Decision Support System for Selection of the Most Sustainable Structural Materials for a Multistory Building Construction

by

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ABSTRACT

In recent years, the performance of the construction industry warns of its increased need for better resource efficiency, improved productivity, less waste and increased value through sustainable construction practices. Existing literature reveals that construction-related spending accounts for 13% of the world's Gross Domestic Product, but its annual productivity growth has increased by 1% over the past 20 years. The core concept of sustainable construction is to maximize value and minimize harm by achieving a balance between social, economic, technical, and environmental aspects, commonly known as the pillars of sustainability. The selection of structural material plays a vital role in building construction since it is the backbone of any structure. Also, the process of producing structural consumes massive amounts of nonrenewable natural resources. Reinforced concrete, structural steel, reinforced masonry, and timber represent the most commonly used structural materials. The decision of selecting the structural material for any construction project is traditionally made based mainly on technical and economic considerations with little or no attention paid to social and environmental aspects. Furthermore, the majority of the available literature on the subject considered a single sustainability aspect, not considering all four sustainability pillars together. When all pillars of sustainability are considered, the process of decision-making becomes more difficult and complicated due to the involvement of a large number of factors influencing the decision. Industry experts have also noted an unfulfilled need for a multi-criteria decision-making (MCDM) technique that can integrate all stakeholders' (project owner, designer and constructor) opinions into the selection process. Hence, this research developed a Decision Support System (DSS) involving MCDM techniques to aid in selecting the most sustainable structural material considering the four pillars of sustainability. A hybrid MCDM method combining AHP, decision matrix, TOPSIS and VIKOR in a Fuzzy environment is used to develop the DSS. Multiple sub-criteria were identified and evaluated through a literature review and expert opinions. A hypothetical 8-story building was considered for a case study to validate the developed DSS. Notable differences