was a lack of a well-defined set of social sustainability metrics.

They provided a list of social sustainability indicators for various project stages. They concluded that all project phases must prioritize stakeholder engagement and public accessibility, health, and safety. In contrast to the previous stages, the end-of-life phase signals were the least significant. Even though each indicator's value was viewed by different respondents with a great deal of consistency, indicators that could be seen in action, such as "health and safety issues."

**Table 2. 3. List of Social Sub-criteria Applied in the Sustainability Evaluation.**

| Criteria | Sub-criteria | Reference |
|---|---|---|
| **Social** | Power of storytelling | (Almén and J. Larsson 2014; Doroudiani and Omidian 2010; Mayhew and Quinlan 1997) |
| | Reflection of owner's reputation after taking a decision | (Buchanan and Abu 2017; Iringova 2017; Lataille 2003; Meacham and McNamee, n.d.) |
| | Emotional Attachment | (Juan, Lai, and Shih 2017; Siddiqui et al. 2015; Wixom and Todd 2005) |
| | Social Acceptance(Building Aesthetics) | (Behm 2005; BICKFORD 2000; Kylili, Fokaides, and Lopez Jimenez 2016) |
| | Historically Significant | (Awad and Jung 2021; Ismaeel and Mohamed 2022; Spengler and Chen 2000; Yang et al. 2009) |

| | | |
|---|---|---|
| | Use of local materials | (Ramírez-Villegas, Eriksson, and Olofsson 2016; Ugochukwu and Chioma 2015) |

### 2.2.4. Environmental Sustainability

Environmental sustainability is the efficient use of natural resources, promoting renewable resources, and protecting the air, water, and land from contamination to avoid Adverse and long-lasting environmental effects (Abidin and Pasquire 2007). Given that it accounts for 36% of global energy consumption, 37% of The construction industry has a substantial environmental impact, contributing to greenhouse gas emissions, accounting for 12% of global potable water use, and responsible for 40% of solid waste creation in developed countries. (Mohammad, Masad, and Al-Ghamdi 2020). Over the past 20 years, there has been a notable advancement in analyzing buildings' environmental sustainability (Bernardi et al. 2017).

Renewable energy, energy efficiency, water efficiency, ecology, conservation, material efficiency, air pollution, pollution control, indoor environmental quality, sustainable site, and land use changes, and management should all be taken into account when building homes to maintain the environment (Roufechaei, Hassan Abu Bakar, and Tabassi 2014). Table 2.4 lists environmental sub-criteria discovered through the literature review and used to evaluate the sustainability of various building projects.

**Table 2. 4 List of Environmental Sub-criteria Applied in the Sustainability Evaluation.**

| Criteria | Sub-criteria | Reference |
|---|---|---|
| | Green House Gas Emission Amount during operation and maintenance | (Chini and Bruening 2003; Hasik et al. 2019; Hein and Houck 2008) |
| | Green House Gas Emission Amount During Construction | (Andrić et al. 2017; Mangold et al. 2016) |
| | Pollution minimization | (Akadiri, Chinyio, and Olomolaiye 2012; J. Liu, Liu, and Wang 2020a; Mangold et al. 2016) |
| | Materials Reuse Potential | (Chini and Bruening 2003; Hein and Houck 2008) |
| | Solid Waste Amount During Construction | (Baloi and Price 2003; Holm and Schaufelberger 2021) |

## 2.3. Current Selected Sub-criteria

### 2.3.1. Green House Gas Emission Amount During Construction

In 2012, the energy industry experienced a record-breaking increase in global CO2 emissions, reaching 31.6 gigatons. (Siller, Kost, and Imboden 2007). Due to its status as the primary contributor of greenhouse gas (GHG) emissions globally, the building sector exerts a significant influence on global warming. The Intergovernmental Panel on Climate Change (IPCC) has published a report that the building industry was responsible for 25% of the global CO2 emissions and 40% of the world's energy use.

From 1999 to 2004, the average yearly increase in worldwide carbon dioxide (CO2) emissions from buildings was 2.7% (Abbas et al. 2006). The four main emission sources on construction sites are the manufacture and transportation of building materials Figure 2.3, the energy consumption of construction equipment, the energy used for processing raw materials, and the disposal of construction waste. They concluded that 88% to 96% of all GHG emissions were attributable to the manufacture of materials and the fuel utilized in building machinery (Yan et al. 2010). This outcome was in line with the findings of (Cass and Mukherjee 2011). According to recent studies, a wider range of technologies are being used to measure GHG emissions in the construction sector. (Melanta, Miller-Hooks, and Avetisyan 2013) utilized the carbon footprint estimating tool (CFET) to assess a construction project for transportation. (Barandica et al. 2013) developed a management information system to analyze the GHG emissions from road projects in Spain in depth.

(Tang, Cass, and Mukherjee 2013) used an interactive simulation-based method to choose the best construction management tactics for reducing GHG emissions caused by unplanned disruptions. However, lowering GHG emissions in the construction industry is proving difficult to achieve despite these theoretical advancements, highly efficient technologies, and various environmentally beneficial policies applied to the building sector. Only a few research included onsite assembly work and construction-related human activities when analyzing the GHG impact of building sites using inadequate system boundaries. Additionally, even though China contributed the most to the rise in global CO2 emissions in 2012 (Yan et al. 2010) said The analysis of GHG emissions from human activities during the building construction phase is still rare and devoid of actual cases in China, even though some authors have already carried out several related studies on GHG analysis in China.

### 2.3.2. Material Reuse Potential

End-of-life considerations are becoming a more crucial part of design. The building has traditionally been destroyed, generating enormous amounts of waste. For example, This generates over 70 million tonnes of waste annually in the UK, most of which has historically been dumped in landfills (Cooper and Gutowski 2017).

There are a few instances of whole buildings being demolished and rebuilt elsewhere. Still, it is more reasonable to anticipate that once a building has reached the end of its useful life, its constituent parts will be recycled or reused. No matter the material, there are few opportunities to reuse structural elements like beams and columns. This is partially due to the challenges involved in separating and disassembling the structural elements, but it is obvious that a dry type of construction is considerably simpler to manage.

In theory, steel structure lends itself to deconstruction, but it is obvious that this depends on adequate connection details with other materials and amongst steel components (Chini and Bruening 2003). Therefore, bolted connections are preferred to welded details since they are more accessible. Separating composite deck floors from the supporting beams and designs that intentionally aim to simplify deconstruction, typically using precast floor pieces with a non-composite structure, is more difficult.

The provenance of materials collected from a demolition site often raises questions (Chini and Bruening 2003). Since it is difficult to identify components and their histories, which is necessary to assess their structural capabilities, most clients and designers are understandably wary. Reuse is likely to remain a minority activity for the foreseeable future due to the practical challenges of doing so and the mindset of most clients and designers.

Therefore, it is more reasonable to anticipate that the practice of recovering recycling materials will continue and grow (Chini and Bruening 2003). Large demolition materials, like masonry and concrete, were traditionally dumped in landfills. However, they are increasingly being used as recycled aggregate in other construction projects; now, 75–80% of such debris is utilized in this manner. The benefits are more closely related to waste reduction than to a decrease in the demand for virgin materials. These are mostly used as low-quality sub-base and fill, for example, in road construction and airport pavements (Mehra et al. 2022). Contrarily, steel can be easily recycled through its production process without sacrificing quality, and a well-established infrastructure exists to handle waste steel. As a result, a very high percentage of steel is recycled, lowering waste generation and the need for iron ore mining (Mehra et al. 2022). Even if some steel is created totally from scrap, the market still necessitates that some steel be produced from newly mined ore.

**Table 2. 5 Embodied energy and carbon footprint for different construction materials.**

| Material | Embodied Energy (MJ/kg) | Carbon kg (CO2/kg) |
|---|---|---|
| **Aggregates** | 0.15 | 0.008 |
| **Cement** | 2.8 - 6.8 | 0.82 |
| **Concrete** | 1.0 | 0.134 |
| **Steel** | 15 - 25 | 1.8 |
| **Timber** | 6 - 11 | 0.5 |

### 2.3.3. Green House Gas Emission Amount During Operation and Maintenance

Although construction projects' life cycle emissions have been thoroughly studied Numerous times, the entire building life cycle has been neglected. According to previous studies, the energy consumption of the use phase has been identified as the most significant single source of emissions, with the life cycle emissions of the construction (including the embodied carbon of building materials) only accounting for one-tenth of the building's total life cycle emissions (Junnila, Horvath, and Guggemos 2006).

As a result, the importance of the construction phase is frequently viewed as minimal. However, the manufacturing stage of an energy-efficient passive house may be responsible for more than half of the building's total life cycle primary energy use, according to some recent research (Gustavsson and Joelsson 2010). This is because buildings are becoming more energy efficient, elevating the relative importance of the construction stage and the emissions contained in the materials. The relationship between the production and use phase emissions is equating due to the energy-efficient building types' higher primary energy demand in the production phase and lower heating requirements in the use phase (Gustavsson and Joelsson 2010).

### 2.3.4. Solid Waste Amount During Construction

Solid waste generated during new construction, renovations, and demolition of buildings and structures is called construction and demolition (C&D) waste. Most of the time, it is disposed of in landfills. Still, recently, the possibility of diverting waste components from landfills has been recognized, making C&D waste a target of interest for recycling. Researchers in various nations have estimated the waste generated during construction and demolition. C&D waste is around one-third of the total materials in US landfills (Kofoworola and Gheewala 2009). Data for several European nations also show that depending on how it is classified, the amount of C&D waste differs from nation to nation. In 1996, C&D waste production in Austria, Denmark, Germany, and the Netherlands was around 300, over 500, 2600, and 900 kg/cap, respectively (J. Liu, Liu, and Wang 2020a).

Additionally, it has been reported that at its height in 1994-1995, C&D waste occupied about 65% of Hong Kong's landfill space (Bossink and Brouwers 1996). Construction waste is produced during tasks like site preparation and constructing new buildings or infrastructure (Rebellon 2012). In the US, the Environmental Protection Agency (USEPA) estimated that 136 million tons of construction-related waste were produced in buildings in 1996 (Cochran et al. 2007). According to another study, the USA's solid waste stream comprises around 29% construction waste (Rogoff and Williams 2012). Construction waste occupies 35% of the landfill area in Canada, and it may make up more than 50% of the debris in a typical UK landfill (Ferguson and Britain 1995). More emphasis is being placed on waste reduction, recovery, reuse, and recycling in most nations to divert as much construction debris as possible from landfills. From low to high, there are five categories of waste impact minimization strategies: avoid, reduce, reuse, recycle, treat, and dispose.

The best approaches to conserve natural resources and preserve the environment after avoiding usage are reduction, reuse, and recycling (Plank 2008). A major principle of waste management is the coordination of these three main effect minimization tactics during the demolition, design, and construction stages. Reduced generation of solid waste and lower costs for waste transportation, disposal, and recycling are two significant benefits of cutting back on C&D waste. Therefore, waste reduction is considered the most successful waste impact-minimizing technique. However, some C&D waste generation is unavoidable, and reuse and recycling techniques are useful ways to lower the amount of C&D waste.

### 2.3.5. Return on Investment (ROI)

Due to the growing competitive challenges of the new economic landscape over the past two decades, training has become a more important strategic aspect for businesses and industries (Glover et al. 1999). The largest industrial trade organization in the United States, the National Organization of Manufacturers (NAM), recently passed a resolution designating worker training as one of its key goals. With this heightened importance has come the realization that training must be subjected to rigorous planning and evaluation. Following regional trends in other industries, training systems' construction, upkeep, and enhancement strongly emphasize ROI (Hein and Houck 2008; Phillips 1994; 1996). Construction companies are under intense strain from growing competition, which calls for more complicated projects to be completed in a shorter time (CII 1992). The construction industry has paid more attention to training during the past ten years as a critical component of its long-term vitality and growth (Glover et al. 1999).

The profitability of an investment in terms of its cost is assessed using the return on investment (ROI), a fundamental financial metric, across many different businesses (Hollenbeck 1996). ROI is an essential factor to consider when evaluating construction projects' economic viability and efficiency. The wise use of resources is crucial because the building sector contributes significantly to global economic activity. To better project outcomes (Zavadskas, Kaklauskas, and Raslanas 2004). In the early stages of building project management, ROI is crucial. Construction companies frequently use ROI as a primary criterion when choosing and prioritizing projects when considering a portfolio of potential projects. Projects with a higher predicted return on investment are frequently prioritized because they are thought to be more likely to produce significant returns than the initial investment (Zavadskas, Kaklauskas, and Raslanas 2004).

This guarantees that funds are distributed to financially sound initiatives. Building projects' cost-benefit analysis (CBA) includes ROI as a critical component. CBAs compare a project's total expenses to anticipated profits, and ROI offers a quantified way to gauge those returns. Stakeholders can choose which initiatives to pursue and which to postpone or discard by evaluating the ROI of various projects (Rosenfeld 2014). Although ROI is a useful indicator, construction projects do involve some risks. The inherent risks and potential setbacks in the building business must be considered. ROI estimates can be modified to include risk elements like cost overruns and construction delays, giving a more nuanced picture of possible returns (Rosenfeld 2014). Project managers can analyze a project's viability realistically with the help of this risk-adjusted ROI.

Construction projects require ROI analyses that go beyond short-term advantages. Additionally, it takes a project's profitability and long-term viability into account. This involves assessing the maintenance and operational costs throughout the project, which may affect the overall return on investment. Strong long-term ROI projects are frequently preferred to help the organization maintain its success and growth. Calculating the ROI is a simple idea, but applying it is complex. Start by compiling a list of all the expenses related to the construction project (Rosenfeld 2014). This covers charges for the project's materials, labor, equipment, permits, engineering and design fees, land acquisition costs, and any other upfront costs. Include any applicable costs, both one-time and continuing. The net gains or returns the construction project created must then be calculated. This often entails estimating the project's lifetime revenue, including money from sales, rent, and other sources. From this revenue, all ongoing project costs, maintenance charges, and ongoing operational costs are deducted (Rosenfeld 2014).

The resultant number is an estimate of net gains. A project with an Optimistic ROI is anticipated to produce a return greater than the initial investment, indicating a potentially successful enterprise. An Adverse ROI, on the other hand, denotes a potential financial loss because it indicates that the project is not expected to bring in enough revenue to repay the costs of the investment. The period used to calculate ROI might significantly impact the outcome (Rosenfeld 2014).

Long-term ROI estimations could be more uncertain and riskier, and they might not fully account for the economic benefits of a project. As a result, it's crucial to indicate the period used to compute ROI and consider the project's anticipated lifespan (Rosenfeld 2014). Consider modifying the ROI calculation for variables like inflation and time value of money to improve accuracy. This can be accomplished by applying a discount rate to future cash flows to account for the time preference of money (Baloi and Price 2003).

### 2.3.6. Demolition Cost

There are many Adverse effects of C&D waste on the environment but taking up a significant amount of land for landfill disposal is one of the biggest. For instance, C&D trash costs the government more than $200 million annually to dispose of in landfills and consumes around 3500 m3 of valuable landfill space daily in Hong Kong (Poon 2007).

The need for huge amounts of C&D waste disposal in the United States cannot be satisfied due to limited landfill capacity and the difficulties of creating new landfills, a major worry of regulators (Ferguson and Britain) 1995). It is vital to manage C&D waste to lessen its detrimental effects on the ecosystem. There have been numerous proposals for reducing the pollution caused by C&D waste, including reducing trash at the source, recycling, reusing, and landfill disposal (Bossink and Brouwers 1996). The two pillars of sustainability in construction, reducing resource consumption and reducing environmental pollution, are two key principles of these management systems (Dutil, Rousse, and Quesada 2011).

However, strong evidence shows that putting these ideas into reality does not have the desired results. The lack of financial incentives to manage C&D waste is the main problem impeding the efficacy of C&D waste management initiatives. In other words, the main worry for all parties involved is whether they may gain additional benefits from undertaking C&D waste management because, up until now, the ecologically benign activity has not been high on the agenda. To address whether adopting C&D waste management procedures is cost-effective, research into cost-benefit analysis of C&D waste management is of utmost relevance (Liyin, Hong, and Griffith 2006).

The potential for selling specific waste materials and the removal of other waste from the site at no cost or a reduced cost, with a subsequent decrease in materials going to landfill at a higher cost, are two of the many economic benefits of waste minimization and recycling (Rogoff and Williams 2012). On the one hand, this will help construction companies cut costs. Subsequently, it improves the contractor's competitiveness by lowering production costs and projecting a better public image (Begum et al. 2006). On the other hand, they can promote recycling and reuse of garbage, delaying the exhaustion of the limited capacity of landfills(Li Hao, Hill, and Yin Shen 2008). As there have been previous attempts to examine the costs and advantages of C&D waste management, this study is not the first to recognize their significance. The cost-effectiveness of C&D waste management can be assessed using several tools from earlier studies.

### 2.3.7. Maintenance Liability

Fundamental phases in all natural cycles include birth, growth, maturity, decline, decay, death, and rebirth. Even though people like maintaining order, this also applies to a structure. Cycle under control, with upkeep till its demise, to serve human purposes (Amaratunga and Baldry 2000). University buildings are strategically located due to their business goals. The university's mission and vision are facilitated and enabled by its buildings. The structure benefits the university organization, the students, professors, parents, and other users and stakeholders. Although the buildings are not new production variables, their relative importance, compared to other university resources, has greatly increased. People's comfort and productivity are correlated with the performance of the buildings they live in, learn in, conduct research in, and work in (such as their homes, offices, schools, universities, and markets), not to mention the effect it has on the social fabric and economic expansion.

Therefore, any shortcomings in the building's functioning represent a loss of value for everyone with a stake in high-quality education. Buildings lose value for a variety of reasons or combined reasons. A structure may not function properly due to bad design, shoddy construction, faulty materials and components, incorrect installations and uses, and a lack of necessary maintenance.

However, even if the building was well-designed, with high-quality workmanship, materials, and professionally installed components, any discrepancy from the anticipated service life is attributed to maintenance. Maintenance would still be crucial even if the variables were accurate. As a result, structures cannot reach their full service life without upkeep.

As the value of the building's structure and the engineering services must be protected and sustained so that they are valuable to the users and clients, the requirement for maintenance will only grow. Building maintenance costs are high and are expected to stay high or perhaps increase in the years to come. For instance, maintenance accounts for around 70% of building running expenditures (Olanrewaju and Abdul-Aziz 2015). It also considers that maintenance work is required for more than 90% of a construction project's lifespan. However, in actuality, a building's life cycle begins when a choice to construct one is taken due to a need for more space (Rondeau, Brown, and Lapides 2012). The enormous expansion in maintenance work is also a result of the rise in land prices.

However, replacing, renovating, converting, or rebuilding every organizational building at once is almost impossible. For example, it is anticipated that it will cost £11 billion to replace the 1960s-era structures in English universities alone (Abdul Lateef, Khamidi, and Idrus 2011). Maintenance is distinctive and prominent compared to renovation, modification, conversion, and rebuilding projects. According to information acquired from the Ministry of Higher Education (MOHE) of Malaysia, maintenance costs for academic buildings increased by over 40% between 2005 and 2009. For instance, maintenance costs climbed from roughly 470 million in 2005 to more than 643 million in 2009.

### 2.3.8. New Construction Cost

The European Construction Industry Federation (FIEC) estimates that the construction industry contributed 6.6% of all employment in Europe in 2010 and made up 9.7% of the European Union's (EU) GDP, with a total construction value of $1186 billion (Alderman and Shelburne 2012). Construction is predicted to have contributed 5.6% of Canada's GDP in 2010 (Nasir et al. 2014). while in the US, the construction sector contributed 5.3% to the nation's GDP in 2011 (Nasir et al. 2014).

The US Bureau of Labor Statistics (BLS) reports that the construction industry directly employed over 11 million people, or roughly 8% of the total US employment. Construction productivity must, therefore, increase because it is a large sector of the national economy and significantly impacts economic growth. Increasing the construction industry's productivity and competitiveness calls for a worldwide viewpoint. Numerous studies have been done that compare production between nations or within nations (Lal 2003; van Ark, O'Mahoney, and Timmer 2008). An important factor in construction projects is considering the cost of new construction when comparing it against demolition and rebuilding. This criterion, sometimes known as "demolish and rebuild," refers to the choice to demolish existing buildings and create new ones. It necessitates thoroughly evaluating the project's goals, expenses, and benefits**.** Accurate and thorough cost estimation is necessary to effectively manage finances in building projects (Goodrum, Haas, and Glover 2002). Expenses for demolition and rebuilding should be divided into groups, including labor, supplies, machinery, licenses, fees for design work, and any other direct costs. This level of detail enables a more accurate comprehension of the project's financial ramifications (Finkel 1997).

Effective financial management considers the project's long-term financial ramifications and the original development expenditures. The running costs, maintenance costs, and energy consumption of a new construction are all factored into the lifecycle cost analysis. This approach aids in determining whether the expense of destruction and reconstruction is long-term financially viable(Doloi 2012). A crucial financial management component is raising the money required for demolition and reconstruction. This can entail securing loans, seeking grants, utilizing public-private partnerships, or investigating additional finance options.

Evaluation of the best financing alternatives based on interest rates, terms, and repayment plans is crucial to effective financial management (Duran, Lenihan, and O'Regan 2006). In order to prevent expensive fines and legal problems, it is crucial to ensure compliance with local building standards and secure required licenses. Any financial penalties or legal issues brought on by noncompliance may have an Adverse effect on the project's budge(Duran, Lenihan, and O'Regan 2006).

### 2.3.9. Emotional Attachment

People still express and act on their strong devotion to specific locales. People and communities give places meaning, and these meanings can be very potent sources of identity. A crucial concern for experts and organizations is understanding and conveying social values in heritage evaluations and conservation activity. However, the quantity of visitors depends on several variables, such as the popularity of the website, its accessibility, or how it is promoted. The heritage sector is always looking into ways to pinpoint and capitalize on social and cultural values. Historically significant sites are now a key research focus on tourists and the host community (Chhabra, Healy, and Sills 2003; Poria, Reichel, and Biran 2006). Before tackling the important concerns involving neighboring heritage sites and local communities, it is necessary to establish what constitutes a local community. Human settlements near a particular heritage site may be seen as the community regarding geography or space (Joppe 1996).

According to Mowforth and Munt's book Tourism and Sustainability (2003), the local communities in Third World nations receive few benefits from tourism because they have little influence over how the industry develops, they lack the financial resources to compete with outside investors, and their opinions are rarely heard, while the need for their opinion is a must when it comes to the decision of building or demolishing old or heritage buildings.

### 2.3.10. Reflection of Owner's Reputation After Taking a Decision

Community-related construction activities, such as housing programs, infrastructure improvements, and public facilities, are inextricably linked to the health and cohesiveness of the communities they serve. These initiatives necessitate careful consideration of numerous stakeholders' interests, making project owners' decisions very public and significant. The decisions taken during the project's lifecycle can greatly impact the owner's reputation (Daniel and Pasquire 2019). In the building sector, the owner seeks to achieve a high-quality facility through quality planning, quality design, and quality construction.

The degree of compliance to a predetermined performance standard is typically used to define and assess quality. During the planning, design, and construction phases, a diligent application of a carefully thought-out quality assurance program conducted through a quality-control system ensures the quality of the finished product. Project owners share three objectives: excellent quality, cheap cost, and quick completion (Smith et al. 1975). However, because they somewhat conflict with one another, these three objectives are rarely fully attained. The owner must explicitly define and express each of these goals, and there must be trade-offs between them.

Additionally, the owner should have the strongest motivation to define these objectives and establish the order of importance for project completion. Because the owner's position is the most crucial, the feasible level of quality starts with them. Anyone seeking or paying for planning, design, and construction services is considered the owner, whether a client, user, contracting officer, or another entity.

Owners are categorized based on their level of sophistication. Owner sophistication might range from an organization with no engineering facilities to one with internal engineering and construction facilities (Demkin and Architects 2001). As a result, the management of a Construction project has not been standardized and is primarily dependent on the creativity and expertise of a certain construction company. Due to the various nationalities of the Construction personnel, this diversity is quite obvious. In practice, various strategies have been applied. Some project owners prefer a high level of involvement, while others prefer a low level of involvement (Al-Jarallah 1983)".

Owners who continually make choices that put sustainability, openness, and the community's well-being first tend to build confidence among stakeholders. Trust is a vital asset that can improve an owner's reputation (Daniel and Pasquire 2019). Stakeholders are more inclined to cooperate and support initiatives when reputable owners, including the local community, government organizations, and investors head them. An owner's reputation can be enhanced by aggressively soliciting the community's input and involving them in decision-making processes (Almahmoud and Doloi 2015). This strategy shows a dedication to diversity and responsiveness, which may result in more community support and buy-in. An owner's reputation can be improved using ethical business practices, such as fair labor procedures, environmental responsibilities, and regulatory compliance (Daniel and Pasquire 2019). The public and regulatory bodies are more likely to favor owners who prioritize ethical matters. On the other hand, owners who emphasize cost-cutting over quality or safety risk their reputations tarnished (Daniel and Pasquire 2019).

### 2.3.11. Social Acceptance (Building Aesthetics)

Given the significance of aesthetics for human physiological and psychological well-being, architects and designers should be aware of the significance of using aesthetic principles to make the environment more "livable" and appealing. Understanding aesthetics also helps people learn how to handle issues in order to create aesthetically beautiful places and contribute significantly to the acceptable standard of living for people (Mahdavinejad et al. 2014).

Architecture is a design process That puts functional elements together to create a physical environment that is functionally effective, economically feasible, and aesthetically beautiful. It generally involves programming, designing, and construction phases. These are the primary evaluation criteria for architectural design education at architecture schools. The statement "An ability to create architectural designs that satisfy both aesthetic and technical requirements" is included as one of the educational goals in the UNESCO/UIA Charter for Architectural Education. Architects make buildings, and cities are made of buildings. The designer simultaneously holds the role of a decision-maker for the future of that environment. The word "aesthetice," which means "to perceive," is the root of the English word "aesthetics." It was first described in 1735 by the philosopher Alexander Gottlieb Baumgarten as "the science of how things are known through the senses." Shortly after Baumgarten introduced its

Latin form (Aesthetica), the word aesthetics was used in German, but it wasn't commonly used in English until the early 19th century.

Building aesthetics encompasses a broader social viewpoint on built environments' visual, spatial, and design elements and goes beyond artistic appreciation (Forceville 2007). As a result, a key factor in completing construction projects is the social approval of architectural aesthetics. This acceptance has a multifaceted effect that affects project outcomes in various ways, both directly and indirectly (Karpouzis et al. 2007). The location's cultural and historical context must be considered while making construction aesthetic decisions. More favorably, stakeholders and the general public receive buildings that respect and complement the region's architectural heritage (Amaral, Meurers, and Ziai 2011). Famous structures can become markers of a community's identity. They increase cultural relevance and a sense of pride, which benefits communal cohesion. The contentment and well-being of a building's occupants can be impacted by its aesthetics (Bubshait and Al-Musaid 1992). Enhancing user experiences in pleasant surroundings increases output, health, and overall pleasure. Buildings with poor aesthetics could be considered eyesores and face criticism from the public, demonstrations, and legal troubles. The reputation of project participants may be affected by aesthetic considerations (Nwanguma and Akah 2019)

### 2.3.12. Historically Significant

Collective memory is a fundamental aspect of historic preservation. "Revalue and re-present the past through saving, maintaining, and/or reconstructing historic structures and artifacts" is the movement's overarching objective in the US. From an ideological standpoint, preservationists favor authenticity over replication.2 (Barthel 1989). The modern preservation movement is in favor of "plurality in preservation," which entails preserving not only buildings of exceptional architectural or historical significance but also tangible structures deemed "representative" of a variety of cultures and historical periods(Barthel 1989; Tyler, Tyler, and Ligibel 2018).

Preservationists initially battled to protect locations associated with American history. Still, over time, they shifted their focus to protecting locations that represented a more inclusive and diverse view of the past. Nowadays, preservationists advocate for preserving Main Streets and historic neighborhoods to preserve community and the vernacular architecture associated with various socioeconomic and architectural histories, including those of the underprivileged and non-White (Barthel 1989). From a strategic standpoint, the movement has succeeded in justifying the preservation of the historic built environment by broadening the scope of its objective. The movement aims to preserve as much of the historic built environment as possible, even though it still supports preserving structures associated with historical personalities and events. The response from preservationists is frequently that they believe the historic built environment to be intrinsically valuable and deserving of preservation. That environment becomes significant to these people simply because of its existence. They are drawn to historic structures with various histories and styles, not just those connected to clearly noteworthy historical figures and events (Barthel 1989).

This viewpoint poses two important queries: For these preservationists, how do their beliefs relate to collective memory? The argument made by opponents of preservationism is that it prioritizes the protection of historic buildings over the interests and rights of local populations and that preservationists are only interested in "buildings, not people." It is more correct to state that preservationists are concerned with "buildings, not history," or more specifically, the histories of buildings rather than the histories of people and events, based on a study of the preservation community in New Orleans, Louisiana (Elliott, Gotham, and Milligan 2004)..

### 2.3.13. Additional Life Span

In many nations worldwide, initiatives to promote sustainability are made or broken by the built environment. Often referred to as the "forty percent sector," the building industry accounts for 40% of the world's energy and resource usage (Dutil, Rousse, and Quesada 2011). Avoiding the creation of new land for new construction is another advantage of repurposing buildings with a certain amount of rehabilitation and adaption. This quality is especially significant for establishments like colleges with restricted land access in the same area as their current operations. Over the past 20 years, there has been a rise in interest in studies concerning the potential consequences of repurposing existing structures. The notion of repurposing, which is synonymous with the concept of adaptive reuse in the literature, is used in this study. Repurposing and adaptive reuse entail keeping most of the original building, such as the structure, while modernizing other components to meet evolving user needs and new requirements (Bullen 2007).

### 2.3.14. Project Duration

Cost, speed, and quality are crucial factors in the country's economic stabilization, brought about by the more prosperous construction sector (Finkel 1997). Meeting the project's initial business case and completing these three tasks within the allotted time frame constitute the project's success metrics. Most of the construction industry's failures are ascribed to project-related issues that cause delays in completion (Bubshait and Al-Musaid 1992).

Over the past five years, research in Asia, Australia, and Africa has focused on the crucial influencing elements contributing to building project delays (Baloi and Price 2003). These studies have made a substantial contribution to identifying important factors that cause delays in construction projects; however, relatively few of them have looked at the relationship between these factors and the size or experience of the firm (Al-Jarallah 1983). For example, large construction companies in Ghana and Saudi Arabia tend to be more prone to project delays than small ones (Bubshait and Al-Musaid 1992). (Bubshait and Al-Musaid 1992) Their analysis of Middle Eastern businesses found that the propensity for delays grows along with the businesses' observed experience. However, the duration of a building project involves intricate interactions with many different variables, which is influenced by those factors (Baloi and Price 2003). Thus, creating a descriptive model that identifies the optimal selection of variables may improve the explained variation for creating a predictive model and make its practical goals easier to comprehend.

### 2.3.15. Current Building Condition

Usually, asset managers must rely on limited information regarding the true condition of their assets when choosing between maintenance and renewal options. Performance measurement is crucial to comparing and creating improvement initiatives (Jensen and Varano

2011). and this typically results in significant financial waste; unnecessary or inappropriate maintenance tasks result in the inefficient utilization of one-third of all maintenance costs. Furthermore, studies show that most construction industry participants—designers, contractors, suppliers, and owners—squander a significant amount of money searching for, verifying, and/or reproducing facility information that ought to be easily accessible (Jones and Sharp 2007). A thorough literature assessment on KPIs for measuring facility performance was conducted. Financial, physical, and functional KPIs were separated and connected to qualitative indicators and evaluation processes (Jones and Sharp 2007).

Primarily in connection to the Facility Condition Index (FCI), which measures the ratio between maintenance costs and the facility's current replacement value, and the Function Index, which measures how well space is used. The FCI is an imprecise indicator of an asset's actual state, as demonstrated by numerous other KPIs examined (Veisi et al. 2022). A building's FCI may be higher. The utility system might be more vulnerable to failure than the FCI for a utility system due to the state of a less expensive component that is essential to its functioning. The FCI cannot explain the state of its essential parts and, as a result, falls short of capturing this crucial distinction on its own.

### 2.3.16. Variance Between Current and Future Energy Use Index (EUI)

At present, the global economy is experiencing significant energy changes. Energy efficiency generated by reducing energy use has been identified as the most important means of providing the world's energy requirements(Gustavsson and Joelsson 2010).

On the other hand, the importance of energy efficiency in old building renovations is often overlooked. Old buildings are energy, material, and technology inefficient. Full renovation of an old building is a complex process that involves the collective effort of various parties, such as architects, engineers, contractors, and building owners. This process provides the opportunity to rectify energy inefficiency and implement energy-saving measures. In the Republic of Ireland, many old buildings face the need for renovation and energy efficiency improvement. However, the effectiveness and suitability of full renovation work in achieving significant energy efficiency improvement have not been fully investigated (Liyin, Hong, and

Griffith 2006). For end-of-life building stock, reducing energy and resource consumption as well as other environmental implications can be accomplished by recovering building waste through material reuse, and recycling is the process of selectively demolishing a building and reusing its systems to repurpose it (Bullen 2007).

The possible life cycle environmental effects of building repurposing through structural reuse and destruction Successive situations involve the construction of a new building adjacent to an existing library tower. These are examined and compared in this study. New building design alternatives with and without a Trombe wall are presented for both scenarios. Using the Athena Eco Calculator for Commercial Assemblies, the life cycle stages of resource extraction and construction, building assembly replacement, maintenance, and repair and disposal were analyzed. The effects of energy use on building operations were left out (Olanrewaju and Abdul-Aziz 2015). Repurposing scenarios demonstrated a possible reduction in six of the seven environmental effect categories evaluated, ranging from 20% to 41%. The Eutrophication Potential has the largest reduction, at 37%, followed by the Smog Potential. Criteria for Human Health is the impact category with the  Acidification Potential, which comes in second at 29%, with the least reduction at 20% (Plank 2008).

When choosing to pursue repurposing following selective deconstruction over destruction and new construction, there is an averted impact of 33 and 34%, respectively, on global warming potential and fossil fuel use. These two metrics are highly associated (Plank 2008). Repurposing has advantages over new development demolition beyond avoiding Adverse environmental effects.

After thoroughly evaluating the sub-criteria in conjunction with industry experts, we have determined sixteen important sub-criteria that show the most significant influence from the previously listed sub-criteria. This selection procedure thoroughly evaluates each sub-criterion's applicability, significance, and potential impact on the final choice. The following sixteen parameters shown in (Table 2.5) were determined to have the greatest impact. As they are the most important variables in our sustainable decision-making process, these sub-criteria will be the core focus of our analysis and decision-making framework.

**Table 2. 6 Selected sub-criteria.**

| Criteria | Sub-criteria |
|---|---|
| **Environmental** | Green House Gas Emission Amount During Construction |
| | Materials Reuse Potential |
| | Green House Gas Emission Amount during operation and maintenance |
| | Solid Waste Amount During Construction |
| **Economical** | Return on Investment (ROI) |
| | Demolition Cost |
| | Maintenance Liability |
| | New Construction Cost |
| **Social** | Emotional Attachment |
| | Reflection of owner's reputation after making a decision |
| | Social Acceptance (Building Aesthetics) |
| | Historically Significant |
| **Technical** | Building addition lifespan |
| | Project Duration |
| | Current Building Condition (FCI) |
| | Variance between current and future Energy Use Index (EUI) |

## 2.4. Current Alternatives for Sustainable Decision-Making

When it comes to selecting the most sustainable method in the realm of building construction, decision-makers confront several options. The choice may have far-reaching consequences for the environment, economic viability, and social elements, adaptive reuse, historic preservation, partial demolition and reconstruction, selling or leasing, EPC, green building certifications, and PPP were considered but not feasible for the decision support system. Large initial investments and complex regulatory approvals make adaptive reuse and historic preservation unfeasible on time and budget. Unexpected costs and structural issues can arise from partial demolition and reconstruction. Property sales and rentals change maintenance but do not guarantee improvements. Long-term contracts and performance guarantee complicate EPC and green building certification. PPPs require extensive stakeholder coordination, delaying decision-making. These issues weakened the DSS, forcing it to prioritize renovations, relocation, and replacement. In this part, we are trying to investigate the current alternatives for sustainable decision-making in building construction, with a focus on four options:

1. Major renovation
2. Minor renovation
3. Building relocating
4. Building replacement

### 2.4.1. Major Renovation for the Building

Buildings now account for 40% of energy consumption and 36% of $CO_2$ emissions (Bourrelle, 2014). Modern buildings typically use less than 3-5 liters of heating oil per square meter per year, but older structures consume over 25 liters on average. Some buildings even require up to 60 liters. (Bourrelle, 2014). Building renovation is gaining popularity worldwide right now (Sartor & Dewallef, 2017). The fundamental cause is that around 35% of EU buildings are over 50 years old (Ball, 2016). As a result, if they are not carefully maintained during their lives, they become less appealing.

For factors such as poor indoor air quality and thermal comfort. In the context of retrofitting, improving energy efficiency (Bertoldi & Mosconi, 2020). Total energy usage and $CO_2$ emissions may be reduced by 5-6% and 5%, respectively(Bourrelle, 2014). Increasing energy efficiency and carbon emissions parameters are not the primary aims of building renovation. Energy and resource-conscious design are known as environmentally friendly concerns. Considering only them for a project is not viable if it is nonfunctional, expensive, and poorly designed. Historical value, identity, beauty, integrity, inventiveness, and so on are all rich, unquantifiable reasons why people continue to cherish and live in their current buildings throughout time, and these must be included in alternative rehabilitation ideas. It thus necessitates considerable considerations in this context to develop a high-performance building (consistent with sustainability in its broadest meaning) using a holistic and integrated design approach (including many stakeholders) that ensures all design goals are accomplished (Ma et al., 2012).

### 2.4.2. Building Replacement

Construction and demolition (C&D) waste refers to waste that is produced during the construction, renovation, or demolition of structures. (Yeheyis et al. 2013). Construction and demolition (C&D) trash often constitutes a significant portion of the municipal solid waste, ranging from 20-30% to over 50%. Most construction and demolition (C&D) waste comprises wooden products, asphalt, drywall, concrete, and masonry. Metals, plastics, soil, shingles, insulation, and paper and cardboard are frequently included in substantial numbers (Yeheyis et al. 2013). 32% of the world's resources, including 12% of water and up to 40% of energy, are used by construction operations. Construction uses about 25% of virgin timber and 40% of all raw resources taken from the land. 32% of the world's resources, including 12% of water and up to 40% of energy, are used by construction operations.

Construction uses about 25% of virgin timber and 40% of all raw resources taken from the land(Yeheyis et al. 2013). C&D waste has had detrimental effects on the environment, economy, public health, and social life (health hazards, use of public space, pest proliferation, and impact on workplace safety), as well as on the environment (water and soil pollution, air pollution, climate change, and adverse effects on flora and fauna) (Jain 2021). Most policies in industrialized countries have supported C&D waste management since the conclusion of World War II. Many of these rules aim to lessen their Adverse effects on the environment. With harsh taxes and penalties, incentives have frequently been implemented to reduce the use of virgin materials and deter landfilling and cremation of C&D waste (Poon 2007).

Waste minimization and avoidance by recycling and reusing waste to energy possibilities (where available) and safe disposal and discharge only as a last resort are the key C&D waste management strategies (Marchettini, Ridolfi, and Rustici 2007). The primary causes of C&D waste production include incorrect design decisions, poor procurement and planning, ineffective material management, leftover raw materials, and unanticipated changes in building design. On the other hand, advancements in construction methods and building design may greatly aid in waste reduction (Bossink and Brouwers 1996).

### 2.4.3. Minor Renovation

Data Constructions play a significant role in environmental effects. On the one hand, they are responsible for about 40% of the energy used in the European Union. Due to this, structures are energy efficient, which is a key component of EU strategy(Simson et al. 2022). On the other hand, they constitute a significant source of hazardous environmental emissions and use many natural resources (materials, water, etc.). According to the European Commission, life cycle assessment (LCA) offers the best framework for evaluating the possible environmental effects of products(Kögler and Goodchild 2006).

Is it more sustainable to renovate rather than create new buildings? This is an issue that has lately been raised on the subject of building LCA (Palacios-Munoz et al. 2018). The majority of the LCA literature is devoted to the new building. Whereas renovation is only partially addressed. It has only lately been investigated how renovating an old building compares to demolishing it and establishing something new (Assefa and Ambler 2017) (Alba-Rodríguez et al. 2017) (Schwartz, Raslan, and Mumovic 2018). The outcomes of such a comparison rely on the construction methods used, and the performance levels attained during renovation and new construction, and the caliber and longevity of the building components.

Life span is a crucial element in the LCA (Pan, Li, and Teng 2018). and the outcome depends heavily on it (Islam, Jollands, and Setunge 2015). (Marsh 2017) also demonstrates that environmental impacts decrease as building lifetime increases. (Marsh 2017) claims that, in contrast to a lifespan of 50 years, a building's environmental effect is reduced by 29% on average during an 80-year lifespan, 38% over a 100-year lifespan, and 44% over a 120-year lifespan. According to (Marteinsson 2005), the primary driver of building destruction in actuality is not physical deterioration but rather subjective perception (44%), followed by a change in use (26%). Just 17% of the projects resulted from deterioration (Marteinsson 2005). This implies that structures are destroyed before they expire physically, which is non-sustainable human behavior. The construction industry might operate more sustainably by altering how people think about a building's service life.

### 2.4.4. Building Relocation.

Structure relocation decisions are difficult since they involve significant financial outlays and a difficult engineering challenge. There are numerous potential reasons for moving. In most cases,the choice to move a structure is influenced by its past. The choice is made simpler if the structure is noteworthy historically. The most common reason for moving historic buildings is to protect them from natural disasters or demolition when they obstruct local development plans. Sometimes, historical buildings are moved to a museum, where they are shown as an exhibit. When the moved structure is significant to its owner, sentimental reasons are the second most common reason for relocation (Paravalos 2006). The third reason is sprucing up the place and getting it ready for a new owner. Nowadays, sales offer made to cleanse the region have become increasingly common. Savings-minded investors may offer a very low price for a structure in return for transferring it from its current site.

When a structure poses a risk to the neighborhood, it may be essential to relocate it, or a whole town or community may need to be moved. An example would be mining activity that endangers life in the area because it damages the environment so severely and degrades it. The decision to relocate a structure that does not fit the surrounding buildings architecturally may also be influenced by new trends and advancements. When deciding to relocate, several factors must be considered (Paravalos 2006). The first is the relocation cost, which must be contrasted with the price of erecting a brand-new building at the desired location. Structure swaps can occasionally be a good solution. Sadly, it needs locating a party eager to buy the building. The size of the building also influences the selection; a larger building requires a more complex (and consequently more expensive) relocation. The distance between the locations is another factor. The expense and difficulty of relocation will increase with distance from the destination location. The price of all licenses, insurance, fuel, transportation, and assistance from service providers must be included in the relocation budget (particularly electricity).

## 2.5. Multi-Criteria Decision-Making and How it Can Be Used

Essential stages in all natural cycles encompass inception, development, maturation, deterioration, decomposition, demise, and regeneration. While individuals prefer maintaining order, this inclination extends to a framework or system. The cycle is managed and maintained until it ceases to function to fulfill human objectives. University buildings are deliberately positioned to align with their commercial objectives. The university's buildings are facilitators and enablers of its mission and vision(Veisi et al. 2022). The structure of the university organization is advantageous for the students, instructors, parents, and other users and stakeholders.

While the buildings themselves are not newly produced variables, their relative significance compared to other university resources has significantly escalated. The performance of buildings, including houses, offices, schools, universities, and markets, directly impacts people's comfort, productivity, social fabric, and economic growth. Hence, deficiencies in the building's operation result in a decrease in the worth of all individuals invested in top-notch schooling (Triantaphyllou 2000). Buildings depreciate due to a multitude of factors, either individually or in combination. A structure's malfunction can be attributed to poor design, substandard construction, defective materials and components, improper installations and usage, and insufficient maintenance. Regardless of the building's excellent design, superior craftsmanship, top-notch materials, and expert installation, any deviation from the expected lifespan is solely attributed to maintenance (Aruldoss, Lakshmi, and Venkatesan, n.d.).

Nevertheless, maintenance would still be required even if the previously indicated factors were precise. Consequently, structures are unable to achieve their maximum lifespan without maintenance. To maintain the value and functionality of a building's structure and engineering services, it is imperative to prioritize and sustain regular maintenance. Failure to do so will result in a decline in value and usefulness over time. The expenditures associated with building upkeep are currently substantial and projected to remain at a high level or even rise. Specifically, maintenance comprises approximately 70% of the total operating expenses for the property.

Furthermore, it is important to consider that maintenance work is necessary for over 90% of the duration of a building project. However, in reality, the life cycle of a structure commences when a decision is made to create it in response to a requirement for additional space (Triantaphyllou 2000). The significant increase in maintenance work can be attributed to the concurrent surge in land values.

However, simultaneously replacing, remodeling, converting, or reconstructing every organizational structure is impractical. For instance, the estimated cost of replacing outdated buildings in English universities from the 1960s is £11 billion (Aruldoss, Lakshmi, and Venkatesan, n.d.). Maintenance stands out and is highly noticeable compared to other projects such as refurbishment, modification, conversion, and rebuilding. As per data from the Ministry of Higher Education (MOHE) of Malaysia, the expenses for maintaining academic buildings increased by more than 40% from 2005 to 2009. For example, the maintenance expenses increased from approximately 470 million in 2005 to over 643 million in 2009.

Buildings are not constructed solely for their purpose but rather to enhance the value they contribute to the objectives and vision of the company. This appears to be the initial stage toward a comprehensive and precise definition. In addition, the definitions fail to include any correlation between maintenance and the efficiency of buildings. In addition, these definitions and understanding can only lead to appropriate upkeep, even if the building is the maintenance focus (Aruldoss, Lakshmi, and Venkatesan, n.d.). There is no valid reason to initiate maintenance services solely based on the physical condition of the structure. The paramount importance for building users or client-occupiers is in the building's capacity to facilitate the execution of activities within and near the structure rather than its physical state. Like other MCDM techniques, the criteria weights, in this case, represent their relative significance in the decision-making process. Due to the diverse viewpoints and interpretations, not all evaluation criteria hold the same significance level (Triantaphyllou 2000).

Subjective and objective methods are the two sorts of weighing techniques, with subjective methods being qualitative and objective methods being quantitative. The subjective approaches assign weights based on the preferences or assessments of decision-makers. Nevertheless, objective methodologies such as the entropy and multiple objective programming determine weights by solving mathematical models, disregarding the decision maker's preferences. The primary objective of Decision Support Systems (DSS) is to streamline the problem-solving process by using both quantitative data and qualitative knowledge. This involves evaluating and prioritizing many choices, ultimately picking the one that best aligns with the set criteria (Aruldoss, Lakshmi, and Venkatesan, n.d.).

MCDM methods encompass a spectrum of approaches, ranging from individual methods like AHP and Fuzzy Sets to a mixture of ways known as the hybrid approach. Hybrid systems in multi-criteria decision making (MCDM) involve the integration or fusion of individual processes with other techniques, such as Analytic Hierarchy Process (AHP) combined with Fuzzy sets, AHP combined with Delphi and Fuzzy sets, Analytic Network Process (ANP) combined with Monte Carlo Simulations (MCS), Fuzzy sets combined with Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), AHP combined with TOPSIS in a Fuzzy environment, AHP combined with ELECTRE and Fuzzy sets, and Group-based Similarity Technique (GST) combined with TOPSIS, among others.

In recent decades, numerous (MCDM) approaches have been created, with the most widely recognized ones being AHP, ANP, TOPSIS, ELECTRE, VIKOR, and PROMETHEE. The following paragraphs provide concise explanations of various widely recognized MCDM methods.

### 2.5.1. Application of MCDM in Construction

In their 2021 study, (Zhu, Meng, and Zhang 2021) examined 530 papers on civil engineering construction published between 2000 and 2019. They specifically assessed the utilization of (MCDM) in the construction industry (Zhu, Meng, and Zhang 2021).

The researchers documented the utilization of 29 individual techniques and 94 combined techniques. The top five single approaches, based on the number of papers they were used in, are as follows: AHP, which was used in 60 papers; Fuzzy theory, which was used in 52 papers; Generic Algorithm, which was used in 24 papers; Data Envelopment Analysis, which was used in 16 papers; and Analytical Neural Process, which was used in 14 papers. The main hybrid approaches used in building are Fuzzy-AHP (mentioned in 53 papers), Fuzzy-TOPSIS (mentioned in 28 papers), AHP-Fuzzy-TOPSIS (mentioned in 8 papers), Fuzzy-ANP (mentioned in 8 papers), ANP-DEMATEL (mentioned in 7 papers), and Fuzzy-DEMATEL (mentioned in 7 papers).

The two dominant hybrid categories consist of approaches that use fuzzy logic (utilized in 159 publications, accounting for 30.00 percent) and ways that incorporate AHP (employed in 104 papers, representing 19.62 percent) (Zhu, Meng, and Zhang 2021). The search conducted in the 'Scopus database using the keywords 'mcdm' and 'construction' for 2020-2021 reveals that 136 newly published journal articles exist. These publications focus on applying single and hybrid approaches to MCDM. Six of the 37 articles employed a single approach, while the remaining 31 combined the fuzzy theory with various methods such as TOPSIS, ANP, AHP, PROMETHEE, CORPAS, GIS, VIKOR, etc. AHP was utilized exclusively in three studies, while in conjunction with other methodologies, it was employed in an additional four pieces. TOPSIS was employed in a total of 7 publications, with two instances of it being used as a standalone approach and the remaining five involving a combination with other methods. PROMETHEE and VIKOR were employed on two occasions each, in addition to other methodologies.

### 2.5.2. Method Chosen for this Research with Justification

As previously mentioned, AHP and TOPSIS are the predominant MCDM methodologies employed in building. Except for a few, these methods were integrated with Fuzzy theory to remove precise values and provide ambiguity to address uncertainties, imprecision, or a lack of information. The fuzzy Analytic Hierarchy Process (FAHP) is a highly effective method for assigning weights to criteria in (MCDM). Consequently, it was employed in this study to provide significance to the sixteen selected criteria.

While the triangle membership function is commonly employed in FAHP due to its simplicity, the trapezoidal function is more effective in dealing with errors, imprecision, or a lack of information. Thus, the trapezoidal membership function was employed in this study. In addition, a basic decision matrix was employed as an experiment to determine the weighting of the criteria. This was done due to the growing discrepancy of data in FAHP when additional criteria are included. The decision to utilize Fuzzy TOPSIS for ranking the options was based on its widespread usage, familiarity, and simplicity as a decision-making tool, which is accepted by both industry and academics.

## 2.6. Literature Review Summary

Sustainable development encompasses the judicious utilization of natural resources, the promotion of economic growth, the reduction of unemployment, the safeguarding of the environment, and the advancement of social progress that caters to the needs of all individuals. The triple bottom line concept prioritizes the economic value, as with most single criterion techniques, and development's environmental and social values. Several academics have contended that technical performance should be explicitly incorporated as a fundamental aspect of infrastructure sustainability theory. They have put forth four pillars (environmental, technical, economic, and social) as the crucial analytical components of sustainability theory for civil infrastructure. Technical sustainability, the fourth pillar, pertains to the aspects associated with the performance, quality, and lifespan of a building or structure.

The construction industry is increasingly focusing on sustainable development due to the expanding limitations on resources, the participation of a larger number of stakeholders, and the need to meet environmental, economic, and social objectives in a balanced manner. Various studies indicate that the building and construction sector is responsible for 36% of worldwide energy consumption and 37% of energy-related carbon dioxide emissions over its entire lifecycle (Schwietzke, Griffin, and Matthews 2011), including construction, operation, maintenance, and demolition. This underwhelming result serves as a stark reminder to the building industry of the urgent need to minimize adverse effects and enhance global sustainability.

The assessment of the technical, economic, social, and environmental aspects of sustainable construction might involve several subsets of criteria, which may vary depending on the type and characteristics of the construction projects. The choice of sub-criteria is likewise contingent upon the user's choices. To complete the compilation of sub-criteria suitable for this research, we are soliciting the viewpoints of multiple industry experts and university researchers.

Multi-criteria decision-making (MCDM) has been widely employed in the construction industry to determine the most optimal choice among multiple possibilities. MCDM approaches generate alternative scenarios, establish criteria, assess alternatives, weigh the criteria, and rank the alternatives. Due to the subjective nature of evaluating criteria, not all criteria hold the same significance level. The criteria weights indicate their respective significance in the decision-making process. MCDM methods encompass individual approaches, such as AHP or Fuzzy Sets, and combinations of methods known as the hybrid approach. Examples of the hybrid approach include Fuzzy sets + TOPSIS, AHP + TOPSIS in a Fuzzy environment, AHP + ELECTRE + Fuzzy sets, and AHP + VIKOR.

## 2.7. Identification of Research Gap

The literature reviews reveal a lack of research on selecting the most sustainable option for old buildings with high maintenance requirements, assessing sustainability indicators of materials, analyzing the energy efficiency of green buildings, and other related topics. Building construction is a highly important task in this industry. However, until now, none of the projects have effectively involved all stakeholders. This framework aims to collaboratively determine the most desirable sustainable alternative for the project from its very beginning.

In addition, while some researchers have contended that the technical aspect is a crucial component of assessing the sustainability of civil infrastructure, there is a lack of comprehensive studies that effectively combine the technical aspect with the economic, social, and environmental aspects to analyze the overall sustainability factors. According to interviews with multiple industry experts, it was determined that the choice of alternatives for historic buildings is typically based on technical and economic considerations. Currently, there is a lack of a systematic instrument that can effectively incorporate all parties' viewpoints and evaluate the various aspects of sustainable construction during the selection process.

Thus, there is now a deficiency in developing a (MCDM) model, also known as a Decision Support System (DSS), that integrates the preferences of all stakeholders to select the most sustainable option and evaluate the four pillars of sustainable construction.

This study aims to create a (MCDM) model that incorporates the preferences of all parties involved. Considering technical, economic, social, and environmental factors, the model will determine the best sustainable option for renovating ancient buildings. The academic community will gain advantages by systematically including technical elements with the regularly utilized three pillars. The MCDM model will benefit the industry by assisting in selecting the most sustainable option.

# Chapter III

# Methodology

## 3.1. Introduction

Decision-makers frequently encounter complex issues when assessing construction projects in their pursuit of sustainable construction practices. Creating a decision support model is necessary due to the requirement for a systematic and thorough approach to evaluate these projects. This chapter outlines the research framework, discusses the hierarchy of decision problems, and clarifies the calculations, specifically using the Fuzzy Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) for sustainable construction project evaluation.

## 3.2. Research Framework

The design of the research framework, as shown in (Figure 3.1), considers the difficulties involved in assessing sustainable construction projects. It incorporates multidisciplinary viewpoints and sustainability facets, including technical, social, environmental, and economic considerations. This framework aims to comprehensively understand project performance and help decision-makers choose the most environmentally friendly options.

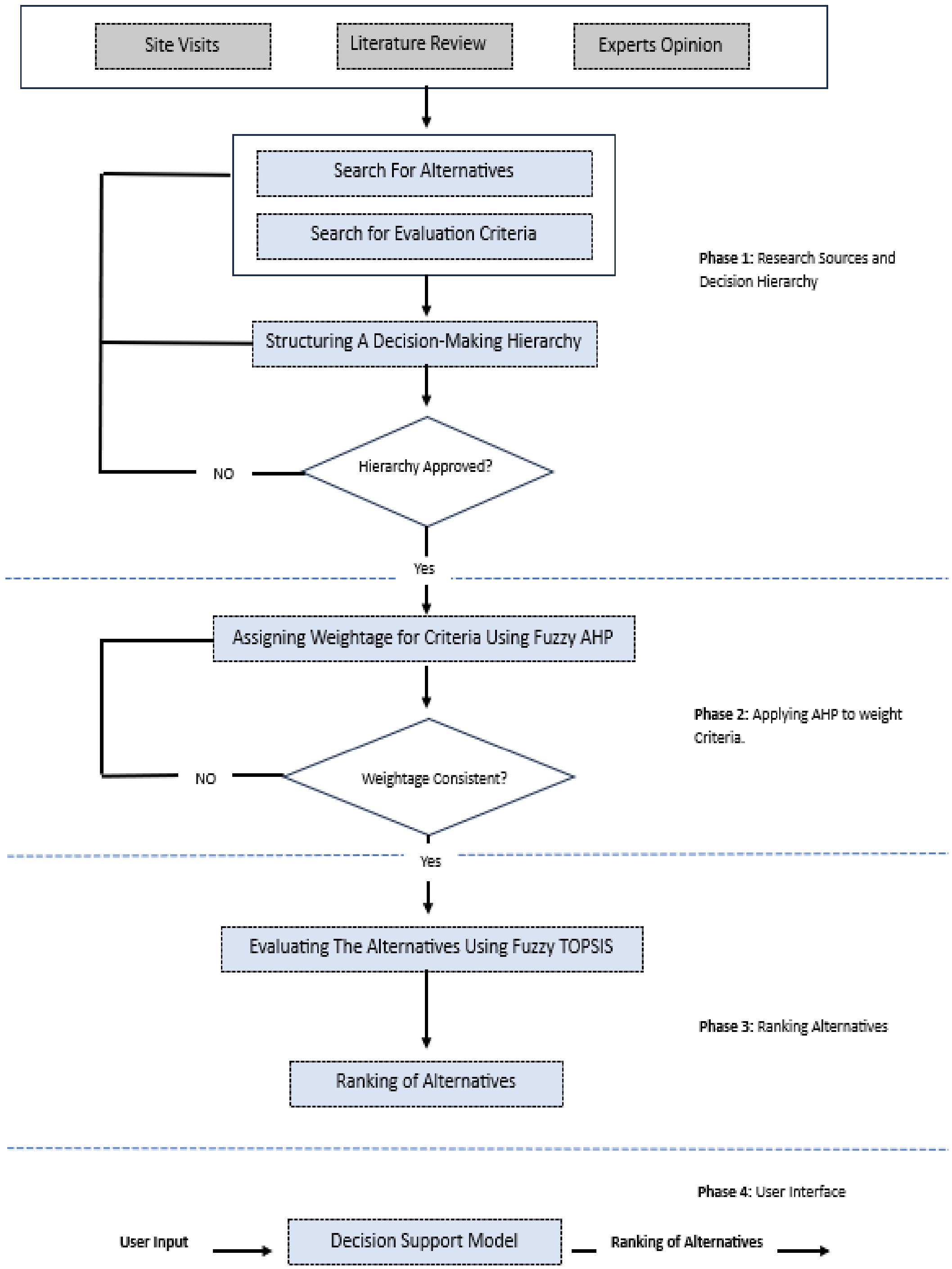


**Figure 3.1. Research Framework**

### 3.3. Assumptions and Considerations

This study considered 16 evaluation criteria, four from each pillar of sustainable construction, and four alternative approaches to dealing with old buildings with unmanageable maintenance requirements. A Fuzzy AHP with a trapezoidal membership function was used to determine the weighting of the criteria. With the weights obtained through Fuzzy AHP, Fuzzy TOPSIS was used to rank the alternatives. It was observed during data collection that the number of criteria increases the inconsistency in pairwise comparison for Fuzzy AHP. To ensure consistency of inputs, users typically had to modify their responses several times. A decision matrix was created using the abovementioned methods to rank the alternatives and assign weights to the criteria.

### 3.4. Hierarchy of Decision Problem

The overall goal of the three-stage decision hierarchy shown in (figure 3.2) is to choose the most sustainable course of action from among four options: major renovation, minor renovation, building replacement, and relocation. These three phases cover sustainability under the four main categories: environmental, economic, social, and technical. Each of these pillars also includes four sub-criteria, resulting in a comprehensive framework for assessing the decision's sustainability.

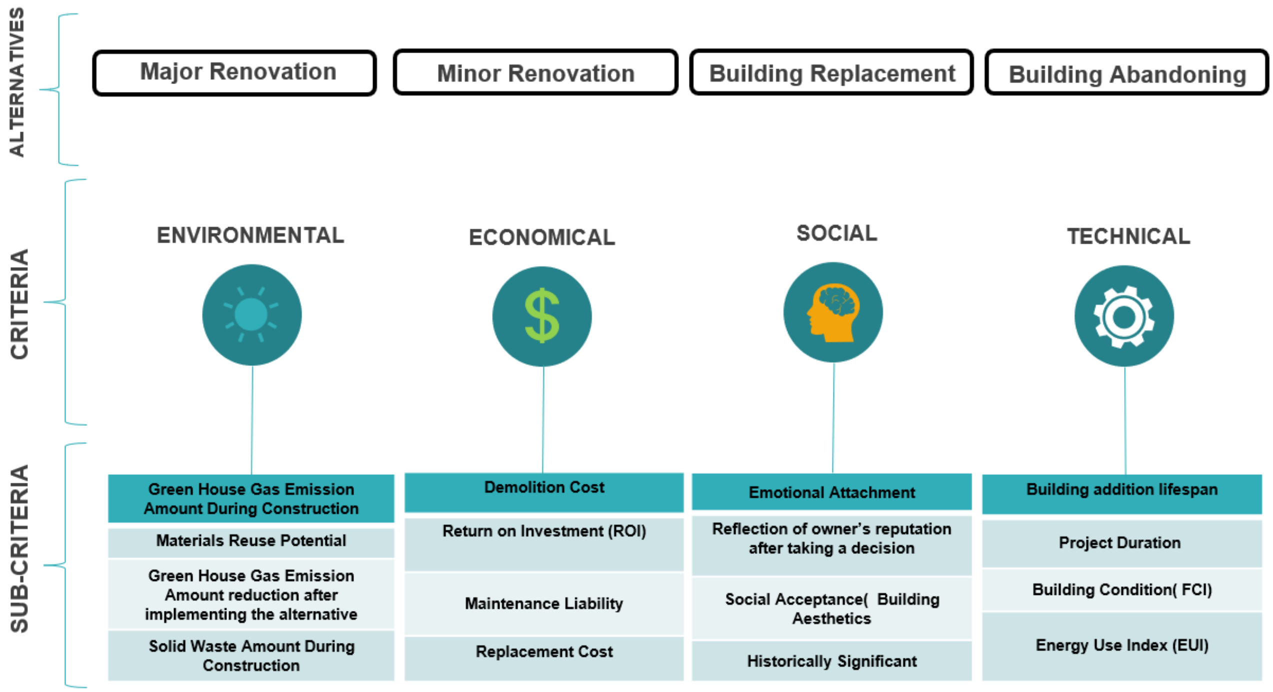


**Figure 3.2. Hierarchy of Decision Problem.**

## 3.5. Converting Objective Values into Subjective Inputs

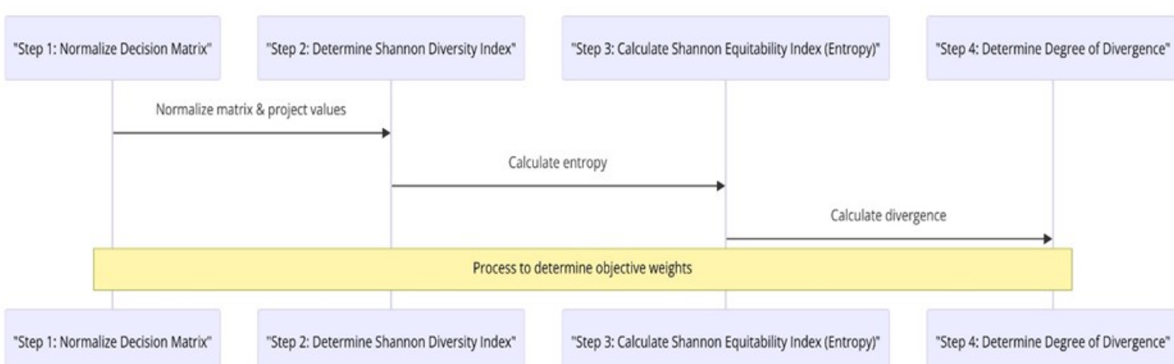


**Figure 3.3. Converting Objective Values into Subjective Inputs**

The TOPSIS extension created by this study integrates subjective and objective weight. The developed approach has the advantage of incorporating end-user tangible information (numerical input) and the decision-maker's experience throughout the decision-making process. In addition to the decision-maker's subjective weights, Shannon's entropy was used in this study to derive subjective weights from objective values as shown in (figure 3.3). Information entropy theory illustrates the importance of evaluating characteristics that can effectively mitigate the effects of subjective factors. The creative approach might present a more thorough approach to making decisions.

**Step 1:** The decision matrix must be normalized for each criterion before entropy weights can be determined objectively. ( $C_j, j = 1{,}2 \dots n;\ n =$ is the criteria number), to obtain the projection value $p_{ij}$ Of each criterion:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}, \text{ where } m\text{= number of alternatives.} \qquad (3.1)$$

**Step 2:** We can determine the Shannon diversity index after normalizing the decision matrix as

$$H = -\sum_{i=1}^{m} p_{ij} \ln p_{ij} \qquad (3.2)$$

**Step 3:** The Shannon Equitability Index, often called entropy, is calculated using the following equation. It is used to quantify the uniformity of values within specific criteria. A symbol represents the entropy value $e_j$

Where,

$$e_j = H/\ln(m) \qquad (3.3)$$

$m$ = total number of alternatives considered in the decision-making process.

**Step 4:** Using the formula $d_j = 1 - e_j$ The degree of divergence can now be determined. The degree of divergence increases with $d_j$ Value. The criteria values with a higher degree of divergence are considered for the range distribution of subjective values within the matrix. Where the maximum value is very high, and the minimum value is very low. Within the range, all other subjective values are evenly distributed. These range values are thought to change the objective to the subjective nature of all other criteria values in the matrix.

## 3.6. Fuzzy Analytic Hierarchy Process

Resolution The fuzzy analytical hierarchy process (FAHP) is a method that utilizes fuzzy logic and is derived from the analytical hierarchy process (AHP). The AHP method is comparable to the fuzzy AHP approach. The AHP scale is transformed into a fuzzy triangular or trapezoidal scale using the fuzzy AHP approach, which can be directly accessed for analysis.

## 3.7. Methodology for Calculating Criteria Weight with Fuzzy AHP

To handle qualitative and quantitative multi-criteria elements in decision-making, (Wind and Saaty 1980) developed a strong and useful tool. This strategy allowed for the ability to perform sensitivity analyses on the ensuing benchmarks and criteria and various alternatives in the decision-making process. Additionally, the paired comparisons simplify calculations and judgments and show the compatibility and incompatibility findings from decision-making based on multiple criteria. To solve problems, the AHP divides them into groups and puts them in a hierarchical framework. This method compares the most important criteria with a pre-established measuring scale. Because the AHP approach relies heavily on expert perception, subjectivity is a factor in retrieval decisions. This method also considers inconsistent limitations for data consistency (Veisi et al. 2022).

### 3.7.1. Define the problem and Determine the Desired Solution

The hierarchical decision-making problem is set up in the first phase. This phase is identical to the traditional AHP methodology. In this instance, the issue has to be explained in terms of the standards for selecting the most sustainable method to deal with old buildings with high maintenance requirements. Technical, economic, social, and environmental factors were considered when deciding which method was the most sustainable. These four sustainability analysis pillars were combined into four criteria each, making sixteen to be compared. The steps of the calculations are shown in Figure 3.4 and explained subsequently.

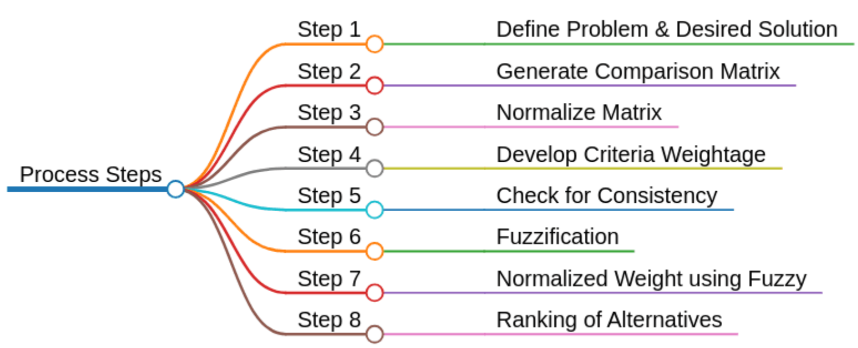


**Figure 3.4. Fuzzy AHP Process**

**Step 1: Generate a Comparison Matrix**

Once we have the specifics of the alternatives and the standards by which they must be evaluated for selecting sustainable materials, we must create a comparison matrix. The used matrix is straightforward, supports the consistency framework well, gathers more data as needed for all possible comparisons, and can evaluate the overall priority sensitivity for changes under consideration. The following are the equations that define pairwise comparisons:

$$a_{i-j} = \frac{w_i}{w_j} \text{ , where } \quad i, j = 1,2,3, \dots n) \tag{3.4}$$

Here, $n$ denotes the number of criteria compared, $w_i$ Are weights for the $i$ criterion and $a_{ij}$ Is the ratio of the weight $i$ and $j$ criteria.

**Table 3. 1 Pairwise comparison of criteria**

| | Criteria 1 | Criteria 2 | Criteria 3 | ....... | Criteria n |
|---|---|---|---|---|---|
| **Criteria 1** | 1 | $a_{1-2}$ | $a_{1-3}$ | ... | $a_{1-n}$ |
| **Criteria 2** | $a_{2-1}$ | 1 | $a_{2-3}$ | ... | $a_{2-n}$ |
| **Criteria 3** | $a_{3-1}$ | $a_{3-1}$ | 1 | ... | $a_{3-n}$ |
| **:** | ... | ... | ... | 1 | ... |
| **Criteria n** | $a_{n-1}$ | $a_{n-2}$ | $a_{n-3}$ | ... | 1 |

**Table 3. 2 Importance Index**

| Importance Index | Definition of Importance Index |
|---|---|
| 1 | Equally Important Preferred |
| | Equally to Moderately Important Preferred |
| 3 | Moderately Important Preferred |
| | Moderately to Strongly Important Preferred |
| 5 | Strongly Important Preferred |
| | Strongly to Very Strongly Important Preferred |
| 7 | Very Strongly Important Preferred |
| | Very Strongly to Extremely Important Preferred |
| 9 | Extremely Important Preferred |

**Step 2: Normalizing the Matrix**

Normalizing the matrix is the next step after understanding the comparison of its criteria in Table 3.1. To accomplish this, divide each cell by the total value of that column. In this case,

$$x_{ij} = \frac{a_{ij}}{\sum a_{ij}} \quad (3.5)$$

**Step 3: Developing Criteria Weightage**

Criteria weightage is the average of the weightage of each row:

$$\tilde{a}_{ij} = \frac{1}{n}\sum x_{ij} \quad (3.6)$$

**Step 4*:* Checking for Consistency**

Saaty listed the values in a set to compare the consistency index (CI) with the random generator (RI) value (Table 3.3). The matrix order n makes this value variable. Consistency must be nearly flawless for a selection to be deemed almost accurate. The following formula is used to calculate consistency's value. First, the weighted value of the criteria, or the eigenvector, must be calculated. The eigenvector can be computed using the equation below:

$$w_{cri-i} \frac{1}{n}\sum \tilde{a}_{ij} \;\; \forall_i \quad (3.7)$$

The eigenvector, in this case, is $w_{cri-i}$, which is calculated by dividing the number of criteria (n) by the sum of the matrix normalization values. We now need to determine the value of lambda, or λ:

$$\lambda_{max} = \frac{1}{n}[\frac{1}{w_{cri-i}} \sum w_{cri-i} x \, w_i] \qquad (3.8)$$

The Consistency Index (CI) value can be ascertained once the maximum lambda value has been obtained.

Here, $CI = \frac{\lambda_{max} - n}{n-1}$ (3.9)

Here, λmax is the largest eigenvalue of the n-order matrix, and CI stands for consistency index. If CI equals zero, then the matrix is consistent (0). Assume the computed CI value is greater than zero (CI> 0). If so, Saaty's limit of inconsistency must be assessed using the Consistency Ratio (CR), commonly referred to as the index value (i.e., the comparison of CI and RI).

**Table 3. 3 Relative Index Value**

| Order n | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0 | 0 | 0.52 | 0.89 | 1.12 | 1.26 | 1.36 | 1.41 | 1.46 | 1.49 | 1.52 | 1.54 | 1.56 | 1.58 | 1.59 | 1.59 |

The order n matrix is compatible with the selected RI value. If a matrix's consistency ratio (CR) is less than 10% (0.1), it is reasonable to accept that each opinion will be inconsistent.

**Step 5:Fuzzification**

Table 3.4 below should be used to Fuzzy the given weights:

**Table 3. 4 Importance index and fuzzy numbers**

| Importance Index | Crisp Number | Fuzzy number $(l, m, n, p)$ |
|---|---|---|
| Extremely more important | 9 | 7,8,9,10 |
| Very strongly more important | 7 | 5,6,7,8 |
| Strongly more important | 5 | 3,4,5,6 |
| Moderately more important | 3 | 1,2,3,4 |
| Equal Importance | 1 | 1,1,1,1 |
| Moderately less important | 1/3 | 1/4, 1/3,1/2 ,1 |

| | | |
|---|---|---|
| **Strongly less important** | 1/5 | 1/6,1/5,1/4,1/3 |
| **Very strongly less important** | 1/7 | 1/8,1/7,1/6,1/5 |
| **Extremely less important** | 1/9 | 1/10,1/9,1/8,1/7 |

| | **Criteria 1** | **Criteria 2** | **Criteria 3** | ....... | **Criteria n** |
|---|---|---|---|---|---|
| **Criteria 1** | 1,1,1,1 | $l_{12,}m_{12,}n_{12,}p_{12}$ | $l_{13,}m_{13,}n_{13,}p_{13}$ | ... | $l_{1n,}m_{1n,}n_{1n,}p_{1n}$ |
| **eria 2** | $l_{21,}m_{21,}n_{21,}p_{21}$ | 1,1,1,1 | $l_{23,}m_{23,}n_{23,}p_{23}$ | ... | $l_{2n,}m_{2n,}n_{2n,}p_{2n}$ |
| **Criteria 3** | $l_{31,}m_{31,}n_{31,}p_{31}$ | $l_{32,}m_{32,}n_{32,}p_{32}$ | 1,1,1,1 | ... | $l_{3n,}m_{3n,}n_{3n,}p_{3n}$ |
| **:** | ... | ... | ... | 1,1,1,1 | ... |
| **Criteria n** | $l_{n1,}m_{n1,}n_{n1,}p_{n1}$ | $l_{n2,}m_{n2,}n_{n2,}p_{n2}$ | $l_{n3,}m_{n3,}n_{n3,}p_{n3}$ | ... | 1,1,1,1 |

### Step 6: Normalized Weight using Fuzzy

Weights are calculated as follows:

$w_{fn-i} = (l_j, m_j, n_j, p_j)/4;\ i,j = 1,2,3 \ldots\ldots m$ (number of criteria), (3.10)

Here,

$l_i = (l_{i1} x l_{i2}\ x l_{i3} x \ldots\ldots l_{in})^{1/n}$ ,

$m_i = (m_{i1} x m_{i2}\ x m_{i3} x \ldots\ldots m_{in})^{1/n}$ ,

$n_i = (n_{i1} x n_{i2}\ x n_{i3} x \ldots\ldots n_{in})^{1/n}$ ,

$p_i = (p_{i1} x p_{i2}\ x p_{i3} x \ldots\ldots p_{in})^{1/n}$ ;

$l_j = l_i x \sum( p_i), m_j = m_i x \sum( n_i), n_j = n_i x \sum( m_i), p_j = p_i x \sum( l_i)$

### 3.7.2. Ranking of Alternatives with Fuzzy TOPSIS (Using AHP Weightage)

With The Fuzzy TOPSIS technique can compare several options against the chosen criteria. The alternative nearest to the Fuzzy Optimistic Ideal Solution (FOS) and farthest from the Fuzzy Adverse Ideal Solution (FAS) is chosen using the TOPSIS method. A FOS comprises each alternative's best performance numbers, whereas a FAS comprises its worst performance values. (Sirisawat and Kiatcharoenpol 2018)

#### 3.7.2.1. Subjective and Objective Weight

This work presents a TOPSIS modification that considers subjective and objective weight. The proposed method can use decision-maker's knowledge by including end users in the decision-making process. To normalize the subjective weights of the criteria that the decision-makers assigned, we base it on Shannon's entropy (Kropivšek et al. 2021).

#### 3.7.2.2. Details of Calculations

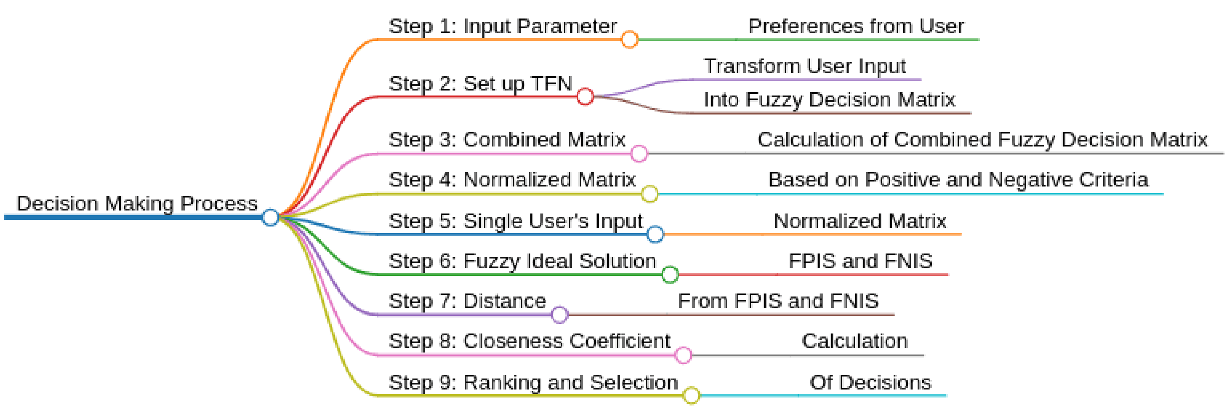


**Figure 3.5. Details of Calculations**

**Step 1: Input Parameter (Preferences) from User**

This step involves compiling the user preferences into a matrix.

| | Alternative 1 | Alternative 2 | ................. | Alternative n |
|---|---|---|---|---|
| Criteria 1 | *High* | *High* | ... | *Medium* |
| eria 2 | *Low* | *Very Low* | .... | *Low* |
| Criteria 3 | *Medium* | *Medium* | ...... | *Medium* |
| : | ... | ... | | ... |
| Criteria n | *Very High* | *High* | ..... | Very *Low* |

**Step 2: Set up a Trapezoidal Fuzzy Number and Transform the User Input into a Fuzzy Decision Matrix**

The FAHP scale utilizes Trapezoidal Fuzzy Numbers (TrFN), defined by four boundary values: a, b, c, and d. The degree of membership increases from a to b, remains constant at one from b to c (indicating full membership in the category for values between c and d), and then declines from c to d (as shown in Figure 3.5). The categories indicated in Table 3.4 were each represented by fuzzy sets using trapezoidal membership functions, as shown in Table 3.5 and Figure 3.6.

**Table 3. 5. Trapezoidal membership functions**

| Number | Linguistic Variable | Trapezoidal Fuzzy Number | | | |
|---|---|---|---|---|---|
| | | a, | b, | c, | d |
| **1** | Very Low | 1, | 1, | 1, | 1 |
| **3** | Low | 1, | 2, | 3, | 4 |
| **5** | Medium | 3, | 4, | 5, | 6 |
| **7** | High | 5, | 6, | 7, | 8 |
| **9** | Very High | 7, | 8, | 9, | 10 |

$$\mu_{trapezoidal}(x: a, b, c, d) = \begin{cases} 0 & x \le a \\ \dfrac{x-a}{b-a} & a \le x \le b \\ 1 & b \le x \le c \\ \dfrac{d-x}{d-c} & c \le x \le d \end{cases}$$

0 $d \leq x$

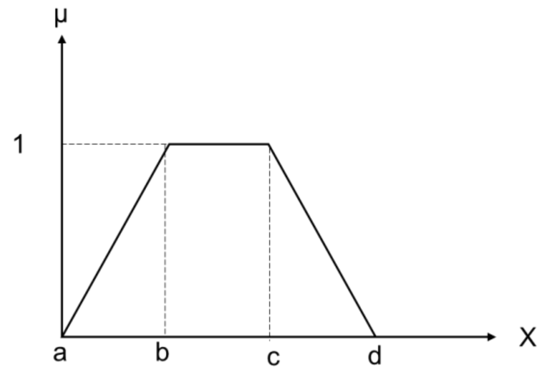


**Figure 3.6. Four parameters describe the trapezoidal membership function.**

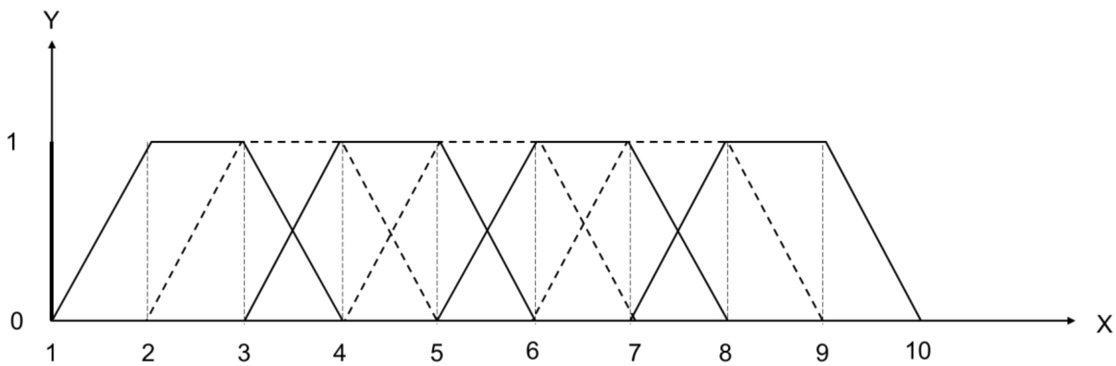


**Figure 3.7. Trapezoidal membership functions.**

**Step 3: Computation of the Merged Fuzzy Decision Matrix**

A combined decision matrix is created once the F-AHP scale value is converted from the AHP comparison value. Using the following formula, the procedure for obtaining a fuzzy combined decision matrix value is demonstrated:

$\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}, d_{ij})$

Where, $a_{ij} = \min_k\{a^k{}_{ij}\}$, $b_{ij} = \frac{1}{K}\sum_{k=1}^{k} b^k{}_{ij}$, $c_{ij} = \frac{1}{K}\sum_{k=1}^{k} c^k{}_{ij}$, $d_{ij} = \max_k\{d^k{}_{ij}\}$(3.11)

**Step 4: Computation of the Normalized Fuzzy Decision Matrix using Beneficial (Optimistc) and Cost (Adverse) Criteria**

The next step is determining the cost (Adverse) and benefit (Optimistic) criteria and creating the fuzzy decision matrix.

$\tilde{r}_{ij}$= ( $\frac{a_{ij}}{d^*_j}, \frac{b_{ij}}{d^*_j}, \frac{c_{ij}}{d^*_j}, \frac{d_{ij}}{d^*_j}$); $c^*_j$=max$_i\{d_{ij}\}$, for benefit criteria (3.12)

$\tilde{r}_{ij}$= ( $\frac{a^-_j}{a_{ij}}, \frac{a^-_j}{b_{ij}}, \frac{a^-_j}{c_{ij}}, \frac{a^-_j}{d_{ij}}$); $a^-_j$=min$_i\{a_{ij}\}$, for cost criteria (3.13)

Then, the matrix is being normalized using the following equation:

$\tilde{v}_{ij}$=$\tilde{r}_{ij}$ x $w_j$;  $w_j = fuzzy\ wightage.$ (3.14)

**Step 5: Normalized Fuzzy Decision Matrix created with input from a single user.**

Subsequently, the fuzzy normalized weight of every criterion derived from Fuzzy AHP is multiplied by the matrix value.

$\tilde{u}_{ij}$=$\tilde{v}_{ij}$x $w_{f.n-i}$ (3.15)

**Step 6: This section describes the process of obtaining the Fuzzy Optimal Solution, Fuzzy Optimistic Solution (FOS), and Fuzzy Adverse Solution (FAS).**

Fuzzy ideal solutions are now obtained from the matrix using the following method:

Fuzzy Optimistic Ideal Solution (FOS):

$A^{*} = (\tilde{u}^{*}{}_{1}, \tilde{u}^{*}{}_{2}, \tilde{u}^{*}{}_{3}, \ldots\ldots \tilde{u}^{*}{}_{n})$, where $\tilde{u}^{*}{}_{j} = \max_{i}\{u_{ij(4)}\}$ (3.16)

Fuzzy Adverse Ideal Solution (FAS):

$A^{-} = (\tilde{u}^{-}{}_{1}, \tilde{u}^{-}{}_{2}, \tilde{u}^{-}{}_{3}, \ldots\ldots \tilde{u}^{-}{}_{n})$, where $\tilde{u}^{*}{}_{j} = \min_{i}\{u_{ij(1)}\}$ (3.17)

**Step 7: Distance from FOS and FAS**

Now, the distance from each possibility is computed using the subsequent formula:

$$d(\tilde{x}, \tilde{y}) = \sqrt{\frac{1}{4}[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2 + (d_1 - d_2)^2]}$$

(3.18)

Where, $a_{1,} b_1, c_1, d_1 = \tilde{u}_{ij}$ ;

$a_{2,} b_2, c_2, d_2 = A^{*}\ for\ positive\ distance\ and\ A^{-}\ for\ negtive\ distance$

**Step 8: Calculation of Closeness Coefficient**

Now, the closeness coefficient $(CC_i)$of each alternative are calculated as

$$CC_i = \frac{d_i^-}{d_i^- + d_i^*};\ d_i^* = \sum_{j=1}^{n} d(\tilde{u}_{ij}, \tilde{u}^{*}{}_{j}) \text{ and } d_i^- = \sum_{j=1}^{n} d(\tilde{u}_{ij}, \tilde{u}^{-}{}_{j})$$

(3.19)

The higher value of the $CC_i$ gets the top ranking.

**Step 9: Ranking of Decisions**

The total number of team members is determined by calculating the combined decision.

$$CC_{team\ i} = \frac{1}{n}\sum CC_{N\ i}\ x\ N_{importance} \quad (3.20)$$

$where, N_{importance} = imporatnce\ \ of\ Nth\ member\ in\ the\ team$, *N= total number of members*

## 3.8. Check for Consistency

### 3.8.1. "Acceptance of Benefits" Condition C1:

To assess if the C1 requirements or accepted benefits have been met, one might compare the difference between the second rank's alternative value and the first rank's alternative value with the DQ value. (Bhuiyan and Masfiqul 2022).

Here,

$$Q(a'') - Q(a')\ \geq DQ,$$

(3.21)

$$DQ = \frac{1}{m-1} \quad (3.22)$$

### 3.8.2. Condition C2: "Acceptance of Stability in Decision Support"

For the alternatives to meet C2 requirements, they must also come in first when it comes to $S_i$ and/or $R_i$ Values. If the C2 conditions are met, the stability of the compromise solution is acknowledged during the decision-making process. The following forms of stability are attained to varying degrees:

a. Based on the "majority rule," if v is greater than 0.5,

b. Based on "consensus," if v is less than 0.5;

c. Vetoed, if v is less than 0.5

If one of the requirements is not met, some suggested compromise options will be provided. A sensible middle-ground resolution could consist of

Alternatives, if $a''$ and $a'$ only if C2 conditions are not met.

Alternatives, $a', a'', \ldots, am$, if C1 conditions are not met

$$Q(am) - Q(a') < DQ \qquad (3.23)$$

## 3.9. Matrix of Decisions

This approach was utilized to determine the weightage of the criteria in addition to the Fuzzy AHP. In this technique, users' preferences for various options are reflected in the percentage of weight assigned to each option. Users can easily and conveniently assign different evaluation criteria at different levels of importance.

### 3.9.1. Procedure for Calculations

In this matrix, users designate their preferences in percentage and weighting. The first step involves allocating weights to the four sustainable construction pillars, totaling 100. Subsequently, under various pillars, they must assign a percentage to each evaluation criteria group (sub-criteria). The percentage of weightage would increase with preference or importance. Out of all, the weightage of that evaluation criteria was determined using the following equation: if the percentage for any sub-criteria falling under the technical pillar is y and the total weightage for that pillar is x.

$$\text{weightage } (w) = (x \times y \text{ in percentage}) \times 0.01 \tag{3.24}$$

### 3.10. Microsoft Excel Utilization for Computation

The DSS model was developed, and data was computed mainly using Microsoft Excel. Numerous templates with the necessary formulas were created to rank the alternatives using Fuzzy TOPSIS and calculate the weightage of the criteria using Fuzzy AHP and decision matrix.

### 3.11. Verification and Validation Technique

Sensitivity analysis was used to verify the created DSS software and Excel templates. In two stages, the model was validated using the opinions and input of numerous experts. The input validation stage was the first. During this stage, experts from academia and industry were emailed Excel templates that included a list of evaluation criteria for sustainable construction, a pairwise comparison of the criteria, a weight distribution for the criteria in the decision matrix, and the ability to assign alternative preferences. They were asked to review the list of selected criteria and provide feedback on their applicability. Their input was used to determine the weightage of the criteria using the FAHP in the pairwise comparison template. Additional input for weighting through a decision matrix was obtained to compare the FAHP results. Finally, Fuzzy TOPSIS was utilized to rank the alternatives based on the inputs from the assigning preferences template. Experts from the industry took part in the first phase and responded via email. The output validation phase came next, and it involved multiple online meetings.

## 3.12. Sensitivity Analysis Technique

Sensitivity analysis refers to examining how the uncertainty in the output of a model, whether numerical or not, can be attributed to various sources of uncertainty in the input of the model. according to (Saltelli 2002). Verification is determining whether the system achieves its intended goals by comparing the output results to different input parameter values (Bakhoum and Brown 2015). Verification compares the output results to input parameter values to see if the system accomplishes its intended goals (AbouHamad and Abu-Hamd 2019). and the development of various scenarios (Bakhoum and Brown 2015) to confirm the model. To ensure that the developed model is sensitive to changes in its input and that the output produces meaningful results, sensitivity analysis was performed in this study by running the model under various scenarios.

# Chapter IV

# Application and Case Study

## 4.1. Introduction

The comprehensive methodology and computation steps utilized in this study were described in detail in Chapter 3. To develop the multi-criteria DSS in the end, this chapter applied those that used multiple sets of data collected from industry and academic experts. Initially, this chapter described the case study and the MCDM and DSS templates used to gather and compile data. Next, Fuzzy AHP and decision matrix were used to calculate the criteria' weightage. In the final stage of the computation, fuzzy TOPIS was used separately, utilizing criteria weightage from fuzzy AHP and decision matrix to rank the alternatives. All stakeholders' inputs were integrated into each step, considering the IPD framework.

## 4.2. MCDM and DSS

Verification compares the output results to input parameter values to see if the system accomplishes its goals (AbouHamad and Abu-Hamd 2019). And the development of various scenarios (Bakhoum and Brown 2015) to confirm the model. To ensure that the developed model is sensitive to changes in its input and that the output produces meaningful results, sensitivity analysis was performed in this study by running the model under various scenarios.

The comprehensive methodology and computation steps utilized in this study were described in detail in Chapter 3. To develop the multi-criteria DSS in the end, this chapter applied those that used multiple sets of data collected from industry and academic experts. Initially, this chapter described the case study and the MCDM and DSS templates used to gather and compile data. Next, Fuzzy AHP and decision matrix were used to calculate the criteria' weightage. In the final stage of the computation, fuzzy TOPIS was used separately, utilizing criteria weightage from fuzzy AHP and decision matrix to rank the alternatives. All stakeholders' inputs were integrated into each step, considering the IPD framework.

#### 4.2.1. Details of The Case Study

**Location & Structure:** Constructed in 1967, this three-story structure is on the University of Alberta's North Campus. It has a mechanical penthouse, a full basement, and a partial sub-basement. It is 5,158 square meters in total area.

**Use and Renovations:** This building houses offices, conference rooms, classrooms, labs, and temperature-controlled archive storage rooms. Between 1995 and 1998, much work was done in the basement, particularly the first and third floors.

**Floors and Foundation:** Concrete cast in place and reinforced with steel makes up the foundation. Concrete slabs that were poured in place make up the basement and sub-basement.

**Walls and Columns:** Reinforced concrete poured in place serves as the structural walls and columns. Concrete block infill walls are used in specific isolated locations.

**Interior Support Structures:** The floor is made of steel-reinforced concrete cast in place and held up by comparable beams, joists, and columns. Interior walls, columns, and beams are a combination of masonry block walls and reinforced concrete that is cast in place.

**Characteristics of Accessibility:** Barrier-free access is made possible by an elevated concrete walkway on the east and southeast sides and a wood-framed ramp at the northeast entrance.

**Stairs & Roofing:** On the west side, across from rooms 1–10 and 1–30, is an exit stair with a steel frame. Concrete beams and columns support the structural concrete slab that serves as the roof, including the mechanical penthouse. Above the northeast and southeast entrances are steel canopies.

## 4.3. Conversion of Quantitative Inputs to Qualitative Values

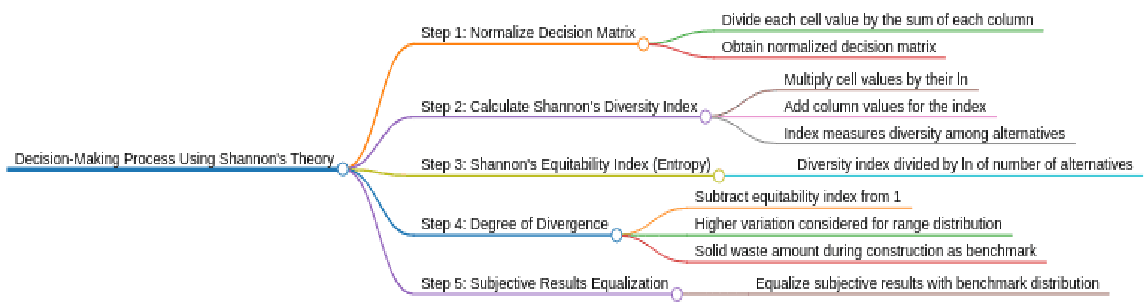


**Figure 4.1. Steps of the Conversion of Quantitative Inputs to Qualitative Values Process**

The process of converting the quantitative inputs to qualitative values is fully explained in detail below and summarized intro figure 4.1.

**Table 4. 1 The calculated number of the quantitative sub-criteria for each alternative**

| Alternatives | Green House Gas Emission Amount During Construction (kg $CO_2$ equivalent/sqm) | Green House Gas Emission Amount during operation and maintenance (kg $CO_2$ equivalent/sqm) | Demolition Cost ($/sqm) | Greenhouse Gas Emission (kg $CO_2$ equivalent/sqm) | Project Duration (Weeks) | Solid Waste Amount During Construction (Tons) | Return on Investment (ROI) % | Maintenance Liability ($/sqm) |
|---|---|---|---|---|---|---|---|---|
| Major Renovation | 430 | 152 | 50 | 115 | 48 | 1.7 | 63.7 | 43 |
| Minor Renovation | 320 | 115 | 95 | 110 | 20 | 0.3 | 52.6 | 52 |
| Building Relocation | 210 | 85 | 80 | 25 | 36 | 0.6 | 78.3 | 45 |
| Building Replacement | 520 | 180 | 65 | 95 | 56 | 2.1 | 72.9 | 23 |

**Step 1:** The inputs in Table 4.1 were derived from the Athena Impact Estimator for Buildings program and a thorough local market investigation. The values in each cell are normalized by dividing them by the sum in each column, representing the total criteria values for all alternatives. The normalized decision matrix is displayed in Table 4.2:

**Table 4. 2 Converted in Normalized Matrix**

| Alternatives | GHG Emission During Construction | GHG Emission Operations | Demolition Cost | GHG Emission | Project Duration | Solid Waste | ROI | Maintenance Liability |
|---|---|---|---|---|---|---|---|---|
| **Major Renovation** | 0.2905 | 0.2857 | 0.1724 | 0.3333 | 0.3000 | 0.3617 | 0.2381 | 0.2638 |
| **Minor Renovation** | 0.2162 | 0.2162 | 0.3276 | 0.3188 | 0.1250 | 0.0638 | 0.1966 | 0.3190 |
| **Building Relocation** | 0.1419 | 0.1598 | 0.2759 | 0.0725 | 0.2250 | 0.1277 | 0.2927 | 0.2761 |
| **Building Replacement** | 0.3514 | 0.3383 | 0.2241 | 0.2754 | 0.3500 | 0.4468 | 0.2725 | 0.1411 |

**Step 2:** Shannon's diversity index is calculated by adding the column values, where each cell value is multiplied by its logarithm (ln) value, as shown in Table 4.3. The Shannon diversity index quantifies the variability of range values for a given criterion across different options.

**Table 4. 3 Shannon diversity index**

| Column | Shannon Diversity Index |
|---|---|
| GHG Emission Amount During Construction (kg CO2 equivalents/sqm) | 1.3348 |
| GHG Emission Amount during operations and maintenance (kg CO2 equivalents/sqm) | 1.3487 |
| Demolition Cost (S/sqm) | 1.3591 |
| Greenhouse Gas Emission (kg CO2 equivalents/sqm) | 1.2760 |
| Project Duration (Weeks) | 1.3242 |
| Solid Waste Amount During Construction (Tons) | 1.1662 |
| Return on Investment (ROI) % | 1.3754 |
| Maintenance Liability (S/sqm) | 1.3477 |

**Step 3:** The equitability index, named after Shannon, is calculated by dividing Shannon's diversity index by the logarithm of the total number of alternatives examined in the decision-making process Table 4.4. The term "entropy value" is another name for it.

**Table 4. 4 Shannon Equitability Index**

| Column | Shannon Equitability Index |
|---|---|

| | |
|---|---|
| GHG Emission Amount During Construction (kg CO2 equivalents/sqm) | 0.9629 |
| GHG Emission Amount during operations and maintenance (kg CO2 equivalents/sqm) | 0.9729 |
| Demolition Cost (S/sqm) | 0.9804 |
| Greenhouse Gas Emission (kg CO2 equivalents/sqm) | 0.9204 |
| Project Duration (Weeks) | 0.9552 |
| Solid Waste Amount During Construction (Tons) | 0.8412 |
| Return on Investment (ROI) % | 0.9922 |
| Maintenance Liability (S/sqm) | 0.9721 |

**Step 4:** The degree of divergence has been determined by subtracting the Shannon equitability index from the unit value. The subjective values inside the matrix are distributed based on the range of criteria values with a higher degree of variation. In this scenario, the quantities of solid waste generated during construction, measured in tons, are used as benchmarks for distribution. In this context, the highest value is considered very high, while the smallest value is considered extremely low. All remaining subjective values are evenly distributed across the range, as depicted in Table 4.6. The range values convert all other criteria values in the matrix from objective to subjective.

**Table 4. 5 Determination of range**

| Linguistic Term | Normalization Scale |
|---|---|
| Very High | [0.3702 <] |
| High | [0.2936 to 0.3702] |
| Medium | [0.217 to 0.2936] |
| Low | [0.1404 to 0.217] |
| Very Low | [< 0.1404] |

**Step 5:** Finally, the subjective results of Table 4.4 values are tabulated in Table 4.6, equalizing with the ranges shown in Table 4.5:

**Table 4. 6 Output subjective results.**

| Alternatives | GHG Emission During Construction | GHG Emission Operations | Demolition Cost | GHG Emission | Project Duration | Solid Waste | ROI | Maintenance Liability |
|---|---|---|---|---|---|---|---|---|
| **Major Renovation** | Medium | Medium | Low | High | High | High | Medium | Medium |
| **Minor Renovation** | Low | Low | High | High | Very Low | Very Low | Low | High |
| **Building Relocation** | Low | Low | Medium | Very Low | Medium | Very Low | Medium | Medium |
| **Building Replacement** | High | High | Medium | Medium | High | Very High | Medium | Low |

## 4.4. Weightage Calculation for Each Criterion Using Fuzzy AHP

### 4.4.1. Criteria and Codes

| Criteria | Sub-criteria | Code | Influence |
|---|---|---|---|
| **Environmental** | Green House Gas Emission Amount During Construction | ENV1 | Cost Criteria |
| | Materials Reuse Potential | ENV2 | Beneficial criteria |
| | Green House Gas Emission Amount during operation and maintenance | ENV3 | Cost Criteria |
| | Solid Waste Amount During Construction | ENV4 | Cost Criteria |
| **Economical** | Return on Investment (ROI) | ECO1 | Beneficial criteria |
| | Demolition Cost | ECO2 | Cost Criteria |
| | Maintenance Liability | ECO3 | Cost Criteria |
| | New Construction Cost | ECO4 | Cost Criteria |
| **Social** | Emotional Attachment | SOC1 | Beneficial criteria |
| | Reflection of owner's reputation after taking a decision | SOC2 | Beneficial criteria |
| | Social Acceptance (Building Aesthetics) | SOC3 | Beneficial criteria |
| | Historically Significant | SOC4 | Beneficial criteria |
| **Technical** | Building addition lifespan | TECH1 | Beneficial criteria |
| | Project Duration | TECH2 | Cost Criteria |

| | | | |
|---|---|---|---|
| | Current Building Condition (FCI) | TECH3 | Beneficial criteria |
| | Variance between current and future Energy Use Index (EUI) | TECH4 | Beneficial criteria |

### 4.4.2. Calculation of Weightage for Each Criterion

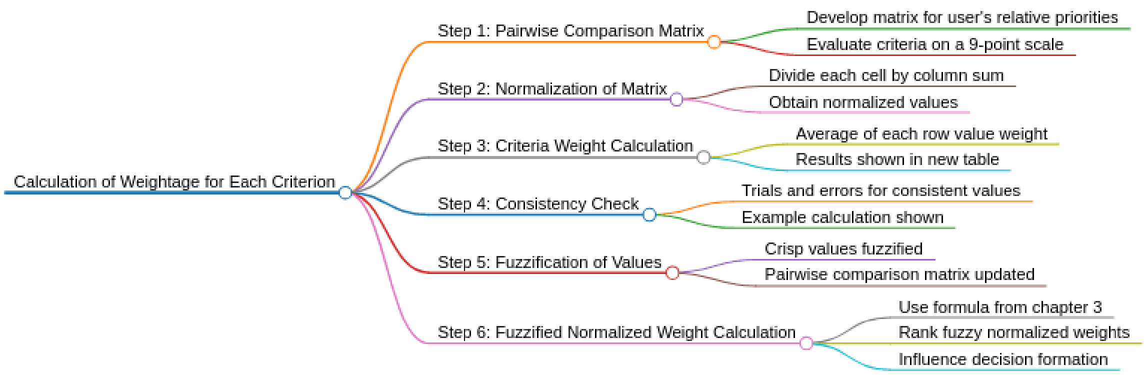


**Figure 4.2. the steps of calculating the weightage of each criterion**

The steps of calculating the weightage of each criterion is fully explained below and summarized in figure 4.2.

**Step 1:** Each user is provided with a pairwise comparison matrix, as displayed in table 4.7, to determine the relative priority of criteria based on their perspective. Every criterion is assessed concerning the others using a 9-point scale, as outlined in chapter 3.

## Table 4. 7 Table of pairwise comparison matrix

| Criteria | TEC1 | TEC2 | TEC3 | TEC4 | ECO1 | ECO2 | ECO3 | ECO4 | SOC1 | SOC2 | SOC3 | SOC4 | ENV1 | ENV2 | ENV3 | ENV4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **TEC1** | 1 | 3 | 5 | 3 | 3 | 3 | 3 | 7 | 3 | 3 | 5 | 3 | 3 | 3 | 3 | 7 |
| **TEC2** | 1/3 | 1 | 3 | 1 | 1 | 1 | 1/3 | 3 | 1/3 | 1/3 | 1 | 1 | 3 | 3 | 3 | 3 |
| **TEC3** | 1/5 | 1/3 | 1 | 1 | 1 | 1 | 1 | 1/3 | 1 | 1/3 | 1 | 1 | 3 | 3 | 3 | 3 |
| **TEC4** | 1/3 | 1 | 1 | 1 | 3 | 3 | 1 | 3 | 3 | 1 | 1 | 1 | 3 | 3 | 3 | 3 |
| **ECO1** | 1/3 | 1 | 1 | 1/3 | 1 | 1 | 1/3 | 1/3 | 1/3 | 1/3 | 1 | 1/3 | 1 | 1 | 1 | 3 |
| **ECO2** | 1/3 | 1 | 1 | 1/3 | 1 | 1 | 1/3 | 3 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 |
| **ECO3** | 1/3 | 3 | 1 | 1 | 3 | 3 | 1 | 3 | 3 | 1 | 1 | 1/3 | 3 | 3 | 3 | 3 |
| **ECO4** | 1/7 | 1/3 | 3 | 1/3 | 3 | 1/3 | 1/3 | 1 | 1 | 1/3 | 1/5 | 1/3 | 1 | 1/3 | 1/3 | 1 |
| **SOC1** | 1/3 | 3 | 1 | 1/3 | 3 | 1 | 1/3 | 1 | 1 | 1/5 | 1 | 1/3 | 1/3 | 3 | 3 | 1 |
| **SOC2** | 1/3 | 3 | 3 | 1 | 3 | 1 | 1 | 3 | 5 | 1 | 1 | 1 | 3 | 3 | 3 | 3 |
| **SOC3** | 1/5 | 1 | 1 | 1 | 1 | 1 | 1 | 5 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 3 |
| **SOC4** | 1/3 | 1 | 1 | 1 | 3 | 1 | 3 | 3 | 3 | 1 | 1/3 | 1 | 1 | 1 | 1 | 1 |
| **ENV1** | 1/3 | 1/3 | 1/3 | 1/3 | 1 | 1/3 | 1/3 | 1 | 3 | 1/3 | 1/3 | 1 | 1 | 1 | 1 | 1 |
| **ENV2** | 1/3 | 1/3 | 1/3 | 1/3 | 1 | 1/3 | 1/3 | 3 | 1/3 | 1/3 | 1/3 | 1 | 1 | 1 | 1 | 1 |
| **ENV3** | 1/3 | 1/3 | 1/3 | 1/3 | 1 | 1/3 | 1/3 | 3 | 1/3 | 1/3 | 1/3 | 1 | 1 | 1 | 1 | 1 |
| **ENV4** | 1/7 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 | 1 | 1 | 1/3 | 1/3 | 1 | 1 | 1 | 1 | 1 |
| **Sum** | 5 1/3 | 20 | 23 1/3 | 12 2/3 | 29 1/3 | 18 2/3 | 14 | 40 2/3 | 27 1/3 | 11 7/8 | 15 7/8 | 17 1/3 | 31 1/3 | 33 1/3 | 33 1/3 | 38 |

**Step 2:** To obtain the normalized value from table 4.7, each cell is divided by the sum of the columns. The standardized matrix is displayed in table 4.8.

## Table 4. 8 Pairwise comparison matrix

| Criteria | ENV1 | ENV2 | ENV3 | ENV4 | ECO1 | ECO2 | ECO3 | ECO4 | SOC1 | SOC2 | SOC3 | SOC4 | TECH1 | TECH2 | TECH3 | TECH4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ENV1** | 0.19 | 0.15 | 0.21 | 0.24 | 0.10 | 0.16 | 0.21 | 0.17 | 0.11 | 0.25 | 0.32 | 0.17 | 0.10 | 0.09 | 0.09 | 0.18 |
| **ENV 2** | 0.06 | 0.05 | 0.13 | 0.08 | 0.03 | 0.05 | 0.02 | 0.07 | 0.01 | 0.03 | 0.06 | 0.06 | 0.10 | 0.09 | 0.09 | 0.08 |
| **ENV 3** | 0.04 | 0.02 | 0.04 | 0.08 | 0.03 | 0.05 | 0.07 | 0.01 | 0.04 | 0.03 | 0.06 | 0.06 | 0.10 | 0.09 | 0.09 | 0.08 |
| **TEC4** | 0.06 | 0.05 | 0.04 | 0.08 | 0.10 | 0.16 | 0.07 | 0.07 | 0.11 | 0.08 | 0.06 | 0.06 | 0.10 | 0.09 | 0.09 | 0.08 |
| **ECO1** | 0.06 | 0.05 | 0.04 | 0.03 | 0.03 | 0.05 | 0.02 | 0.01 | 0.01 | 0.03 | 0.06 | 0.02 | 0.03 | 0.03 | 0.03 | 0.08 |
| **ECO2** | 0.06 | 0.05 | 0.04 | 0.03 | 0.03 | 0.05 | 0.02 | 0.07 | 0.04 | 0.08 | 0.06 | 0.06 | 0.10 | 0.09 | 0.09 | 0.08 |
| **ECO3** | 0.06 | 0.15 | 0.04 | 0.08 | 0.10 | 0.16 | 0.07 | 0.07 | 0.11 | 0.08 | 0.06 | 0.02 | 0.10 | 0.09 | 0.09 | 0.08 |
| **ECO4** | 0.03 | 0.02 | 0.13 | 0.03 | 0.10 | 0.02 | 0.02 | 0.02 | 0.04 | 0.03 | 0.01 | 0.02 | 0.03 | 0.01 | 0.01 | 0.03 |
| **SOC1** | 0.06 | 0.15 | 0.04 | 0.03 | 0.10 | 0.05 | 0.02 | 0.02 | 0.04 | 0.02 | 0.06 | 0.02 | 0.01 | 0.09 | 0.09 | 0.03 |
| **SOC2** | 0.06 | 0.15 | 0.13 | 0.08 | 0.10 | 0.05 | 0.07 | 0.07 | 0.18 | 0.08 | 0.06 | 0.06 | 0.10 | 0.09 | 0.09 | 0.08 |
| **SOC3** | 0.04 | 0.05 | 0.04 | 0.08 | 0.03 | 0.05 | 0.07 | 0.12 | 0.04 | 0.08 | 0.06 | 0.17 | 0.10 | 0.09 | 0.09 | 0.08 |
| **SOC4** | 0.06 | 0.05 | 0.04 | 0.08 | 0.10 | 0.05 | 0.21 | 0.07 | 0.11 | 0.08 | 0.02 | 0.06 | 0.03 | 0.03 | 0.03 | 0.03 |
| **TEC1** | 0.06 | 0.02 | 0.01 | 0.03 | 0.03 | 0.02 | 0.02 | 0.02 | 0.11 | 0.03 | 0.02 | 0.06 | 0.03 | 0.03 | 0.03 | 0.03 |
| **TEC2** | 0.06 | 0.02 | 0.01 | 0.03 | 0.03 | 0.02 | 0.02 | 0.07 | 0.01 | 0.03 | 0.02 | 0.06 | 0.03 | 0.03 | 0.03 | 0.03 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **TEC3** | 0.06 | 0.02 | 0.01 | 0.03 | 0.03 | 0.02 | 0.02 | 0.07 | 0.01 | 0.03 | 0.02 | 0.06 | 0.03 | 0.03 | 0.03 | 0.03 |
| **TEC4** | 0.03 | 0.02 | 0.01 | 0.03 | 0.01 | 0.02 | 0.02 | 0.02 | 0.04 | 0.03 | 0.02 | 0.06 | 0.03 | 0.03 | 0.03 | 0.03 |

**Step 3:** Criteria weight is the average of each row value weight in the table above (Table 4.8). The results are shown in Table 4.9.

**Table 4. 9 Criteria weightage**

| Criteria | Sub-criteria | Code | Criteria Weight |
|---|---|---|---|
| **Environmental** | Green House Gas Emission Amount During Construction | ENV1 | 0.17 |
| | Materials Reuse Potential | ENV2 | 0.06 |
| | Green House Gas Emission Amount during operation and maintenance | ENV3 | 0.06 |
| | Solid Waste Amount During Construction | ENV4 | 0.08 |
| **Economical** | Return on Investment (ROI) | ECO1 | 0.04 |
| | Demolition Cost | ECO2 | 0.06 |
| | Maintenance Liability | ECO3 | 0.09 |
| | New Construction Cost | ECO4 | 0.03 |
| **Social** | Emotional Attachment | SOC1 | 0.05 |
| | Reflection of owner's reputation after taking a decision | SOC2 | 0.09 |
| | Social Acceptance(Building Aesthetics) | SOC3 | 0.08 |
| | Historically Significant | SOC4 | 0.07 |
| **Technical** | Building addition lifespan | TECH1 | 0.03 |
| | Project Duration | TECH2 | 0.03 |
| | Current Building Condition (FCI) | TECH3 | 0.06 |
| | Variance between current and future Energy Use Index (EUI) | TECH4 | 0.03 |

**Step 4:** Obtaining a satisfactory consistency value becomes challenging when multiple criteria need to be examined with each other. The users conducted multiple iterations and experiments to obtain consistent values. Below is a sample computation of the consistency tests for one of the users, specifically the designer from team 3.

Value of $\lambda_{max} = \frac{1}{16}[\frac{1}{0.08}\sum(0.08x1 + 0.05x3 + \cdots) + \frac{1}{0.05}\left(\frac{0.08x1}{3} + 0.05x1 + \cdots\right) + \cdots ..]$

=18.35,

Here, n=16. CI= $\frac{18.35-16}{16-1}$ = 0.145

From Table 3.2, we get RI for n= 16 is 1.5

So, CR= 0.145/1.59 = 9.12% < 10%, an acceptable result.

**Step 5:** The crisp values of table 4.9 are fuzzified using the fuzzification table. The pairwise input comparison matrix is shown in Table 4.10 below.

**Table 4. 10 Fuzzification of the pairwise comparison matrix**

| Criteria | ENV1 | ENV2 | ENV3 | ENV4 | ECO1 | ECO2 | ECO3 | ECO4 |
|---|---|---|---|---|---|---|---|---|
| **ENV1** | 1,1,1,1 | 1,2,3,4 | 1,1,1,1 | 1,2,3,4 | 1,1,1,1 | 1,2,3,4 | 1,1,1,1 | 1,2,3,4 |
| **ENV2** | 1/4,1/3,1/2,1 | 1,1,1,1 | 1,1,1,1 | 1,2,3,4 | 1/4,1/3,1/2,1 | 1,1,1,1 | 1,1,1,1 | 1,2,3,4 |
| **ENV3** | 1,1,1,1 | 1,1,1,1 | 1,1,1,1 | 1,2,3,4 | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1,1,1,1 | 1,2,3,4 |
| **ENV4** | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1,1,1,1 | 1/8,1/7,1/6,1/5 | 1/6,1/5,1/4,1/3 | 1/4,1/3,1/2,1 | 1,1,1,1 |
| **ECO1** | 1,1,1,1 | 1,2,3,4 | 1,2,3,4 | 5,6,7,8 | 1,1,1,1 | 1,2,3,4 | 1,2,3,4 | 3,4,5,6 |
| **ECO2** | 1/4,1/3,1/2,1 | 1,1,1,1 | 1,2,3,4 | 3,4,5,6 | 1/4,1/3,1/2,1 | 1,1,1,1 | 1,2,3,4 | 1,2,3,4 |
| **ECO3** | 1,1,1,1 | 1,1,1,1 | 1,1,1,1 | 1,2,3,4 | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1,1,1,1 | 1,1,1,1 |
| **ECO4** | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1,1,1,1 | 1/6,1/5,1/4,1/3 | 1/4,1/3,1/2,1 | 1,1,1,1 | 1,1,1,1 |
| **SOC1** | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1,1,1,1 | 1/4,1/3,1/2,1 | 1,1,1,1 | 1,1,1,1 | 1,2,3,4 |
| **SOC2** | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1,1,1,1 | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1,1,1,1 | 1,1,1,1 |
| **SOC3** | 1,1,1,1 | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1,1,1,1 | 1,2,3,4 |
| **SOC4** | 1,1,1,1 | 1/4,1/3,1/2,1 | 1/6,1/5,1/4,1/3 | 1,1,1,1 | 1/4,1/3,1/2,1 | 1/6,1/5,1/4,1/3 | 1,1,1,1 | 1,1,1,1 |
| **TEC1** | 1,1,1,1 | 3,4,5,6 | 1,2,3,4 | 3,4,5,6 | 1,1,1,1 | 3,4,5,6 | 3,4,5,6 | 7,8,9,10 |
| **TEC2** | 1,1,1,1 | 1,2,3,4 | 1,1,1,1 | 1,2,3,4 | 1,1,1,1 | 1,2,3,4 | 1,2,3,4 | 3,4,5,6 |
| **TEC3** | 1,1,1,1 | 1,2,3,4 | 1,1,1,1 | 3,4,5,6 | 1,1,1,1 | 1,2,3,4 | 1,2,3,4 | 1,2,3,4 |
| **TEC4** | 1,1,1,1 | 1,2,3,4 | 1,2,3,4 | 1,2,3,4 | 1/4,1/3,1/2,1 | 1,1,1,1 | 1,1,1,1 | 1,1,1,1 |

| Criteria | SOC1 | SOC2 | SOC3 | SOC4 | TEC1 | TEC2 | TEC3 | TEC4 |
|---|---|---|---|---|---|---|---|---|
| **ENV1** | 1,2,3,4 | 1,2,3,4 | 1,1,1,1 | 1,1,1,1 | 1,1,1,1 | 1,1,1,1 | 1,1,1,1 | 1,1,1,1 |
| **ENV2** | 1,2,3,4 | 1,2,3,4 | 1,2,3,4 | 1,2,3,4 | 1/6,1/5,1/4,1/3 | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 |
| **ENV3** | 1,2,3,4 | 1,2,3,4 | 1,2,3,4 | 3,4,5,6 | 1/4,1/3,1/2,1 | 1,1,1,1 | 1,1,1,1 | 1/4,1/3,1/2,1 |
| **ENV4** | 1,1,1,1 | 1,1,1,1 | 1,2,3,4 | 1,1,1,1 | 1/6,1/5,1/4,1/3 | 1/4,1/3,1/2,1 | 1/6,1/5,1/4,1/3 | 1/4,1/3,1/2,1 |
| **ECO1** | 1,2,3,4 | 1,2,3,4 | 1,2,3,4 | 1,2,3,4 | 1,1,1,1 | 1,1,1,1 | 1,1,1,1 | 1,2,3,4 |
| **ECO2** | 1,1,1,1 | 1,2,3,4 | 1,2,3,4 | 3,4,5,6 | 1/6,1/5,1/4,1/3 | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1,1,1,1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **ECO3** | 1,1,1,1 | 1,1,1,1 | 1,1,1,1 | 1,1,1,1 | 1/6,1/5,1/4,1/3 | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1,1,1,1 |
| **ECO4** | 1/4,1/3,1/2,1 | 1,1,1,1 | 1/4,1/3,1/2,1 | 1,1,1,1 | 1/10,1/9,1/8,1/7 | 1/6,1/5,1/4,1/3 | 1/4,1/3,1/2,1 | 1,1,1,1 |
| **SOC1** | 1,1,1,1 | 1,1,1,1 | 1,1,1,1 | 1,2,3,4 | 1/6,1/5,1/4,1/3 | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 |
| **SOC2** | 1,1,1,1 | 1,1,1,1 | 1,2,3,4 | 1,2,3,4 | 1/8,1/7,1/6,1/5 | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1,1,1,1 |
| **SOC3** | 1,1,1,1 | 1/4,1/3,1/2,1 | 1,1,1,1 | 1,1,1,1 | 1/6,1/5,1/4,1/3 | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1,1,1,1 |
| **SOC4** | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1,1,1,1 | 1,1,1,1 | 1/8,1/7,1/6,1/5 | 1/6,1/5,1/4,1/3 | 1/6,1/5,1/4,1/3 | 1/4,1/3,1/2,1 |
| **TEC1** | 3,4,5,6 | 5,6,7,8 | 3,4,5,6 | 5,6,7,8 | 1,1,1,1 | 1,2,3,4 | 3,4,5,6 | 1,2,3,4 |
| **TEC2** | 1,2,3,4 | 1,2,3,4 | 1,2,3,4 | 3,4,5,6 | 1/4,1/3,1/2,1 | 1,1,1,1 | 1,2,3,4 | 1,2,3,4 |
| **TEC3** | 1,2,3,4 | 1,2,3,4 | 1,2,3,4 | 3,4,5,6 | 1/6,1/5,1/4,1/3 | 1/4,1/3,1/2,1 | 1,1,1,1 | 1,1,1,1 |
| **TEC4** | 1,2,3,4 | 1,1,1,1 | 1,1,1,1 | 1,2,3,4 | 1/4,1/3,1/2,1 | 1/4,1/3,1/2,1 | 1,1,1,1 | 1,1,1,1 |

**Step 6**: Fuzzified normalized weight is calculated using the formula and steps described in chapter 3. Fuzzy normalized weights are obtained and ranked. As shown in Table 4.11below By giving weight to any preference, the fuzzy normalized weight criteria values play a critical role in shaping and forming decisions. Sensitivity analysis refers to examining how the uncertainty in the output of a model, whether numerical or not, can be attributed to various sources of uncertainty in the input of the model. according to (Saltelli 2002). Verification is determining whether the system achieves its intended goals by comparing the output results to different input parameter values (Bakhoum and Brown 2015).

**Table 4. 11 Fuzzified normalized weight and global ranking.**

| | Sub-Criteria | Fuzzy Normalized Weight | |
|---|---|---|---|
| **1** | Project Duration | 0.158318451 | 1 |
| **2** | Historically Significant | 0.064000784 | 6 |
| **3** | Reflection of owner's reputation after taking a decision | 0.053257453 | 9 |
| **4** | Demolition Cost | 0.080289479 | 4 |
| **5** | Green House Gas Emission Amount During Construction | 0.041846885 | 11 |
| **6** | Green House Gas Emission Amount during operation and maintenance | 0.06180469 | 7 |
| **7** | Maintenance Liability | 0.083209501 | 3 |
| **8** | Emotional Attachment | 0.035836956 | 15 |
| **9** | Materials Reuse Potential | 0.050000604 | 10 |
| **10** | Return on Investment (ROI) | 0.088777478 | 2 |
| **11** | Building addition lifespan | 0.069400133 | 5 |

| | | | |
|---|---|---|---|
| **12** | Solid Waste Amount During Construction | 0.059885849 | 8 |
| **13** | Variance between current and future Energy Use Index (EUI) | 0.040576789 | 12 |
| **14** | Social Acceptance/ Building Aesthetics | 0.039386366 | 13 |
| **15** | New Construction Cost | 0.039386366 | 13 |
| **16** | Current Building Condition (FCI) | 0.034022216 | 16 |

The fuzzified normalized weightage of the criterion will vary among users based on the input in the comparison matrix.

**Table 4. 12 Summary of the weighted criteria scores, which have been fuzzified and normalized, for all stakeholders.**

| | Owner 1 | Owner 2 | Owner 3 | Constructor 1 | Constructor 2 | Constructor 3 | Designer 1 | Designer 2 | Designer 3 |
|---|---|---|---|---|---|---|---|---|---|
| **Green House Gas Emission Amount During Construction** | 0.06 | 0.06 | 0.07 | 0.09 | 0.12 | 0.05 | 0.07 | 0.05 | 0.09 |
| **Materials Reuse Potential** | 0.04 | 0.07 | 0.05 | 0.11 | 0.02 | 0.06 | 0.08 | 0.11 | 0.07 |
| **Green House Gas Emission Amount during operation and maintenance** | 0.05 | 0.06 | 0.06 | 0.07 | 0.10 | 0.05 | 0.05 | 0.05 | 0.04 |
| **Solid Waste Amount During Construction** | 0.06 | 0.09 | 0.03 | 0.06 | 0.03 | 0.03 | 0.07 | 0.06 | 0.04 |
| **Return on Investment (ROI)** | 0.13 | 0.04 | 0.11 | 0.12 | 0.01 | 0.06 | 0.11 | 0.14 | 0.08 |
| **Demolition Cost** | 0.18 | 0.07 | 0.06 | 0.14 | 0.01 | 0.05 | 0.12 | 0.14 | 0.08 |
| **Maintenance Liability** | 0.06 | 0.09 | 0.04 | 0.06 | 0.10 | 0.04 | 0.06 | 0.07 | 0.06 |
| **New Construction Cost** | 0.05 | 0.05 | 0.03 | 0.03 | 0.11 | 0.03 | 0.04 | 0.02 | 0.03 |
| **Emotional Attachment** | 0.04 | 0.06 | 0.04 | 0.02 | 0.04 | 0.04 | 0.04 | 0.02 | 0.03 |
| **Reflection of owner's reputation after taking a decision** | 0.10 | 0.09 | 0.04 | 0.06 | 0.07 | 0.03 | 0.08 | 0.09 | 0.03 |
| **Historically Significant** | 0.04 | 0.08 | 0.04 | 0.09 | 0.01 | 0.03 | 0.04 | 0.10 | 0.03 |
| **Social Acceptance (Building Aesthetics)** | 0.03 | 0.07 | 0.03 | 0.02 | 0.09 | 0.02 | 0.03 | 0.04 | 0.02 |
| **Building addition lifespan** | 0.05 | 0.05 | 0.17 | 0.03 | 0.09 | 0.12 | 0.07 | 0.03 | 0.18 |
| **Project Duration** | 0.04 | 0.04 | 0.10 | 0.03 | 0.08 | 0.12 | 0.05 | 0.03 | 0.07 |
| **Current Building Condition (FCI)** | 0.04 | 0.05 | 0.08 | 0.04 | 0.04 | 0.14 | 0.05 | 0.03 | 0.07 |
| **Variance between current and future Energy Use Index (EUI)** | 0.04 | 0.05 | 0.06 | 0.04 | 0.08 | 0.13 | 0.03 | 0.02 | 0.07 |

## 4.5. Ranking of Alternatives with Fuzzy TOPSIS Using Fuzzy AHP Weightage

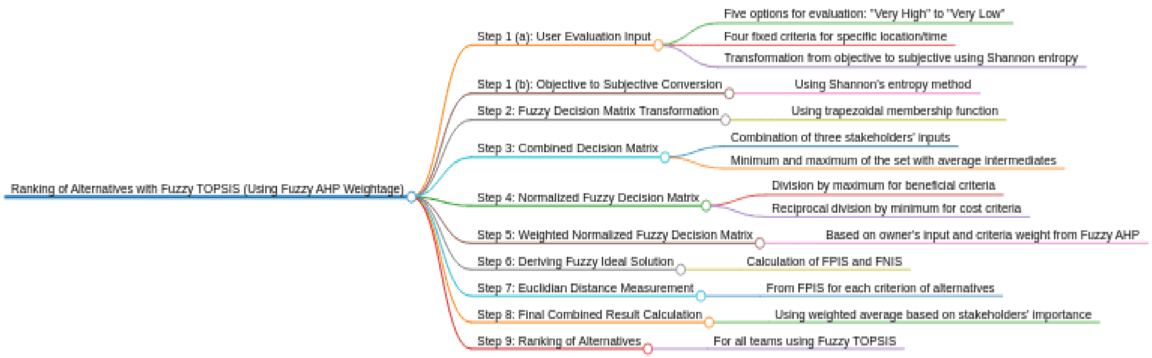


**Figure 4.3. Ranking of Alternatives with Fuzzy TOPSIS Using Fuzzy AHP Weightage**

Steps of the ranking process are fully explained below and summarized in Figure 4.3.

**Step 1 (a):** Table 4.13 displays one of the user's inputs while evaluating alternatives using several criteria. The user can choose five options: "Very High, High, Medium, Low, and Very Low." Furthermore, precisely eight predetermined criteria are set for a certain location and time, each with an objective value. Nevertheless, these values convert from an objective to a subjective state by utilizing the Shannon entropy technique, as illustrated in Table 4.14.

**Table 4. 13 Input parameter of stakeholder**

| Alternatives<br>Criteria | Major Renovation | Minor Renovation | Building Relocation | Building Replacement |
|---|---|---|---|---|
| Environmental | | | | |
| Green House Gas Emission Amount During Construction | 430 | 320 | 210 | 520 |
| Materials Reuse Potential | Medium | High | Very High | Medium |
| Green House Gas Emission Amount during operation and maintenance | 152 | 115 | 85 | 180 |
| Solid Waste Amount During Construction | 1.7 | 0.3 | 0.6 | 2.1 |
| Economic | | | | |
| Return on Investment (ROI) % | 63.7 | 52.6 | 78.3 | 72.9 |
| Demolition Cost | 50 | 95 | 80 | 95 |
| Maintenance Liability | 43 | 52 | 45 | 23 |
| New Construction Cost | 170 | 110 | 95 | 65 |
| Social | | | | |
| Emotional Attachment | High | High | Very High | High |
| Reflection of owner's reputation after taking a decision | Very High | Medium | Medium | Very High |

| | | | | |
|---|---|---|---|---|
| Social Acceptance (Building Aesthetics) | Medium | Medium | High | Medium |
| Historically Significant | Low | Low | High | Very High |
| Technical | | | | |
| Building addition lifespan | High | Medium | Low | Very High |
| Project Duration | 48 | 20 | 36 | 56 |
| Current Building Condition (FCI) | High | Medium | Low | High |
| Variance between current and future Energy Use Index (EUI) | Very Low | High | Very High | Medium |

**Step 1 (b):** Objective values are converted into subjective values using Shannon's entropy method, as shown in Table 4.14.

**Table 4. 14 Objective values are converted into subjective values.**

| Alternatives<br>Criteria | Major Renovation | Minor Renovation | Building Relocation | Building Replacement |
|---|---|---|---|---|
| Environmental | | | | |
| Green House Gas Emission Amount During Construction | **High** | **High** | **Medium** | **Very High** |
| Materials Reuse Potential | Medium | High | Very High | Medium |
| Green House Gas Emission Amount during operation and maintenance | **Very High** | **High** | **Medium** | **Very High** |
| Solid Waste Amount During Construction | **Very High** | **Low** | **Medium** | **Very High** |
| Economic | | | | |
| Return on Investment (ROI) % | **High** | **Medium** | **Very High** | **High** |
| Demolition Cost | **Medium** | **High** | **High** | **Very High** |
| Maintenance Liability | **High** | **Very High** | **High** | **Low** |
| New Construction Cost | **Very High** | **High** | **Medium** | **Low** |
| Social | | | | |
| Emotional Attachment | High | High | Very High | High |
| Reflection of owner’s reputation after taking a decision | Very High | Medium | Medium | Very High |
| Social Acceptance (Building Aesthetics) | Medium | Medium | High | Medium |
| Historically Significant | Low | Low | High | Very High |
| Technical | | | | |
| Building addition lifespan | High | Medium | Low | Very High |
| Project Duration | **High** | **Low** | **Medium** | **Very High** |
| Current Building Condition (FCI) | High | Medium | Low | High |
| Variance between current and future Energy Use Index (EUI) | Very Low | High | Very High | Medium |

**Step 2:** The user's input table is converted into a fuzzy decision matrix utilizing the trapezoidal membership function outlined in Chapter 3.

**Table 4. 15 Fuzzy decision matrix**

| Criteria | ENV1 | ENV2 | ENV3 | ENV4 | ECO1 | ECO2 | ECO3 | ECO4 |
|---|---|---|---|---|---|---|---|---|
| **Major Renovation** | 7,8,9,10 | 3,4,5,6 | 7,8,9,10 | 5,6,7,8 | 5,6,7,8 | 3,4,5,6 | 1,1,1,1 | 1,2,3,4 |
| **Minor Renovation** | 5,6,7,8 | 5,6,7,8 | 3,4,5,6 | 5,6,7,8 | 5,6,7,8 | 1,2,3,4 | 3,4,5,6 | 7,8,9,10 |
| **Building Relocation** | 5,6,7,8 | 7,8,9,10 | 5,6,7,8 | 5,6,7,8 | 1,2,3,4 | 1,1,1,1 | 3,4,5,6 | 7,8,9,10 |
| **Building Replacement** | 7,8,9,10 | 3,4,5,6 | 5,6,7,8 | 5,6,7,8 | 3,4,5,6 | 3,4,5,6 | 1,1,1,1 | 3,4,5,6 |
| | **SOC1** | **SOC2** | **SOC3** | **SOC4** | **TCH1** | **TCH 2** | **TCH 3** | **TCH 4** |
| | 5,6,7,8 | 7,8,9,10 | 3,4,5,6 | 1,2,3,4 | 7,8,9,10 | 5,6,7,8 | 5,6,7,8 | 1,1,1,1 |
| | 5,6,7,8 | 3,4,5,6 | 3,4,5,6 | 1,2,3,4 | 7,8,9,10 | 5,6,7,8 | 3,4,5,6 | 5,6,7,8 |
| | 7,8,9,10 | 3,4,5,6 | 5,6,7,8 | 5,6,7,8 | 1,1,1,1 | 1,1,1,1 | 1,2,3,4 | 7,8,9,10 |
| | 5,6,7,8 | 7,8,9,10 | 3,4,5,6 | 7,8,9,10 | 5,6,7,8 | 3,4,5,6 | 5,6,7,8 | 3,4,5,6 |

**Step 3:** The Combined Decision Matrix is formed by aggregating the fuzzy input values of three stakeholders for the same team Table. The combination is structured such that the initial value of each cell is the least value from the set, the fourth value is the highest value from the set, and the intermediate values are the average of the corresponding values in the set.

**Table 4. 16 Combined Decision Matrix**

| Criteria | ENV1 | ENV2 | ENV3 | ENV4 | ECO1 | ECO2 | ECO3 | ECO4 |
|---|---|---|---|---|---|---|---|---|
| **Major Renovation** | 5.0,7.3,8.3, 10.0 | 1.0,3.3,4.3, 6.0 | 3.0,6.0,7. 0,10.0 | 5.0,6.7,7. 7,10.0 | 5.0,6.0,7.0, 8.0 | 3.0,4.0,5.0,6 .0 | 1.0,2.3, 3.0,6.0 | 1.0,2.0,3 .0,4.0 |
| **Minor Renovation** | 5.0,6.0,7.0, 8.0 | 5.0,6.0,7.0, 8.0 | 3.0,4.7,5. 7,8.0 | 3.0,4.7,5. 7,8.0 | 5.0,6.0,7.0, 8.0 | 1.0,2.0,3.0,4 .0 | 3.0,4.7, 5.7,8.0 | 7.0,8.0,9 .0,10.0 |
| **Building Relocation** | 5.0,6.0,7.0, 8.0 | 7.0,8.0,9.0, 10.0 | 5.0,6.0,7. 0,8.0 | 3.0,5.3,6. 3,8.0 | 1.0,2.0,3.0, 4.0 | 1.0,1.0,1.0,1 .0 | 3.0,4.0, 5.0,6.0 | 7.0,8.0,9 .0,10.0 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Building Replaceme | 3.0,5.3,6.3,10.0 | 1.0,2.3,3.0,6.0 | 3.0,5.3,6.3,8.0 | 5.0,6.0,7.0,8.0 | 3.0,4.0,5.0,6.0 | 3.0,4.0,5.0,6.0 | 1.0,2.3,3.0,6.0 | 3.0,4.7,5.7,8.0 |

| Criteria | SOC1 | SOC2 | SOC3 | SOC4 | TEC1 | TEC2 | TEC3 | TEC4 |
|---|---|---|---|---|---|---|---|---|
| Major Renovation | 3.0,6.0,7.0,10.0 | 5.0,6.7,7.7,10.0 | 3.0,4.0,5.0,6.0 | 1.0,2.0,3.0,4.0 | 7.0,8.0,9.0,10.0 | 5.0,6.7,7.7,10.0 | 5.0,7.3,8.3,10.0 | 1.0,1.3,1.7,4.0 |
| Minor Renovation | 1.0,4.7,5.7,8.0 | 1.0,2.7,3.7,6.0 | 3.0,5.3,6.3,8.0 | 1.0,2.7,3.7,6.0 | 7.0,8.0,9.0,10.0 | 3.0,5.3,6.3,8.0 | 1.0,4.0,5.0,8.0 | 3.0,5.3,6.3,8.0 |
| Building Relocation | 5.0,6.0,7.0,8.0 | 1.0,3.3,4.3,6.0 | 5.0,6.0,7.0,8.0 | 5.0,6.7,7.7,10.0 | 1.0,1.0,1.0,1.0 | 1.0,2.0,2.3,6.0 | 1.0,1.7,2.3,4.0 | 5.0,7.3,8.3,10.0 |
| Building Replaceme | 5.0,5.3,6.3,8.0 | 5.0,6.7,7.7,10.0 | 3.0,4.0,5.0,6.0 | 5.0,6.7,7.7,10.0 | 5.0,6.0,7.0,8.0 | 3.0,5.3,6.3,8.0 | 3.0,5.3,6.3,8.0 | 1.0,3.3,4.3,6.0 |

**Step 4:** The normalized Fuzzy Decision Matrix is computed by considering the criteria category, whether they are advantageous or cost related. When considering advantageous criteria, the membership function is divided by the highest value of the sets. On the other hand, cost criteria are calculated by taking the reciprocal values and dividing them by the lowest values of the set.

**Table 4. 17 Normalized Fuzzy Decision Matrix**

| Criteria | ENV1 | ENV 2 | ENV 3 | ENV 4 | ECO1 | ECO2 | ECO3 | ECO4 |
|---|---|---|---|---|---|---|---|---|

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Major Renovation | 0.5,0.7,0.8,1.0 | 0.1,0.3,0.4,0.6 | 0.3,0.6,0.7,1.0 | 0.5,0.7,0.8,1.0 | 0.1,0.1,0.2,0.2 | 0.2,0.2,0.3,0.3 | 0.2,0.3,0.4,1.0 | 0.1,0.2,0.3,0.4 |
| Minor Renovation | 0.5,0.6,0.7,0.8 | 0.5,0.6,0.7,0.8 | 0.3,0.5,0.6,0.8 | 0.3,0.5,0.6,0.8 | 0.1,0.1,0.2,0.2 | 0.3,0.3,0.5,1.0 | 0.1,0.2,0.2,0.3 | 0.7,0.8,0.9,1.0 |
| Building Relocation | 0.5,0.6,0.7,0.8 | 0.7,0.8,0.9,1.0 | 0.5,0.6,0.7,0.8 | 0.3,0.5,0.6,0.8 | 0.3,0.3,0.5,1.0 | 1.0,1.0,1.0,1.0 | 0.2,0.2,0.3,0.3 | 0.7,0.8,0.9,1.0 |
| Building Replacement | 0.3,0.5,0.6,1.0 | 0.1,0.2,0.3,0.6 | 0.3,0.5,0.6,0.8 | 0.5,0.6,0.7,0.8 | 0.2,0.2,0.3,0.3 | 0.2,0.2,0.3,0.3 | 0.2,0.3,0.4,1.0 | 0.3,0.5,0.6,0.8 |

| Criteria | SOC1 | SOC2 | SOC3 | SOC4 | TEC1 | TEC2 | TEC3 | TEC4 |
|---|---|---|---|---|---|---|---|---|
| Major Renovation | 0.3,0.6,0.7,1.0 | 0.5,0.7,0.8,1.0 | 0.4,0.5,0.6,0.8 | 0.1,0.2,0.3,0.4 | 0.1,0.1,0.1,0.1 | 0.1,0.1,0.2,0.2 | 0.1,0.1,0.1,0.2 | 0.1,0.1,0.2,0.4 |
| Minor Renovation | 0.1,0.5,0.6,0.8 | 0.1,0.3,0.4,0.6 | 0.4,0.7,0.8,1.0 | 0.1,0.3,0.4,0.6 | 0.1,0.1,0.1,0.1 | 0.1,0.2,0.2,0.3 | 0.1,0.2,0.3,1.0 | 0.3,0.5,0.6,0.8 |
| Building Relocation | 0.5,0.6,0.7,0.8 | 0.1,0.3,0.4,0.6 | 0.6,0.8,0.9,1.0 | 0.5,0.7,0.8,1.0 | 1.0,1.0,1.0,1.0 | 0.2,0.4,0.5,1.0 | 0.3,0.4,0.6,1.0 | 0.5,0.7,0.8,1.0 |
| Building Replacement | 0.5,0.5,0.6,0.8 | 0.5,0.7,0.8,1.0 | 0.4,0.5,0.6,0.8 | 0.5,0.7,0.8,1.0 | 0.1,0.1,0.2,0.2 | 0.1,0.2,0.2,0.3 | 0.1,0.2,0.2,0.3 | 0.1,0.3,0.4,0.6 |

**Step 5:** Weighted Normalized Fuzzy Decision Matrix based on owner's input and criteria weight derived from Fuzzy AHP.

## Table 4. 18 Weighted Normalized Fuzzy Decision Matrix

| Criteria | ENV 1 | ENV 2 | ENV 3 | ENV4 | ECO1 | ECO2 | ECO3 | ECO4 |
|---|---|---|---|---|---|---|---|---|
| Major Renovation | 0.24,0.41,0.52,0.7 | 0.02,0.07,0.12,0.2 | 0.13,0.30,0.40,0.6 | 0.07,0.11,0.15,0.2 | 0.07,0.09,0.12,0.1 | 0.03,0.05,0.08,0.1 | 0.01,0.01,0.02,0.0 | 0.00,0.01,0.03,0.0 |
| Minor Renovation | 0.17,0.25,0.34,0.4 | 0.14,0.20,0.27,0.3 | 0.06,0.12,0.18,0.3 | 0.04,0.08,0.11,0.2 | 0.07,0.09,0.12,0.2 | 0.02,0.04,0.10,0.3 | 0.02,0.03,0.04,0.1 | 0.14,0.18,0.23,0.3 |
| Building Relocation | 0.17,0.25,0.34,0.4 | 0.27,0.35,0.44,0.5 | 0.16,0.23,0.31,0.4 | 0.04,0.09,0.13,0.2 | 0.03,0.07,0.16,0.4 | 0.06,0.06,0.06,0.1 | 0.02,0.03,0.05,0.1 | 0.14,0.18,0.23,0.3 |
| Building Replacement | 0.15,0.30,0.40,0.7 | 0.02,0.05,0.08,0.2 | 0.09,0.20,0.28,0.4 | 0.07,0.10,0.14,0.2 | 0.05,0.08,0.13,0.2 | 0.03,0.05,0.08,0.1 | 0.01,0.01,0.02,0.1 | 0.03,0.05,0.08,0.1 |

| Criteria | SOC1 | SOC2 | SOC3 | SOC4 | TEC1 | TEC2 | TEC3 | TEC4 |
|---|---|---|---|---|---|---|---|---|
| Major Renovation | 0.06,0.14,0.19,0.3 | 0.13,0.20,0.26,0.4 | 0.04,0.07,0.11,0.2 | 0.00,0.01,0.02,0.1 | 0.12,0.15,0.19,0.2 | 0.05,0.08,0.11,0.2 | 0.04,0.06,0.08,0.1 | 0.01,0.01,0.01,0.1 |
| Minor Renovation | 0.02,0.11,0.16,0.3 | 0.01,0.04,0.07,0.1 | 0.04,0.09,0.14,0.2 | 0.00,0.01,0.03,0.0 | 0.12,0.15,0.19,0.2 | 0.06,0.09,0.13,0.3 | 0.03,0.06,0.10,0.5 | 0.09,0.19,0.26,0.4 |
| Building Relocation | 0.14,0.19,0.25,0.3 | 0.01,0.05,0.08,0.1 | 0.11,0.16,0.22,0.3 | 0.06,0.10,0.14,0.2 | 0.17,0.17,0.17,0.2 | 0.02,0.04,0.05,0.1 | 0.02,0.07,0.15,0.3 | 0.21,0.35,0.44,0.6 |
| Building Replacement | 0.10,0.13,0.17,0.25 | 0.13,0.20,0.26,0.38 | 0.04,0.07,0.11,0.1 | 0.09,0.14,0.18,0.2 | 0.11,0.14,0.20,0.2 | 0.04,0.06,0.09,0.2 | 0.05,0.08,0.11,0.2 | 0.02,0.08,0.13,0.2 |

**Step 6:** The fuzzy ideal solution is generated using a weighted normalized Fuzzy Decision Matrix. We obtain two types of ideal solutions from this matrix: the Fuzzy Optimistic ideal solution (FOS) and the Fuzzy Adverse ideal solution (FAS). These solutions are then reported in Table 4.19.

**Table 4. 19 Fuzzy Ideal Solution**

| Criteria | ENV 1 | ENV 2 | ENV 3 | ENV4 | ECO1 | ECO2 | ECO3 | ECO4 |
|---|---|---|---|---|---|---|---|---|
| A*FOS | 0.24,0.41, 0.52,0.70 | 0.27,0.35, 0.44,0.54 | 0.13,0.30,0.40,0.63 | 0.07,0.11, 0.15,0.23 | 0.03,0.07, 0.16,0.42 | 0.02,0.04, 0.10,0.26 | 0.02,0.03, 0.05,0.08 | 0.14,0.18, 0.23,0.28 |
| A- FAS | 0.03,0.19, 0.28,0.45 | 0.02,0.05, 0.08,0.20 | 0.06,0.12,0.18,0.30 | 0.04,0.08, 0.11,0.18 | 0.03,0.07, 0.16,0.42 | 0.02,0.04, 0.10,0.26 | 0.01,0.01, 0.02,0.04 | 0.00,0.01, 0.03,0.04 |

| Criteria | SOC1 | SOC2 | SOC3 | SOC4 | TEC1 | TEC2 | TEC3 | TEC4 |
|---|---|---|---|---|---|---|---|---|
| A*FOS | 0.14,0.23, 0.29,0.39 | 0.13,0.20, 0.26,0.38 | 0.11,0.16,0.22,0.28 | 0.09,0.14, 0.18,0.26 | 0.11,0.14, 0.20,0.27 | 0.06,0.09, 0.13,0.27 | 0.03,0.06, 0.10,0.48 | 0.21,0.35, 0.44,0.59 |
| A- FAS | 0.02,0.11, 0.16,0.25 | 0.01,0.04, 0.07,0.14 | 0.04,0.07,0.11,0.16 | 0.00,0.01, 0.02,0.04 | 0.11,0.14, 0.20,0.27 | 0.02,0.04, 0.05,0.10 | 0.02,0.07, 0.15,0.32 | 0.01,0.01, 0.01,0.02 |

**Step 7:**The Euclidean distance of each criterion for any alternative has been measured in this stage. The table labeled 4.20 displays the distance from the FOS.

## Table 4. 20 Distance from the FOS

| Criteria | ENV 1 | ENV 2 | ENV 3 | ENV4 | ECO1 | ECO2 | ECO3 | ECO4 | SOC1 | SOC2 | SOC3 | SOC4 | TEC1 | TEC2 | TEC3 | TEC4 | SUM (di*) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Major Renovation** | 0.00 | 0.30 | 0.00 | 0.00 | 0.14 | 0.09 | 0.03 | 0.19 | 0.11 | 0.00 | 0.10 | 0.15 | 0.02 | 0.06 | 0.18 | 0.41 | **1.76** |
| **Minor Renovation** | 0.18 | 0.17 | 0.22 | 0.04 | 0.13 | 0.07 | 0.00 | 0.00 | 0.13 | 0.19 | 0.07 | 0.14 | 0.02 | 0.00 | 0.00 | 0.17 | **1.52** |
| **Building Relocation** | 0.23 | 0.00 | 0.13 | 0.03 | 0.00 | 0.00 | 0.00 | 0.08 | 0.00 | 0.18 | 0.00 | 0.04 | 0.06 | 0.10 | 0.08 | 0.00 | **0.94** |
| **Building Replacement** | 0.10 | 0.32 | 0.14 | 0.02 | 0.11 | 0.09 | 0.03 | 0.15 | 0.10 | 0.00 | 0.10 | 0.00 | 0.00 | 0.04 | 0.13 | 0.29 | **1.62** |

## Table 4. 21 Stakeholder ranking: Team 3 Owner

| Alternatives | di* | $di^{-}$ | CC | Rank |
|---|---|---|---|---|
| **Major Renovation** | 3.05 | 2.50 | 0.451072 | 2 |
| **Minor Renovation** | 3.67 | 2.19 | 0.373384 | 3 |
| **Building Relocation** | 2.06 | 3.50 | 0.629555 | 1 |
| **Building Replacement** | 3.09 | 1.84 | 0.373156 | 4 |

**Step 8:** The final combined result of Team 3's stakeholders is calculated using the weights assigned to each person multiplied by the corresponding $CC_i$. The owner's viewpoint has been given. In this situation, the opinions of one team member were given a higher priority, with a weighting of 40%, compared to the opinions of the other two team members, which were given a weighted of 30% each.

**Table 4. 22 The combined result of Team 3**

| | CC(Owner) | CC(Constructor) | CC(Designer) | Weighted CC | Rank |
|---|---|---|---|---|---|
| **Importance of Opinion** | 0.4 | 0.3 | 0.3 | | |
| **Alternatives** | | | | | |
| **Major Renovation** | 0.451072 | 0.3888 | 0.3139 | 0.3653 | 4 |
| **Minor Renovation** | 0.373384 | 0.4873 | 0.4756 | 0.4590 | 2 |
| **Building Relocation** | 0.629555 | 0.6365 | 0.7026 | 0.6404 | 1 |
| **Building Replacement** | 0.373156 | 0.3966 | 0.3209 | 0.3786 | 3 |

**Step 9:** The ranking of alternatives is decided similarly for teams 1 and 2. The comprehensive outcomes of all groups utilizing Fuzzy TOPSIS are presented in Table 4.26.

**Table 4. 23 The outcome of all teams was calculated using the Fuzzy TOPSIS method.**

| | **Team 1** | | **Team 2** | | **Team 3** | |
|---|---|---|---|---|---|---|
| **Alternatives** | Weighted CC | Rank | Weighted CC | Rank | Weighted CC | Rank |
| **Major Renovation** | 0.5753 | 1 | 0.7572 | 1 | 0.3653 | 4 |
| **Minor Renovation** | 0.5502 | 2 | 0.5441 | 2 | 0.4590 | 2 |
| **Building Relocation** | 0.3915 | 4 | 0.1892 | 4 | 0.6404 | 1 |
| **Building Replacement** | 0.4327 | 3 | 0.3884 | 3 | 0.3786 | 3 |

## 4.6. Ranking of Alternatives with Fuzzy TOPSIS Using Decision Matrix Weightage

Previously, the Fuzzy TOPSIS ranking was done using the criteria weightage of Fuzzy AHP. The same process has been repeated using the weightage obtained through the decision matrix to compare outcomes in the subsequent phase. Table 4.24 shows the result of this combination.

**Table 4. 24 Ranking of alternatives with Fuzzy TOPSIS using decision matrix weightage**

| | Team 1 | | Team 2 | | Team 3 | |
|---|---|---|---|---|---|---|
| Alternatives | Weighted CC | Rank | Weighted CC | Rank | Weighted CC | Rank |
| **Major Renovation** | 0.7551 | 1 | 0.6542 | 1 | 0.2753 | 3 |
| **Minor Renovation** | 0.6802 | 2 | 0.4741 | 2 | 0.4730 | 2 |
| **Building Relocation** | 0.4705 | 3 | 0.2092 | 4 | 0.5694 | 1 |
| **Building Replacement** | 0.3827 | 4 | 0.4337 | 3 | 0.3476 | 4 |

## 4.7. Results and Discussions

Firstly, the fuzzified normalized weightage of criteria was derived using the Analytic Hierarchy Process (AHP) for nine replies. The stakeholders considered return on investment (ROI) and project duration crucial criteria and assigned them a larger weightage in figure 4.4. more details are provided. Team 1 allocated a greater weight to technical factors and less to environmental criteria. The technical, economic, and social factors of Team 2 have similar weightage, but they ascribed comparatively low emphasis to the environmental criterion. Contrarily, Team 3 evenly allocated the weightage among all criteria, with the greatest emphasis on environmental factors. The weight derived from these calculations is later used to rank the alternatives. The acceptance of the results in this method was determined by evaluating the consistency ratio, which was below 10% in all instances. Subsequently, the calculation progressed to evaluating alternatives using Fuzzy TOPSIS, wherein the criteria weightage was determined through Fuzzy AHP. The outcome of this procedure is determined based on the closeness coefficient (CC); a higher CC indicates a higher ranking.

The weighted CC of any team was determined by assigning weights of 40%, 30%, and 30% to the opinions of the owner, constructor, and designer, respectively, in the group decision-making process. As shown in Figure 4.8, Team 1 achieved final weighted CC scores of 0.7551, 0.6802, 0.4705, and 0.3827 for Major Renovation, Minor Renovation, Building Relocation, and Building Replacement, respectively. The group's top goal was to rank the alternatives as follows: Major Renovation was the priority, Minor Renovation was the second priority, Building Replacement was the third, and Building Relocation was the last priority. Team 2's weighted CC scores for Major Renovation, Minor Renovation, Building Relocation, and Building Replacement were 0.6542, 0.4741, 0.2092, and 0.4337, respectively. According to their choices, Major Renovation was the top pick, followed by Minor Renovation, Building Relocation, and Building Replacement. For Team 3, the weighted CC values were 0.2753, 0.4730, 0.5694, and 0.3476 for Major Renovation, Minor Renovation, Building Relocation, and Building Replacement, respectively.

The group's initial option was building relocation, followed by minor renovation, building replacement, and major renovation. Teams 1 and 2 choose Major Renovation as their first choice and Building Relocation as their last choice. Contrarily, Team 3 considered Building Relocation as their final option after exhausting all other possibilities, including Major Renovation.

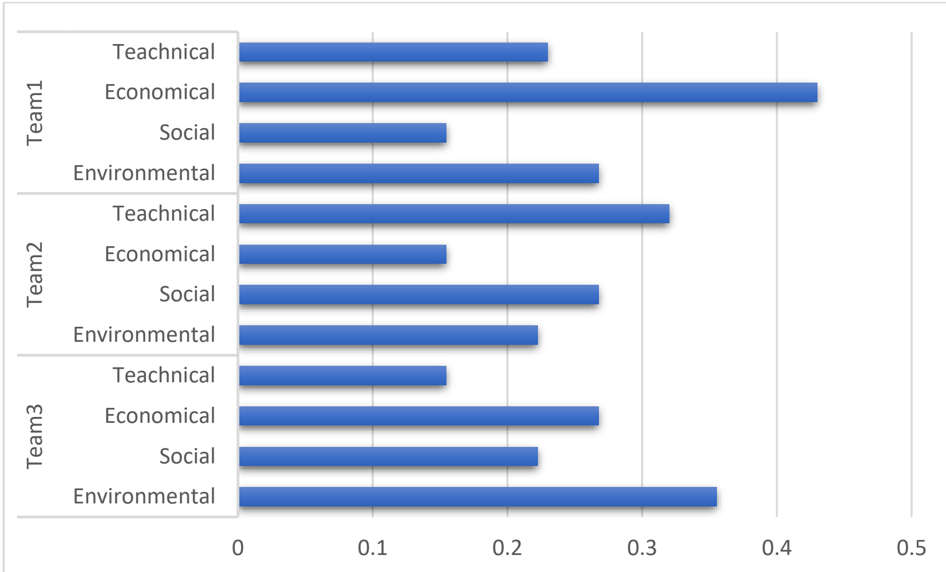


**Figure 4.4. Summary of the fuzzified normalized weightage of all teams.**

Furthermore, we utilized a decision matrix alongside Fuzzy AHP to determine the weightage of the criterion in this study. The fuzzy analytical hierarchy process (AHP) is a commonly employed technique for determining the relative importance of criteria. However, when the number of criteria is extensive, users may find it challenging to conduct pairwise comparisons for all of them, leading to increased result inconsistency. To ensure consistency in the pairwise comparisons conducted in this study, we had to carefully analyze the responses of individuals multiple times in many instances. In this approach, users are unable to assign specific weights to criteria. Instead, the calculation process automatically determines the weights based on the pairwise comparisons provided by the users. Users must avoid making unreasonable criteria comparisons, which can lead to inconsistency.

In contrast to Fuzzy AHP, the decision matrix utilized a direct approach to allocate preference and weightage to the users. The participants could discern the relative significance of the criteria and provide weightage to them. The process is considerably faster and completely free from any possibility of inconsistency. The outcome reveals disparities in the calculated significance of criteria due to discrepancies in input approaches and calculation methodologies.

The data analysis and findings indicate that the choice made by this model relies totally on the inputs provided by the user. This system utilizes the users' input to compute the relative importance of criteria and the preferences for various options. Thus, it can be inferred that achieving a sustainable choice is only feasible if the stakeholders alter their conventional thought process centered around immediate financial benefits and actively pursue a sustainable resolution. Among the three teams examined in this study, two belonged to conventional construction sectors, while the third team consisted of individuals engaged in either researching or implementing sustainable construction practices. The results demonstrated a correlation between their organizational style and the preference for Teams 1 and 2, which focused more on technical and economic factors.

Chapter V

# Verification and Validation

## 5.1. Introduction

This chapter explored the techniques for checking and validating calculations and constructing decision support systems (DSS). The DSS underwent input and output validation by gathering expert feedback and suggestions. Additionally, the calculations and functionality of the DSS were verified via sensitivity analysis.

## 5.2. Sensitivity Analysis

Sensitivity analysis examines the impact of modifications to input elements or variables on the output of a system. The verification process involves analyzing the output outcomes of the system using different input parameters to ensure that it meets its intended purpose. The research involved doing sensitivity analysis by implementing the generated model across many situations to verify its responsiveness to changes in input and the generation of relevant output. The choice produced by the multi-criteria choice Support System (DSS) in this study relies on two types of user inputs: inputs for determining the weight of the criteria and preferences for ranking alternatives based on the qualities of the criteria, such as 'very high,' 'high,' and so on. The process is elaborated upon in the following sections.

### 5.2.1. Criteria Weightage Sensitivity

An analysis was conducted to assess the sensitivity of user input and criteria weight, identifying four distinct scenarios. Table 5.1 displays four sets of weights for criterion to represent four cases. The generated DSS was evaluated using several scenarios to observe how they influenced the $CC_i$Values that reflect the ranking of alternatives. In each case, Table 5.1 demonstrates that one pillar's criterion weights were given greater importance than the weights provided to the other pillars. The findings in Table 5.2 and the results shown in Figure 5.1 indicate that changing the weights of the criterion considerably impacts the $CC_i$ Values of the alternatives. If the weightage of any sustainability pillar is increased, placing greater importance on it, the value of $CC_i$ Likewise increases dramatically and greatly impacts ranking.

**Table 5. 1 Scenarios based on the sustainability pillar's focus.**

| Criteria | Sub-Criteria | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|---|---|---|---|---|---|
| **Environmental** | Green House Gas Emission Amount During Construction | **0.10** | 0.05 | 0.05 | 0.05 |
| | Materials Reuse Potential | **0.10** | 0.05 | 0.05 | 0.05 |
| | Green House Gas Emission Amount during operation and maintenance | **0.10** | 0.05 | 0.05 | 0.05 |
| | Solid Waste Amount During Construction | **0.10** | 0.05 | 0.05 | 0.05 |
| **Economical** | Return on Investment (ROI) | 0.05 | **0.10** | 0.05 | 0.05 |
| | Demolition Cost | 0.05 | **0.10** | 0.05 | 0.05 |
| | Maintenance Liability | 0.05 | **0.10** | 0.05 | 0.05 |
| | New Construction Cost | 0.05 | **0.10** | 0.05 | 0.05 |
| **Social** | Emotional Attachment | 0.05 | 0.05 | **0.10** | 0.05 |
| | Reflection of owner's reputation after making a decision | 0.05 | 0.05 | **0.10** | 0.05 |
| | Social Acceptance (Building Aesthetics) | 0.05 | 0.05 | **0.10** | 0.05 |
| | Historically Significant | 0.05 | 0.05 | **0.10** | 0.05 |
| **Technical** | Building addition lifespan | 0.05 | 0.05 | 0.05 | **0.10** |

| | | | | | |
|---|---|---|---|---|---|
| | Project Duration | 0.05 | 0.05 | 0.05 | **0.10** |
| | Current Building Condition (FCI) | 0.05 | 0.05 | 0.05 | **0.10** |
| | Variance between current and future Energy Use Index (EUI) | 0.05 | 0.05 | 0.05 | **0.10** |

Table 5.1 assigned a greater weight value of 0.10 to four criteria for each scenario inside one sustainability pillar, while the remaining 12 criteria were given a weight of 0.05 apiece. The users' input regarding their preferences for different alternatives was held constant to analyze its influence on the decision-making process. The alternative with a larger contribution to Optimistic criteria would be given a higher rank, while Adverse or cost elements would have the opposite impact. To validate the results, the weightage of criteria from this table was applied in the same sample Fuzzy TOPSIS calculation, as described in Chapter 4, to rank the alternatives. A different set of ranking results was obtained for each scenario for the alternatives. The only change made was in the weightage given to the criterion,

while the user preferences remained the same. The output results for various scenarios are displayed in Table 5.2.

**Table 5. 2 $CC_i$ values for four scenarios**

| $CC_i$ | Scenario 1 | | | | | Scenario 2 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Owner** | **Constructor** | **Designer** | **Overall** | **Rank** | **Owner** | **Constructor** | **Designer** | **Overall** | **Rank** |
| **Major Renovation** | 0.467 | 0.503 | 0.458 | 0.412 | 2 | 0.287 | 0.393 | 0.337 | 0.334 | 4 |
| **Minor Renovation** | 0.531 | 0.623 | 0.585 | 0.714 | 1 | 0.625 | 0.534 | 0.616 | 0.595 | 1 |
| **Building Relocations** | 0.372 | 0.404 | 0.538 | 0.372 | 3 | 0.451 | 0.471 | 0.478 | 0.465 | 2 |
| **Building Replacement** | 0.355 | 0.374 | 0.353 | 0.401 | 4 | 0.409 | 0.441 | 0.394 | 0.414 | 3 |

| | Scenario 3 | | | | | Scenario 4 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Owner | Constructor | Designer | Overall | Rank | Owner | Constructor | Designer | Overall | Rank |
| **Major Renovation** | 0.308 | 0.398 | 0.339 | 0.345 | 4 | 0.269 | 0.432 | 0.318 | 0.332 | 4 |
| **Minor Renovation** | 0.308 | 0.357 | 0.390 | 0.347 | 3 | 0.404 | 0.418 | 0.425 | 0.415 | 2 |
| **Building Relocations** | 0.638 | 0.610 | 0.678 | 0.642 | 1 | 0.304 | 0.376 | 0.335 | 0.338 | 3 |
| **Building Replacement** | 0.479 | 0.477 | 0.434 | 0.465 | 2 | 0.676 | 0.553 | 0.655 | 0.633 | 1 |

In scenario 1, it was noted that increasing the weightage of environmental pillars impacted the ranking of Building Replacement for Team 3, which is now placed as the fourth priority after giving higher priority to technological, economic, social, and environmental aspects. When evaluating the total impact of Team 3, assigning greater importance to environmental factors led to Minor Renovation having a higher. $CC_i$ Value. Conversely, prioritizing social and environmental factors resulted in building relocation having a better outcome. $CC_i$ Value. Minor Renovation was given greater weight when prioritizing economic factors. The same explanations are relevant for other circumstances as well.

### 5.2.2. Sensitivity Analysis of User Preferences for Alternatives

The user's input determines the ranking of the choices. This study examines four situations to analyze the fluctuation of the $CC_i$ The value results from different user inputs regarding alternate preferences. In this case, all the criteria were assigned equal importance to assess the model's sensitivity in accurately representing the user's input preferences.

#### 5.2.2.1. Scenario 1

Earlier In scenario 1, lower preference values were assigned to the cost criteria (indicating that lower costs are preferred). In comparison, higher preference values were assigned to the benefit criteria (indicating that larger benefits are preferred) for Alternative 1.

The preferences were sequentially adjusted by one increment for the successive alternatives (i.e., from very high to high, high to medium afterward). Each criterion weight was uniformly set to 0.0625, indicating equal relevance for all decision-makers in the team (owner, constructor, and designer). The alternatives were assessed using the provided inputs, as illustrated in Table 5.3.

**Table 5. 3 User Input for Scenario 1**

| **Criteria Category** | **Input Value** | | | |
|---|---|---|---|---|
| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 |
| **Beneficial criteria (9 criteria)** | Very high (7,8,9,10) | High (5,6,7,8) | Medium (3,4,5,6) | Low (1,2,3,4) |
| **Cost Criteria (7 criteria)** | Low (1,2,3,4) | Medium (3,4,5,6) | High (5,6,7,8) | Very high (7,8,9,10) |

The outcome of this example user input is displayed in Table 5.4. The ranking result indicates that increasing the input value of advantageous criteria and decreasing the input values in cost criteria led to an increase in the $CC_i$ Value.

**Table 5. 4 $CC_i$ values for scenario 1**

| **Alternatives** | $CC_i$ | **Rank** |
|---|---|---|
| **Alternative 1** | 1 | 1 |
| **Alternative 2** | 0.622 | 2 |
| **Alternative 3** | 0.468 | 3 |
| **Alternative 4** | 0.216 | 4 |

Alternative 1 was optimized under the most favorable circumstances in this scenario (Scenario 1). The advantageous criteria had the highest level of choice, while the cost criteria received a lower preference level. Simultaneously, the weighting for all criteria and the relevance of stakeholders were maintained at a consistent and equal level. Alternative 1 achieved the greatest value. $CC_i$, which was anticipated to determine the sensitivity of the model. Similarly, the priority for Alternatives 2, 3, and 4 was gradually changed based on user input, which was reflected in the system's output as intended (Table 5.4).

#### 5.2.2.2. Scenario 2

In scenario 2, each option was assessed with equivalent preferences for all benefit and cost criteria. For example, option 1 had a 'very high' preference for all beneficial and cost criteria, as indicated in Table 5.5, to see its impact on the output. The outcome is organized and presented in Table 5.6.

**Table 5. 5 User input for Scenario 2**

| Criteria Category | Input Value | | | |
|---|---|---|---|---|
| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 |
| **Beneficial criteria (9 criteria)** | Very high (7,8,9,10) | High (5,6,7,8) | Medium (3,4,5,6) | Low (1,2,3,4) |
| **Cost Criteria (7 criteria)** | Very high (7,8,9,10) | High (5,6,7,8) | Medium (3,4,5,6) | Low (1,2,3,4) |

**Table 5. 6 $CC_i$values for scenario 2**

| Alternatives | $CC_i$ | Rank |
|---|---|---|
| **Alternative 1** | 0.073 | 4 |
| **Alternative 2** | 0.454 | 3 |
| **Alternative 3** | 0.652 | 2 |
| **Alternative 4** | 0.806 | 1 |

In scenario 2, the greatest preferences (Very High) were indicated for both the beneficial and cost criteria. Nevertheless, prioritizing certain criteria would enhance the ranking regarding advantageous factors, but it would have a contrary impact on cost-related criteria. The ranking result of scenario 2 indicated that an increase in the input value of the cost criteria led to a decrease in the value of $CC_i$ From scenario 1. Alternative 4 contributed value $CC_i$ By having a lower preferred input in cost criteria. Similarly, the priority for Alternatives 2, 3, and 4 was gradually changed based on user input, and this change was reflected in the system's output as intended (Table 5.4)

#### 5.2.2.3. Scenario 3

In this case, the options are assessed in Table 5.7, where each alternative is provided with the same user input. The results are presented in Table 5.8.

**Table 5. 7 User input for Scenario 3**

| Criteria Category | Input Value | | | |
|---|---|---|---|---|
| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 |
| **Technical Criteria** | Very High (7,8,9,10) | High (5,6,7,8) | Medium (3,4,5,6) | Low (1,2,3,4) |
| **Economic Criteria** | Low (1,2,3,4) | Very High (7,8,9,10) | High (5,6,7,8) | Medium (3,4,5,6) |
| **Social Criteria** | Medium (3,4,5,6) | Low (1,2,3,4) | Very High (7,8,9,10) | High (5,6,7,8) |
| **Environmental Criteria** | High (5,6,7,8) | Medium (3,4,5,6) | Low (1,2,3,4) | Very High (7,8,9,10) |

**Table 5. 8 $CC_i$values for Scenario 3**

| Alternatives | $CC_i$ | Rank |
|---|---|---|
| **Alternative 1** | 0.5378 | 1 |
| **Alternative 2** | 0.3692 | 2 |
| **Alternative 3** | 0.5378 | 1 |

| | | |
|---|---|---|
| **Alternative 4** | 0.3692 | 2 |

In scenario 3, it is evident that despite each choice having the same user preferences set to it (with "Very High" for 4 criteria, "High" for 4 criteria, "Medium" for 4 criteria, and "Low" for 4 criteria), the result differed. This is attributed to the presence of advantageous and cost-related criteria. The $CC_i$ Values for Alternatives 2 and 4 were adversely affected by higher cost criteria values. This indicates that the created model is responsive to the input provided on its fundamental cost-benefit criteria.

#### 5.2.2.4. Scenario 4

In this process, the alternatives are assessed using user input randomly assigned for several criteria groupings, referred to as pillars. The results of this evaluation are then presented in Table 5.10, while Table 5.9 displays the specific criteria used.

**Table 5. 9 User input for Scenario 4**

| | **Input Value** | | | |
|---|---|---|---|---|
| **Criteria Category** | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 |
| **Technical** | High<br>(5,6,7,8)) | High<br>(5,6,7,8) | Medium<br>(3,4,5,6) | Medium<br>(3,4,5,6) |
| **Economic** | Low<br>(1,2,3,4) | Very high<br>(7,8,9,10) | Very high<br>(7,8,9,10) | Medium<br>(3,4,5,6) |
| **Social** | Medium<br>(3,4,5,6) | Low<br>(1,2,3,4) | Very high<br>(7,8,9,10) | High<br>(5,6,7,8) |
| **Environmental** | Low<br>(1,2,3,4) | Medium<br>(3,4,5,6) | Low<br>(1,2,3,4) | Very high<br>(7,8,9,10) |

**Table 5. 10 $CC_i$values for scenario 4**

| Alternatives | | $CC_i$ Rank |
|---|---|---|
| **Alternative 1** | 0.3380 | 4 |
| **Alternative 2** | 0.3964 | 3 |
| **Alternative 3** | 0.6260 | 1 |
| **Alternative 4** | 0.4245 | 2 |

In scenario 4, the output result shows that option 3 obtained a higher rank with a greater. $CC_i$ Value. This is because alternative 3 was randomly assigned more inputs with higher values. Alternative 3 was highly preferred across multiple advantageous factors, resulting in a high $CC_i$ value and placing it at the top of the ranking.

# Chapter VI

# Conclusion and Recommendations

### 6.1. Overview of findings

Sustainable building seeks to minimize negative impacts and maximize benefits by effectively managing sustainability's social, economic, technical, and environmental aspects. Historically, construction projects have been chosen primarily based on their return on investment, focusing on technical and economic factors, while social and environmental factors have been given less importance. Considering all aspects of sustainability complicates decision-making by incorporating several elements into the choosing process. Therefore, in most instances, the project stakeholders choose not to utilize a structured decision-making procedure to identify the most environmentally friendly options. The construction industry is crucial for economic development and productivity, generating numerous job possibilities. Nevertheless, this industry has faced criticism because of its excessive utilization of global resources, elevated levels of energy consumption, and significant emissions of greenhouse gases. Consequently, it needs enhanced resource efficiency, heightened output, reduced waste, and heightened value.

The fundamental principle of sustainable building encompasses the judicious utilization of natural resources, the promotion of escalating levels of economic growth, the mitigation of unemployment rates, the provision of sufficient environmental protection, and the assurance of enhanced social advancement that acknowledges the demands of all individuals. Prior research has explored the feasibility of managing old buildings sustainably. However, none of these studies have incorporated the perspectives of all parties involved, including the owner, design team, and constructors, within the Integrated Project Delivery (IPD) framework. This framework is used from the beginning of the project to determine the most desirable sustainable option. In addition, while some researchers have contended that the technical aspect is a crucial component of evaluating the sustainability of civil infrastructure, there is a lack of comprehensive studies that effectively combine the technical aspect with the economic, social, and environmental aspects to analyze the overall sustainability factors. The consultation with multiple industry experts revealed that structural material selection is typically based on technical and economic considerations. Currently, there is a lack of a systematic instrument that can effectively incorporate all parties' viewpoints and evaluate the various aspects of sustainable construction during the selection process.

MCDM approaches enhance stakeholders' decision-making by efficiently utilizing timely and relevant data, information, and knowledge management. This study created a decision support system (DSS) that used a combination of multiple criteria decision-making (MCDM) techniques to evaluate different options for addressing old buildings with high maintenance costs. The DSS incorporated the preferences of all stakeholders and used an integrated project delivery (IPD) framework. The evaluation considered sustainability's technical, economic, social, and environmental aspects to identify the most sustainable alternative.

## 6.2. Summary of The Research

This study employed a hybrid methodology to create a decision support system to address the previously described issue. This was achieved using Fuzzy AHP, decision matrix, and Fuzzy TOPSIS multi-criteria decision-making methodologies. The analysis was based on a comprehensive literature review and consultation meetings with business and academic professionals. The review focused on the selection process for alternatives to address old constructions from the perspective of sustainable construction practices. It included the identification of each alternative used for old educational constructions and the examination of their sustainability. The study revealed that construction companies make decisions regarding the structure based on technical and economic factors. However, it was found that there is a lack of a sustainable decision-making mechanism in place. Prior research in this field has concentrated on either the technical or economic aspects exclusively or has taken into account simply the three pillars of sustainable construction. Nevertheless, several researchers and industry experts have contended that technical performance should be explicitly incorporated as a fundamental aspect of infrastructure sustainability theory. Thus, this study incorporated four fundamental components in the Decision Support System (DSS) to achieve a viable and enduring solution.

The evaluation criteria for measuring the technical, economic, social, and environmental aspects of sustainable construction differ depending on the construction projects' type and characteristics and the parties' preferences. The list of sub-criteria relevant to this research was finalized by obtaining the opinions of multiple industry experts and academic scholars.

Deconstruction procedures often involve major renovation, minor renovation, relocation, and replacement. Building replacement is the most common option due to its efficiency and cost-effectiveness. Paradoxically, demolition is a prominent means of causing environmental deterioration and poses harm to the ecology and environment. This situation has raised concerns regarding exploring alternate building construction methods to attain sustainability.

Multi-criteria decision-making (MCDM) has been widely employed in the construction sector to determine the most optimal choice among multiple possibilities. MCDM techniques facilitate the generation of alternative scenarios, the establishment of criteria, the assessment of alternatives, the weighing of criteria, and the ranking of alternatives. The fuzzy analytical hierarchy process (AHP) is highly effective for assigning weights to criteria in multiple-criteria decision-making (MCDM). This research employed the Fuzzy AHP to assign weights to the sixteen selected assessment criteria. The trapezoidal membership function was selected due to its ability to manage uncertainties, imprecision, and lack of information.

Furthermore, a straightforward decision matrix was employed to determine the weighting of the criteria, as the inconsistency of data becomes more pronounced in FAHP when the number of criteria increases. The decision to utilize Fuzzy TOPSIS for ranking the options was based on its widespread usage, familiarity, and ease of use as a decision-making tool. Additionally, it is widely accepted by both industry and academics. Examining the outcomes with Fuzzy TOPSIS confirms its dependability in the building sector. The DSS was specifically built with the IPD project delivery approach in mind, as it has a greater impact on sustainability by involving all stakeholders from the beginning of the project. Additionally, it aims to enhance the outcomes of the triple constraint (money, time, and quality) by aligning the project team's goals and implementing a system of shared risk and reward.

The gathered data were examined and computed through multiple stages. While the Fuzzy AHP approach is commonly employed for determining criteria weightage, we have observed that users have challenges making pairwise comparisons when the number of criteria is extensive. Consequently, this leads to an escalation in result inconsistency. Thus, with Fuzzy AHP, we utilized a decision matrix to determine the weightage of criteria. The results indicate that variations in input procedures and calculation methodologies lead to discrepancies in the computed weightage of the criterion. However, a significant discovery was made that individuals who assigned greater significance to a certain criterion in Fuzzy AHP also did so for the decision matrix. The weightage of the criteria determined using Fuzzy AHP was subsequently utilized in Fuzzy TOPSIS to rank the alternatives. These two methodologies have both similarities and variations in their computation techniques. Both approaches rely on the concept of an aggregating function that measures proximity to the optimal solution.

Nevertheless, these methods employ distinct forms of normalization. TOPSIS, for instance, utilizes a ranking index that computes the distance from both positive and negative ideal solutions. Consequently, the top option, according to TOPSIS, is also ranked highest in the index.

Significant disparities existed in the ultimate placement of the various teams' choices. Major Renovation was prioritized in certain circumstances, while Building Replacement was prioritized in others. Among the three teams examined in this study, two were affiliated with conventional construction sectors, while the third team consisted of individuals engaged in researching or implementing sustainable construction practices. The results demonstrated the organizational behavior and indicated that Teams 1 and 2 were more inclined towards technical and economic elements. Due to their considerably reduced emphasis on social and environmental considerations, Major Renovation and Minor Renovation emerged as the top-ranked alternatives in their selection process.

In contrast, considering both social and environmental factors, Team 3's preferences were more evenly distributed. As a result, Building Relocation was the top choice for the structural material in this case study. The choice made by this choice Support System (DSS) is fully contingent upon the inputs provided by the user. This system utilizes the users' input regarding the importance assigned to certain criteria and their preferences for different alternatives to do calculations. If users prioritize economic benefit over environmental considerations, the product will align with their preferences. In contrast, if the stakeholders carefully analyze all aspects of sustainable building and consider the project's life cycle aligns with sustainable construction, as demonstrated by the choice of Team 3 in this study.

The Decision Support System (DSS) has been created to aid decision-makers in selecting a sustainable choice within an Integrated Product Development (IPD) framework. The developed DSS software offers several notable advantages. Firstly, it is a collaborative tool that allows all stakeholders to contribute their inputs within the IPD framework for decision-making. Secondly, users can edit and modify alternatives and evaluation criteria according to their requirements. Additionally, users can assign varying levels of importance to different criteria. The software is capable of handling both qualitative and quantitative data. Qualitative inputs are captured through users' preferences, such as 'very high' or 'high,' while quantitative inputs are represented as computed numerical values.

Furthermore, stakeholders can determine the significance of their opinions in group decision-making. Lastly, the software is a versatile model that can be applied to various sustainable group decision-making scenarios. This DSS, which is convenient, adjustable, and simple, is anticipated to enhance objectivity, transparency, and consistency in sustainable construction. Additionally, it will systematize the process.

The notable contributions of this research include a comprehensive analysis of literature, expert opinions, and industry practices to determine the elements that influence the process of picking the most sustainable alternative. The incorporation of technical elements into the widely recognized three pillars (economic, social, and environmental) of sustainability for evaluation includes a detailed examination of a specific instance. The application involves utilizing two distinct (MCDM) methods: Fuzzy TOPSIS. These methods rank options by incorporating Shannon's entropy to handle qualitative and quantitative data. Additionally, trapezoidal membership functions are utilized to obtain more realistic outcomes. The objective is to create a Decision Support System (DSS) that aids decision-makers in selecting evaluation criteria and determining their relative importance. This DSS will utilize qualitative and quantitative methods within an Integrated Project Delivery (IPD) framework. Its purpose is to assist in choosing the most sustainable approach for addressing issues related to old buildings and resolving various construction-related problems.

## 6.3. Conclusion

Increases The building industry's overall performance raises significant concerns about the need to mitigate negative impacts and enhance global sustainability. Choosing suitable sustainable methods for handling historic buildings can contribute to achieving sustainability in the construction industry. Every method possesses unique sustainability attributes, meaning that one method may be economically efficient but have a greater negative impact on the environment or be aesthetically unsuitable for the surroundings. Multi-criteria decision-making is crucial for choosing the best sustainable method among multiple choices. The implemented Decision Support System (DSS) is anticipated to improve impartiality and uniformity in the selection process and aid in making more informed decisions on the sustainability of construction projects. This study posited that achieving a sustainable sector necessitates stakeholders moving away from the conventional approach of evaluating short-term costs and benefits. Instead, they should strive to balance all aspects of sustainable construction to optimize value and reduce negative impacts. Hence, it is the responsibility of individuals to make deliberate choices to enhance the equilibrium between progress and sustainability, thereby creating a harmonious society for future generations.

## 6.4. Limitation of This Study

The research did not prioritize the structural analysis of buildings or consider the technical process from the designer's perspective. Instead, it aimed to identify the most sustainable option among the feasible alternatives for selecting the most suitable method for renovating an old educational building within the IPD framework. Hence, this study did not include an in-depth examination of the structural analysis. Major Renovation, Minor Renovation, Building Relocation, and Building Replacement were considered solutions for the structural elements, excluding other composites. The implemented Decision Support System (DSS) underwent testing using a hypothetical case study involving an aging educational facility in Edmonton, Alberta. The evaluation process incorporated the perspectives of nine experts from both academia and industry.

The inclusion of regulators, end users, and external stakeholders in a decision support system (DSS) aimed at selecting the most sustainable alternatives for old buildings with high maintenance costs is subject to notable constraints. The main obstacle is the significant amount of time needed to collect thorough data from each project, resulting in a delay in the decision-making process. Moreover, the involvement of various stakeholders adds a significant degree of intricacy to the computations, as the system needs to consider a wide range of different and potentially contradictory priorities and viewpoints. The intricacy of the ranking system can undermine its efficacy, as it becomes progressively challenging to precisely evaluate and assign weight to each factor. As a result, the greater number of stakeholders can result in less accurate and dependable results, making it unfeasible to involve such a wide range of participants in the DSS.

## 6.5. Recommendations For Future Works

Aside from TOPSIS, researchers can employ additional methodologies such as PROMETHEE, DEMATEL, CBA, ANP, and VIKOR to validate the applications produced in this study. This study focused exclusively on selecting methods for dealing with historic structures. However, there is potential for future evaluation of the overall building's sustainability utilizing the created Decision Support System (DSS). Researchers can collect a substantial number of samples for the Analytic Hierarchy Process (AHP) and decision matrix to compare the outcomes of criteria weightage. Upon doing TOPSIS, we observed discrepancies in the ranking results. Further analysis is warranted to thoroughly examine and provide commentary on these inconsistencies.

.

## Reference

Abbas, A., G. Fathifazl, O.B. Isgor, A.G. Razaqpur, B. Fournier, and S. Foo. 2006. "Environmental Benefits of Green Concrete." In *2006 IEEE EIC Climate Change Conference*, 1–8. https://doi.org/10.1109/EICCCC.2006.277204.

Abdul Lateef, Olanrewaju Ashola, Mohd Faris Khamidi, and Arazi Idrus. 2011. "Appraisal of the Building Maintenance Management Practices of Malaysian Universities." *Journal of Building Appraisal* 6 (3): 261–75. https://doi.org/10.1057/jba.2011.3.

Abidin, Nazirah Zainul, and Christine L. Pasquire. 2007. "Revolutionize Value Management: A Mode towards Sustainability." *International Journal of Project Management* 25 (3): 275–82. https://doi.org/10.1016/j.ijproman.2006.10.005.

AbouHamad, Mona, and Metwally Abu-Hamd. 2019. "Framework for Construction System Selection Based on Life Cycle Cost and Sustainability Assessment." *Journal of Cleaner Production* 241 (December):118397. https://doi.org/10.1016/j.jclepro.2019.118397.

Akadiri, Peter O., Ezekiel A. Chinyio, and Paul O. Olomolaiye. 2012. "Design of A Sustainable Building: A Conceptual Framework for Implementing Sustainability in the Building Sector." *Buildings* 2 (2): 126–52. https://doi.org/10.3390/buildings2020126.

Alba-Rodríguez, Mª. Desirée, Alejandro Martínez-Rocamora, Patricia González-Vallejo, Antonio Ferreira-Sánchez, and Madelyn Marrero. 2017. "Building Rehabilitation versus Demolition and New Construction: Economic and Environmental Assessment." *Environmental Impact Assessment Review* 66 (September):115–26. https://doi.org/10.1016/j.eiar.2017.06.002.

Alderman, Delton, and Robert Shelburne. 2012. "The Economic Situation and Construction-Sector Developments in the UNECE Region, 2011-2012." In *Forest Products Annual Market Review 2011-2012*, by United Nations Economic Commission for Europe, 11–23. Geneva Timber and Forest Study Papers. UN. https://doi.org/10.18356/5cce7244-en.

Al-Jarallah, Mohammed I. 1983. "Construction Industry in Saudi Arabia." *Journal of Construction Engineering and Management* 109 (4): 355–68. https://doi.org/10.1061/(ASCE)0733-9364(1983)109:4(355).

Almahmoud, Essam, and Hemanta Kumar Doloi. 2015. "Assessment of Social Sustainability in Construction Projects Using Social Network Analysis." *Facilities* 33 (3/4): 152–76. https://doi.org/10.1108/F-05-2013-0042.

Almén, Lena, and Tore J. Larsson. 2014. "Health and Safety Coordinators in Building Projects." *Built Environment Project and Asset Management* 4 (3): 251–63. https://doi.org/10.1108/BEPAM-05-2013-0012.

Amaral, Luiz, Detmar Meurers, and Ramon Ziai. 2011. "Analyzing Learner Language: Towards a Flexible Natural Language Processing Architecture for Intelligent Language Tutors." *Computer Assisted Language Learning* 24 (1): 1–16. https://doi.org/10.1080/09588221.2010.520674.

Amaratunga, Dilanthi, and David Baldry. 2000. "Assessment Offacilities Management Performance in Higher Education Properties." *Facilities* 18 (7/8): 293–301. https://doi.org/10.1108/02632770010340681.

Andrić, Ivan, André Pina, Paulo Ferrão, Bruno Lacarrière, and Olivier Le Corre. 2017. "The Impact of Renovation Measures on Building Environmental Performance: An Emergy Approach." *Journal of Cleaner Production* 162 (September):776–90. https://doi.org/10.1016/j.jclepro.2017.06.053.

Ark, Bart van, Mary O'Mahoney, and Marcel P. Timmer. 2008. "The Productivity Gap between Europe and the United States: Trends and Causes." *Journal of Economic Perspectives* 22 (1): 25–44. https://doi.org/10.1257/jep.22.1.25.

Aruldoss, Martin, T Miranda Lakshmi, and V Prasanna Venkatesan. n.d. "A Survey on Multi Criteria Decision Making Methods and Its Applications." *American Journal of Mechanical Engineering*.

Assefa, Getachew, and Chelsea Ambler. 2017. "To Demolish or Not to Demolish: Life Cycle Consideration of Repurposing Buildings." *Sustainable Cities and Society* 28 (January):146–53. https://doi.org/10.1016/j.scs.2016.09.011.

Awad, Jihad, and Chuloh Jung. 2021. "Evaluating the Indoor Air Quality after Renovation at the Greens in Dubai, United Arab Emirates." *Buildings* 11 (8): 353. https://doi.org/10.3390/buildings11080353.

Bakhoum, Emad S., and David C. Brown. 2015. "An Automated Decision Support System for Sustainable Selection of Structural Materials." *International Journal of Sustainable Engineering* 8 (2): 80–92. https://doi.org/10.1080/19397038.2014.906513.

Baloi, Daniel, and Andrew D. F. Price. 2003. "Modelling Global Risk Factors Affecting Construction Cost Performance." *International Journal of Project Management* 21 (4): 261–69. https://doi.org/10.1016/S0263-7863(02)00017-0.

Barandica, Jesús M., Gonzalo Fernández-Sánchez, Álvaro Berzosa, Juan A. Delgado, and Francisco J. Acosta. 2013. "Applying Life Cycle Thinking to Reduce Greenhouse Gas Emissions from Road Projects." *Journal of Cleaner Production* 57 (October):79–91. https://doi.org/10.1016/j.jclepro.2013.05.036.

Barthel, Diane. 1989. "Historic Preservation: A Comparative Analyses." *Sociological Forum* 4 (1): 87–105. https://doi.org/10.1007/BF01112618.

Begum, Rawshan Ara, Chamhuri Siwar, Joy Jacqueline Pereira, and Abdul Hamid Jaafar. 2006. "A Benefit–Cost Analysis on the Economic Feasibility of Construction Waste Minimisation: The Case of Malaysia." *Resources, Conservation and Recycling* 48 (1): 86–98. https://doi.org/10.1016/j.resconrec.2006.01.004.

Behm, Michael. 2005. "Linking Construction Fatalities to the Design for Construction Safety Concept." *Safety Science* 43 (8): 589–611. https://doi.org/10.1016/j.ssci.2005.04.002.

Bennett, Martin, and Peter James. 1999. "Key Themes in Environmental, Social and Sustainability Performance Evaluation and Reporting." In *Sustainable Measures*. Routledge.

Bernardi, Elena, Salvatore Carlucci, Cristina Cornaro, and Rolf André Bohne. 2017. "An Analysis of the Most Adopted Rating Systems for Assessing the Environmental Impact of Buildings." *Sustainability* 9 (7): 1226. https://doi.org/10.3390/su9071226.

Bhuiyan, Alam, and Mohammad Masfiqul. 2022. "Decision Support System for Selection of the Most Sustainable Structural Materials for a Multistory Building Construction." ERA. Fall 2022. https://doi.org/10.7939/r3-wqxt-b806.

BICKFORD, SUSAN. 2000. "Constructing Inequality: City Spaces and the Architecture of Citizenship." *Political Theory* 28 (3): 355–76. https://doi.org/10.1177/0090591700028003003.

Biseniece, Edīte, Gatis Žogla, Agris Kamenders, Reinis Purviņš, Kristaps Kašs, Ruta Vanaga, and Andra Blumberga. 2017. "Thermal Performance of Internally Insulated Historic Brick Building in Cold Climate: A Long Term Case Study." *Energy and Buildings* 152 (October):577–86. https://doi.org/10.1016/j.enbuild.2017.07.082.

Bohanec, Marko. 2022. "DEX (Decision EXpert): A Qualitative Hierarchical Multi-Criteria Method." In *Multiple Criteria Decision Making: Techniques, Analysis and Applications*, edited by Anand J. Kulkarni, 39–78. Singapore: Springer Nature. https://doi.org/10.1007/978-981-16-7414-3_3.

Bossink, B. a. G., and H. J. H. Brouwers. 1996. "Construction Waste: Quantification and Source Evaluation." *Journal of Construction Engineering and Management* 122 (1): 55–60. https://doi.org/10.1061/(ASCE)0733-9364(1996)122:1(55).

Branco, Jorge M., and João P. Araújo. 2010. "Lateral Resistance of Log Timber Walls Subjected to Horizontal Loads." In . http://repositorium.sdum.uminho.pt/.

Bubshait, Abdulaziz A., and Abdulaziz A. Al-Musaid. 1992. "Owner Involvement in Construction Projects in Saudi Arabia." *Journal of Management in Engineering* 8 (2): 176–85. https://doi.org/10.1061/(ASCE)9742-597X(1992)8:2(176).

Buchanan, Andrew H., and Anthony Kwabena Abu. 2017. *Structural Design for Fire Safety*. John Wiley & Sons.

Bullen, Peter A. 2007. "Adaptive Reuse and Sustainability of Commercial Buildings." *Facilities* 25 (1/2): 20–31. https://doi.org/10.1108/02632770710716911.

Cass, D., and A. Mukherjee. 2011. "Calculation of Greenhouse Gas Emissions for Highway Construction Operations by Using a Hybrid Life-Cycle Assessment Approach: Case Study for Pavement Operations." *Journal of Construction Engineering and Management* 137 (11): 1015–25. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000349.

Chhabra, Deepak, Robert Healy, and Erin Sills. 2003. "Staged Authenticity and Heritage Tourism." *Annals of Tourism Research* 30 (3): 702–19. https://doi.org/10.1016/S0160-7383(03)00044-6.

Chini, Abdol, and Stuart Bruening. 2003. "Deconstruction and Materials Reuse in the United States," January.

Choi, Junho, and Jun Kim. 2023. "Techno-Economic Feasibility Study for Deep Renovation of Old Apartment." *Journal of Cleaner Production* 382 (January):135396. https://doi.org/10.1016/j.jclepro.2022.135396.

Cochran, Kimberly, Timothy Townsend, Debra Reinhart, and Howell Heck. 2007. "Estimation of Regional Building-Related C&D Debris Generation and Composition: Case Study for Florida, US." *Waste Management* 27 (7): 921–31. https://doi.org/10.1016/j.wasman.2006.03.023.

Cooper, Daniel R., and Timothy G. Gutowski. 2017. "The Environmental Impacts of Reuse: A Review." *Journal of Industrial Ecology* 21 (1): 38–56. https://doi.org/10.1111/jiec.12388.

Daniel, Emmanuel Itodo, and Christine Pasquire. 2019. "Creating Social Value within the Delivery of Construction Projects: The Role of Lean Approach." *Engineering, Construction and Architectural Management* 26 (6): 1105–28. https://doi.org/10.1108/ECAM-06-2017-0096.

Demkin, Joseph A., and The American Institute of Architects. 2001. *The Architect's Handbook of Professional Practice*. John Wiley & Sons.

Doloi, Hemanta. 2012. "Understanding Impacts of Time and Cost Related Construction Risks on Operational Performance of PPP Projects." *International Journal of Strategic Property Management* 16 (3): 316–37. https://doi.org/10.3846/1648715X.2012.688774.

Doroudiani, S., and H. Omidian. 2010. "Environmental, Health and Safety Concerns of Decorative Mouldings Made of Expanded Polystyrene in Buildings." *Building and Environment* 45 (3): 647–54. https://doi.org/10.1016/j.buildenv.2009.08.004.

Duran, Xavier, Helena Lenihan, and Bernadette O'Regan. 2006. "A Model for Assessing the Economic Viability of Construction and Demolition Waste Recycling—the Case of

Ireland.” *Resources, Conservation and Recycling* 46 (3): 302–20. https://doi.org/10.1016/j.resconrec.2005.08.003.

Dutil, Yvan, Daniel Rousse, and Guillermo Quesada. 2011. “Sustainable Buildings: An Ever Evolving Target.” *Sustainability* 3 (2): 443–64. https://doi.org/10.3390/su3020443.

Elkington, John. 1998. “Partnerships from Cannibals with Forks: The Triple Bottom Line of 21st-Century Business.” *Environmental Quality Management* 8 (1): 37–51. https://doi.org/10.1002/tqem.3310080106.

Elliott, James R., Kevin Fox Gotham, and Melinda J. Milligan. 2004. “Framing the Urban: Struggles Over HOPE VI and New Urbanism in a Historic City.” *City & Community* 3 (4): 373–94. https://doi.org/10.1111/j.1535-6841.2004.00093.x.

Farahani, Abolfazl, Holger Wallbaum, and Jan-Olof Dalenbäck. 2020. “Cost-Optimal Maintenance and Renovation Planning in Multifamily Buildings with Annual Budget Constraints.” *Journal of Construction Engineering and Management* 146 (3): 04020009. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001778.

Farzanehrafat, Morvarid, Ali Akbar Nezhad, and Parviz Ghoddousi. 2015. *Analysis of Different Views towards Social Sustainability in Construction*. https://doi.org/10.22260/ISARC2015/0113.

Ferguson, J., and Institution of Civil Engineers (Great Britain). 1995. *Managing and Minimizing Construction Waste: A Practical Guide*. Thomas Telford.

Ferreira, Susana, and Mirko Moro. 2011. “Constructing Genuine Savings Indicators for Ireland, 1995–2005.” *Journal of Environmental Management* 92 (3): 542–53. https://doi.org/10.1016/j.jenvman.2010.09.015.

Finkbeiner, Matthias, Erwin M. Schau, Annekatrin Lehmann, and Marzia Traverso. 2010. “Towards Life Cycle Sustainability Assessment.” *Sustainability* 2 (10): 3309–22. https://doi.org/10.3390/su2103309.

Finkel, Gerald. 1997. *The Economics of the Construction Industry*. M.E. Sharpe.

Forceville, Charles. 2007. “Book Review of: Re-Viewing Space: Figurative Language in Architects’ Assessment of Built Space. Rosario Caballero, Berlin & New York: Mouton de Gruyter, 2006, 261 Pages, $118, ISBN13: 978-3-11-018520-1.” *Metaphor and Symbol - METAPHOR SYMB* 22 (June):275–80. https://doi.org/10.1080/10926480701357687.

Glover, Robert W., Donald W. Long, Carl T. Haas, and Christine Alemany. 1999. “Return on Investment (ROI) Analysis of Education and Training in the Construction Industry,” March. https://doi.org/10.26153/tsw/41156.

Goodrum, Paul M., Carl T. Haas, and Robert W. Glover. 2002. “The Divergence in Aggregate and Activity Estimates of US Construction Productivity.” *Construction*

*Management and Economics* 20 (5): 415–23. https://doi.org/10.1080/01446190210145868.

Gustavsson, Leif, and Anna Joelsson. 2010. "Life Cycle Primary Energy Analysis of Residential Buildings." *Energy and Buildings* 42 (2): 210–20. https://doi.org/10.1016/j.enbuild.2009.08.017.

Hasik, Vaclav, Elizabeth Escott, Roderick Bates, Stephanie Carlisle, Billie Faircloth, and Melissa M. Bilec. 2019. "Comparative Whole-Building Life Cycle Assessment of Renovation and New Construction." *Building and Environment* 161 (August):106218. https://doi.org/10.1016/j.buildenv.2019.106218.

Hein, Michael F., and Katie D. Houck. 2008. "Construction Challenges of Adaptive Reuse of Historical Buildings in Europe." *International Journal of Construction Education and Research* 4 (2): 115–31. https://doi.org/10.1080/15578770802229466.

Hill, Richard C., and Paul A. Bowen. 1997. "Sustainable Construction: Principles and a Framework for Attainment." *Construction Management and Economics* 15 (3): 223–39. https://doi.org/10.1080/014461997372971.

Hollenbeck, Kevin. 1996. "A Framework for Assessing the Economic Benefits and Costs of Workplace Literacy Training." *Upjohn Institute Working Papers*, January. https://doi.org/10.17848/wp96-42.

Holm, Len, and John E. Schaufelberger. 2021. *Construction Cost Estimating*. Routledge.

Iringova, Agnes. 2017. "Revitalisation of External Walls in Listed Buildings in the Context of Fire Protection." *Procedia Engineering*, CRRB 2016 – 18th INTERNATIONAL CONFERENCE ON REHABILITATION AND RECONSTRUCTION OF BUILDINGS, 195 (January):163–70. https://doi.org/10.1016/j.proeng.2017.04.539.

Islam, Hamidul, Margaret Jollands, and Sujeeva Setunge. 2015. "Life Cycle Assessment and Life Cycle Cost Implication of Residential Buildings—A Review." *Renewable and Sustainable Energy Reviews* 42 (February):129–40. https://doi.org/10.1016/j.rser.2014.10.006.

Ismaeel, Walaa S. E., and Ahmed Gouda Mohamed. 2022. "Indoor Air Quality for Sustainable Building Renovation: A Decision-Support Assessment System Using Structural Equation Modelling." *Building and Environment* 214 (April):108933. https://doi.org/10.1016/j.buildenv.2022.108933.

Iyer-Raniga, Usha, Priyanka Erasmus, Pekka Huovila, and Soumen Maity. 2020. "Circularity in the Built Environment: A Focus on India." In *International Business, Trade and Institutional Sustainability*, edited by Walter Leal Filho, Paulo R. Borges de Brito, and Fernanda Frankenberger, 739–55. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-26759-9_43.

Jain, Mayur Shirish. 2021. “A Mini Review on Generation, Handling, and Initiatives to Tackle Construction and Demolition Waste in India.” *Environmental Technology & Innovation* 22 (May):101490. https://doi.org/10.1016/j.eti.2021.101490.

Jensen, P.A., and M. Varano. 2011. “Technical Due Diligence: Study of Building Evaluation Practice.” *Journal of Performance of Constructed Facilities* 25 (3): 217–22. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000156.

Jones, Keith, and Mark Sharp. 2007. “A New Performance-based Process Model for Built Asset Maintenance.” Edited by Edward Finch. *Facilities* 25 (13/14): 525–35. https://doi.org/10.1108/02632770710822616.

Joppe, Marion. 1996. “Sustainable Community Tourism Development Revisited.” *Tourism Management* 17 (7): 475–79. https://doi.org/10.1016/S0261-5177(96)00065-9.

Juan, Yi-Kai, Wan-Ying Lai, and Shen-Guan Shih. 2017. “Building Information Modeling Acceptance and Readiness Assessment in Taiwanese Architectural Firms.” *Journal of Civil Engineering and Management* 23 (3): 356–67. https://doi.org/10.3846/13923730.2015.1128480.

Junnila, Seppo, Arpad Horvath, and Angela Acree Guggemos. 2006. “Life-Cycle Assessment of Office Buildings in Europe and the United States.” *Journal of Infrastructure Systems* 12 (1): 10–17. https://doi.org/10.1061/(ASCE)1076-0342(2006)12:1(10).

Kaminsky, Jessica. 2015. “The Fourth Pillar of Infrastructure Sustainability: Tailoring Civil Infrastructure to Social Context.” *Construction Management and Economics* 33 (4): 299–309. https://doi.org/10.1080/01446193.2015.1050425.

Karpouzis, K., G. Caridakis, S. -E. Fotinea, and E. Efthimiou. 2007. “Educational Resources and Implementation of a Greek Sign Language Synthesis Architecture.” *Computers & Education*, Web3D Technologies in Learning, Education and Training, 49 (1): 54–74. https://doi.org/10.1016/j.compedu.2005.06.004.

Kehily, Dermot, Barry McAuley, and Alan Hore. 2012. “Leveraging Whole Life Cycle Costs When Utilising Building Information Modelling Technologies.” *International Journal of 3-D Information Modeling (IJ3DIM)* 1 (4): 40–49. https://doi.org/10.4018/ij3dim.2012100105.

Kofoworola, Oyeshola Femi, and Shabbir H. Gheewala. 2009. “Estimation of Construction Waste Generation and Management in Thailand.” *Waste Management* 29 (2): 731–38. https://doi.org/10.1016/j.wasman.2008.07.004.

Kögler, Klaus, and Robert Goodchild. 2006. “The European Commission’s Communication ‘Integrated Product Policy: Building on Environmental Life-Cycle Thinking’*.” In *Governance of Integrated Product Policy*. Routledge.

Kropivšek, Jože, Petra Grošelj, Leon Oblak, and Matej Jošt. 2021. "A Comprehensive Evaluation Model for Wood Companies Websites Based on the AHP/R-TOPSIS Method." *Forests* 12 (6): 706. https://doi.org/10.3390/f12060706.

Kylili, Angeliki, Paris A. Fokaides, and Petra Amparo Lopez Jimenez. 2016. "Key Performance Indicators (KPIs) Approach in Buildings Renovation for the Sustainability of the Built Environment: A Review." *Renewable and Sustainable Energy Reviews* 56 (April):906–15. https://doi.org/10.1016/j.rser.2015.11.096.

Lal, Kishori. 2003. "Measurement of Output, Value Added, GDP in Canada and the United States: Similarities and Differences." Paris: OECD. https://doi.org/10.1787/101477551445.

Lataille, Jane. 2003. *Fire Protection Engineering in Building Design*. Butterworth-Heinemann.

Le, An Thi Hoai, Kenneth Sungho Park, Niluka Domingo, Eziaku Rasheed, and Nalanie Mithraratne. 2018. "Sustainable Refurbishment for School Buildings: A Literature Review." *International Journal of Building Pathology and Adaptation* 39 (1): 5–19. https://doi.org/10.1108/IJBPA-01-2018-0009.

Levitt, Raymond E. 2007. "CEM Research for the Next 50 Years: Maximizing Economic, Environmental, and Societal Value of the Built Environment1." *Journal of Construction Engineering and Management* 133 (9): 619–28. https://doi.org/10.1061/(ASCE)0733-9364(2007)133:9(619).

Li Hao, Jian, Martyn James Hill, and Li Yin Shen. 2008. "Managing Construction Waste On-site through System Dynamics Modelling: The Case of Hong Kong." *Engineering, Construction and Architectural Management* 15 (2): 103–13. https://doi.org/10.1108/09699980810852646.

Liao, Haolan, Rong Ren, and Lu Li. 2023. "Existing Building Renovation: A Review of Barriers to Economic and Environmental Benefits." *International Journal of Environmental Research and Public Health* 20 (5): 4058. https://doi.org/10.3390/ijerph20054058.

Liu, Jingkuang, Yedan Liu, and Xuetong Wang. 2020a. "An Environmental Assessment Model of Construction and Demolition Waste Based on System Dynamics: A Case Study in Guangzhou." *Environmental Science and Pollution Research* 27 (30): 37237–59. https://doi.org/10.1007/s11356-019-07107-5.

———. 2020b. "An Environmental Assessment Model of Construction and Demolition Waste Based on System Dynamics: A Case Study in Guangzhou." *Environmental Science and Pollution Research* 27 (30): 37237–59. https://doi.org/10.1007/s11356-019-07107-5.

Liu, Yupeng, Deyong Yu, Bin Xun, Yun Sun, and Ruifang Hao. 2014. "The Potential Effects of Climate Change on the Distribution and Productivity of Cunninghamia

Lanceolata in China." *Environmental Monitoring and Assessment* 186 (1): 135–49. https://doi.org/10.1007/s10661-013-3361-6.

Liyin, Shen, Yao Hong, and Alan Griffith. 2006. "Improving Environmental Performance by Means of Empowerment of Contractors." *Management of Environmental Quality: An International Journal* 17 (3): 242–57. https://doi.org/10.1108/14777830610658674.

Lowe, David J., Margaret W. Emsley, and Anthony Harding. 2006. "Predicting Construction Cost Using Multiple Regression Techniques." *Journal of Construction Engineering and Management* 132 (7): 750–58. https://doi.org/10.1061/(ASCE)0733-9364(2006)132:7(750).

Mahdavinejad, Mohammadjavad, Raha Bahtooei, Seyyed Mohammadmahdi Hosseinikia, Mahsa Bagheri, Ayoob Aliniaye Motlagh, and Fatemeh Farhat. 2014. "Aesthetics and Architectural Education and Learning Process." *Procedia - Social and Behavioral Sciences*, 5th World Conference on Educational Sciences, 116 (February):4443–48. https://doi.org/10.1016/j.sbspro.2014.01.963.

Mangold, Mikael, Magnus Österbring, Holger Wallbaum, Liane Thuvander, and Paula Femenias. 2016. "Socio-Economic Impact of Renovation and Energy Retrofitting of the Gothenburg Building Stock." *Energy and Buildings* 123 (July):41–49. https://doi.org/10.1016/j.enbuild.2016.04.033.

Marchettini, N., R. Ridolfi, and M. Rustici. 2007. "An Environmental Analysis for Comparing Waste Management Options and Strategies." *Waste Management* 27 (4): 562–71. https://doi.org/10.1016/j.wasman.2006.04.007.

Marsh, Rob. 2017. "Building Lifespan: Effect on the Environmental Impact of Building Components in a Danish Perspective." *Architectural Engineering and Design Management* 13 (2): 80–100. https://doi.org/10.1080/17452007.2016.1205471.

Marteinsson, Björn. 2005. "Service Life Estimation in Building Design : A Development of the Factor Method." http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-201.

Mayhew, Claire, and Michael Quinlan. 1997. "Subcontracting and Occupational Health and Safety in the Residential Building Industry." *Industrial Relations Journal* 28 (3): 192–205. https://doi.org/10.1111/1468-2338.00054.

Meacham, Brian, and Margaret McNamee. n.d. "Fire Safety Challenges of 'Green' Buildings and Attributes."

Mehra, Sukanya, Mandeep Singh, Geetika Sharma, Shiv Kumar, Navishi, and Pooja Chadha. 2022. "Impact of Construction Material on Environment." In *Ecological and Health Effects of Building Materials*, edited by Junaid Ahmad Malik and Shriram Marathe, 427–42. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-76073-1_22.

Melanta, Suvish, Elise Miller-Hooks, and Hakob G. Avetisyan. 2013. “Carbon Footprint Estimation Tool for Transportation Construction Projects.” *Journal of Construction Engineering and Management* 139 (5): 547–55. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000598.

Mohammad, Malek, Eyad Masad, and Sami G. Al-Ghamdi. 2020. “3D Concrete Printing Sustainability: A Comparative Life Cycle Assessment of Four Construction Method Scenarios.” *Buildings* 10 (12): 245. https://doi.org/10.3390/buildings10120245.

Nasir, Hassan, Hani Ahmed, Carl Haas, and Paul M. Goodrum. 2014. “An Analysis of Construction Productivity Differences between Canada and the United States.” *Construction Management and Economics* 32 (6): 595–607. https://doi.org/10.1080/01446193.2013.848995.

Nwanguma, RW, and Utibe Akah. 2019. “REVIEW OF VISUAL QUALITY IN ARCHITECTURAL DESIGN THROUGH THE PRINCIPLES OF AESTHETICS” 1 (January):102–6.

Olanrewaju, Abdul Lateef, and Abdul-Rashid Abdul-Aziz. 2015. “Sustainability Maintenance Initiatives.” In *Building Maintenance Processes and Practices: The Case of a Fast Developing Country*, edited by Abdul Lateef Olanrewaju and Abdul-Rashid Abdul-Aziz, 293–315. Singapore: Springer. https://doi.org/10.1007/978-981-287-263-0_10.

Olsson, Per, Carl Folke, and Fikret Berkes. 2004. “Adaptive Comanagement for Building Resilience in Social–Ecological Systems.” *Environmental Management* 34 (1): 75–90. https://doi.org/10.1007/s00267-003-0101-7.

Palacios-Munoz, B., L. Gracia-Villa, I. Zabalza-Bribián, and B. López-Mesa. 2018. “Simplified Structural Design and LCA of Reinforced Concrete Beams Strengthening Techniques.” *Engineering Structures* 174 (November):418–32. https://doi.org/10.1016/j.engstruct.2018.07.070.

Pan, Wei, Kaijian Li, and Yue Teng. 2018. “Rethinking System Boundaries of the Life Cycle Carbon Emissions of Buildings.” *Renewable and Sustainable Energy Reviews* 90 (July):379–90. https://doi.org/10.1016/j.rser.2018.03.057.

Papadopoulos, Agis M., Theodoros G. Theodosiou, and Kostas D. Karatzas. 2002. “Feasibility of Energy Saving Renovation Measures in Urban Buildings: The Impact of Energy Prices and the Acceptable Pay Back Time Criterion.” *Energy and Buildings* 34 (5): 455–66. https://doi.org/10.1016/S0378-7788(01)00129-3.

Paravalos, Peter. 2006. *Moving a House with Preservation in Mind*. Rowman Altamira.

Petzek, Edward, Luiza Toduţi, and Radu Băncilă. 2016. “Deconstruction of Bridges an Environmental Sustainable Concept.” *Procedia Engineering*, Bridges in Danube Basin 2016 – New trends in bridge engineering and efficient solution for large and medium span bridges, 156 (January):348–55. https://doi.org/10.1016/j.proeng.2016.08.307.

Phillips, Jack J. 1994. *Measuring Return on Investment*. American Society for Training and Development.

———. 1996. “ROI: The Search for Best Practices.” *Training & Development* 50 (2): 42–48.

Plank, Roger. 2008. “The Principles of Sustainable Construction.” *The IES Journal Part A: Civil & Structural Engineering* 1 (4): 301–7. https://doi.org/10.1080/19373260802404482.

Poon, C. S. 2007. “Reducing Construction Waste.” *Waste Management*, no. 12, 1715–16.

Poria, Yaniv, Arie Reichel, and Avital Biran. 2006. “Heritage Site Management: Motivations and Expectations.” *Annals of Tourism Research* 33 (1): 162–78. https://doi.org/10.1016/j.annals.2005.08.001.

Ramírez-Villegas, Ricardo, Ola Eriksson, and Thomas Olofsson. 2016. “Assessment of Renovation Measures for a Dwelling Area – Impacts on Energy Efficiency and Building Certification.” *Building and Environment* 97 (February):26–33. https://doi.org/10.1016/j.buildenv.2015.12.012.

Rebellon, Luis Fernando Marmolejo. 2012. *Waste Management: An Integrated Vision*. BoD – Books on Demand.

Rehm, Michael, and Rochelle Ade. 2013. “Construction Costs Comparison between ‘Green’ and Conventional Office Buildings.” *Building Research & Information* 41 (2): 198–208. https://doi.org/10.1080/09613218.2013.769145.

“Re-Thinking Sustainability in 2021.” 2021. Quest Resource Management Group. January 26, 2021. https://www.questrmg.com/2021/01/26/re-thinking-sustainability-in-2021/.

Rodrigues, Fernanda, Raquel Matos, Ana Alves, Paulo Ribeirinho, and Hugo Rodrigues. 2018. “Building Life Cycle Applied to Refurbishment of a Traditional Building from Oporto, Portugal.” *Journal of Building Engineering* 17 (May):84–95. https://doi.org/10.1016/j.jobe.2018.01.010.

Rogoff, Marc J., and John F. Williams. 2012. *Approaches to Implementing Solid Waste Recycling Facilities*. William Andrew.

Rondeau, Edmond P., Robert Kevin Brown, and Paul D. Lapides. 2012. *Facility Management*. John Wiley & Sons.

Rosenfeld, Yehiel. 2014. “Root-Cause Analysis of Construction-Cost Overruns.” *Journal of Construction Engineering and Management* 140 (1): 04013039. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000789.

Roufechaei, Kamand M., Abu Hassan Abu Bakar, and Amin Akhavan Tabassi. 2014. "Energy-Efficient Design for Sustainable Housing Development." *Journal of Cleaner Production* 65 (February):380–88. https://doi.org/10.1016/j.jclepro.2013.09.015.

Saghatforoush, Ehsan, Bambang Trigunarsyah, and Eric Too. 2012. "Assessment of Operability and Maintainability Success Factors in Provision of Extended Constructability Principles." In *Proceedings of the 9th International Congress on Civil Engineering [Civilica - Encyclopedia of Civil Engineering Series]*, edited by M. Azhari, 1–10. Iran: CIVILICA - BoomSazeh Construction Technology Development Co. http://9icce.ir/web/guest/home.

Sakalasooriya, Nishan. 2021. "Conceptual Analysis of Sustainability and Sustainable Development." *Open Journal of Social Sciences* 09 (03): 396. https://doi.org/10.4236/jss.2021.93026.

Saltelli, Andrea. 2002. "Sensitivity Analysis for Importance Assessment." *Risk Analysis* 22 (3): 579–90. https://doi.org/10.1111/0272-4332.00040.

Schwartz, Yair, Rokia Raslan, and Dejan Mumovic. 2018. "The Life Cycle Carbon Footprint of Refurbished and New Buildings – A Systematic Review of Case Studies." *Renewable and Sustainable Energy Reviews* 81 (January):231–41. https://doi.org/10.1016/j.rser.2017.07.061.

Schwietzke, Stefan, W. Michael Griffin, and H. Scott Matthews. 2011. "Relevance of Emissions Timing in Biofuel Greenhouse Gases and Climate Impacts." *Environmental Science & Technology* 45 (19): 8197–8203. https://doi.org/10.1021/es2016236.

Sev, Aysin. 2009. "How Can the Construction Industry Contribute to Sustainable Development? A Conceptual Framework." *Sustainable Development* 17 (3): 161–73. https://doi.org/10.1002/sd.373.

Shen, Li-yin, Vivian W. Y. Tam, Leona Tam, and Ying-bo Ji. 2010. "Project Feasibility Study: The Key to Successful Implementation of Sustainable and Socially Responsible Construction Management Practice." *Journal of Cleaner Production* 18 (3): 254–59. https://doi.org/10.1016/j.jclepro.2009.10.014.

Siddiqui, Zishan K., Rebecca Zuccarelli, Nowella Durkin, Albert W. Wu, and Daniel J. Brotman. 2015. "Changes in Patient Satisfaction Related to Hospital Renovation: Experience with a New Clinical Building." *Journal of Hospital Medicine* 10 (3): 165–71. https://doi.org/10.1002/jhm.2297.

Siller, Thomas, Michael Kost, and Dieter Imboden. 2007. "Long-Term Energy Savings and Greenhouse Gas Emission Reductions in the Swiss Residential Sector." *Energy Policy* 35 (1): 529–39. https://doi.org/10.1016/j.enpol.2005.12.021.

Silvius, A.J. Gilbert, and Ron P.J. Schipper. 2014. "Sustainability in Project Management: A Literature Review and Impact Analysis." *Social Business* 4 (1): 63–96. https://doi.org/10.1362/204440814X13948909253866.

Simson, Raimo, Endrik Arumägi, Kirsten Engelund Thomsen, Kim Bjarne Wittchen, and Jarek Kurnitski. 2022. "Danish, Estonian and Finnish NZEB Requirements Comparison with European Commission Recommendations for Office Buildings in Nordic and Oceanic Climates." *E3S Web of Conferences* 356:01017. https://doi.org/10.1051/e3sconf/202235601017.

Sirisawat, Pornwasin, and Tossapol Kiatcharoenpol. 2018. "Fuzzy AHP-TOPSIS Approaches to Prioritizing Solutions for Reverse Logistics Barriers." *Computers & Industrial Engineering* 117 (March):303–18. https://doi.org/10.1016/j.cie.2018.01.015.

Smith, Stephen E., Woodrow W. Wilson, William C. Burns, and Robert A. Rubin. 1975. "Contractual Relationships in Construction." *Journal of the Construction Division* 101 (4): 907–21. https://doi.org/10.1061/JCCEAZ.0000570.

Spengler, John D., and Qingyan Chen. 2000. "Indoor Air Quality Factors in Designing a Healthy Building." *Annual Review of Energy and the Environment* 25 (1): 567–600. https://doi.org/10.1146/annurev.energy.25.1.567.

Tang, Pei, Darrell Cass, and Amlan Mukherjee. 2013. "Investigating the Effect of Construction Management Strategies on Project Greenhouse Gas Emissions Using Interactive Simulation." *Journal of Cleaner Production* 54 (September):78–88. https://doi.org/10.1016/j.jclepro.2013.03.046.

"Tracking Progress | Globalabc." n.d. Accessed April 5, 2024. https://globalabc.org/our-work/tracking-progress-global-status-report.

Triantaphyllou, Evangelos. 2000. "Multi-Criteria Decision Making Methods." In *Multi-Criteria Decision Making Methods: A Comparative Study*, edited by Evangelos Triantaphyllou, 5–21. Applied Optimization. Boston, MA: Springer US. https://doi.org/10.1007/978-1-4757-3157-6_2.

Tyler, Norman, Ilene R. Tyler, and Ted J. Ligibel. 2018. *Historic Preservation, Third Edition: An Introduction to Its History, Principles, and Practice (Third Edition)*. W. W. Norton & Company.

Ugochukwu, Iwuagwu Ben, and M. Iwuagwu Ben Chioma. 2015. "Local Building Materials: Affordable Strategy for Housing the Urban Poor in Nigeria." *Procedia Engineering*, Defining the future of sustainability and resilience in design, engineering and construction, 118 (January):42–49. https://doi.org/10.1016/j.proeng.2015.08.402.

Veisi, Hadi, Reza Deihimfard, Alireza Shahmohammadi, and Yasoub Hydarzadeh. 2022. "Application of the Analytic Hierarchy Process (AHP) in a Multi-Criteria Selection of Agricultural Irrigation Systems.” *Agricultural Water Management* 267 (June):107619. https://doi.org/10.1016/j.agwat.2022.107619.

Verbeeck, G., and H. Hens. 2010. “Life Cycle Inventory of Buildings: A Calculation Method.” *Building and Environment* 45 (4): 1037–41. https://doi.org/10.1016/j.buildenv.2009.10.012.

Wind, Yoram, and Thomas L. Saaty. 1980. “Marketing Applications of the Analytic Hierarchy Process.” *Management Science* 26 (7): 641–58. https://doi.org/10.1287/mnsc.26.7.641.

Wixom, Barbara H., and Peter A. Todd. 2005. “A Theoretical Integration of User Satisfaction and Technology Acceptance.” *Information Systems Research* 16 (1): 85–102. https://doi.org/10.1287/isre.1050.0042.

Wong, Franky W.H., D. Darshi De Saram, Patrick T.I. Lam, and Daniel W.M. Chan. 2006. “A Compendium of Buildability Issues from the Viewpoints of Construction Practitioners.” *Architectural Science Review* 49 (1): 81–90. https://doi.org/10.3763/asre.2006.4910.

Wong, Yee Choong, Karam M. Al-Obaidi, and Norhayati Mahyuddin. 2018. “Recycling of End-of-Life Vehicles (ELVs) for Building Products: Concept of Processing Framework from Automotive to Construction Industries in Malaysia.” *Journal of Cleaner Production* 190 (July):285–302. https://doi.org/10.1016/j.jclepro.2018.04.145.

Yan, Hui, Qiping Shen, Linda C.H. Fan, Yaowu Wang, and Lei Zhang. 2010. “Greenhouse Gas Emissions in Building Construction: A Case Study of One Peking in Hong Kong.” *Building and Environment* 45 (4): 949–55. https://doi.org/10.1016/j.buildenv.2009.09.014.

Yang, Wonho, Jongryeul Sohn, Jihwan Kim, Busoon Son, and Jinchul Park. 2009. “Indoor Air Quality Investigation According to Age of the School Buildings in Korea.” *Journal of Environmental Management* 90 (1): 348–54. https://doi.org/10.1016/j.jenvman.2007.10.003.

Yeheyis, Muluken, Kasun Hewage, M. Shahria Alam, Cigdem Eskicioglu, and Rehan Sadiq. 2013. “An Overview of Construction and Demolition Waste Management in Canada: A Lifecycle Analysis Approach to Sustainability.” *Clean Technologies and Environmental Policy* 15 (1): 81–91. https://doi.org/10.1007/s10098-012-0481-6.

Yip, Hon-lun, Hongqin Fan, and Yat-hung Chiang. 2014. “Predicting the Maintenance Cost of Construction Equipment: Comparison between General Regression Neural Network and Box–Jenkins Time Series Models.” *Automation in Construction* 38 (March):30–38. https://doi.org/10.1016/j.autcon.2013.10.024.

Yılmaz, Mustafa, and Adem Bakış. 2015. “Sustainability in Construction Sector.” *Procedia - Social and Behavioral Sciences*, World Conference on Technology, Innovation and Entrepreneurship, 195 (July):2253–62. https://doi.org/10.1016/j.sbspro.2015.06.312.

Zabihi, Hossein, Farah Habib, and Leila Mirsaeedie. 2013. “Definitions, Concepts and New Directions in Industrialized Building Systems (IBS).” *KSCE Journal of Civil Engineering* 17 (6): 1199–1205. https://doi.org/10.1007/s12205-013-0020-y.

Zavadskas, Edmundas Kazimieras, Artūras Kaklauskas, and Saulius Raslanas. 2004. “Evaluation of Investments into Housing Renovation.” *International Journal of Strategic Property Management* 8 (3): 177–90. https://doi.org/10.1080/1648715X.2004.9637516.

Zhong, Xiaohua, and Xiangming Chen. 2017. “Demolition, Rehabilitation, and Conservation: Heritage in Shanghai’s Urban Regeneration, 1990–2015.” *Journal of Architecture and Urbanism* 41 (2): 82–91. https://doi.org/10.3846/20297955.2017.1294120.

Zhong, Yun, and Peng Wu. 2015. “Economic Sustainability, Environmental Sustainability and Constructability Indicators Related to Concrete- and Steel-Projects.” *Journal of Cleaner Production* 108 (December):748–56. https://doi.org/10.1016/j.jclepro.2015.05.095.

Zhu, Xingyu, Xianhai Meng, and Min Zhang. 2021. “Application of Multiple Criteria Decision Making Methods in Construction: A Systematic Literature Review.” *Journal of Civil Engineering and Management* 27 (6): 372–403. https://doi.org/10.3846/jcem.2021.15260.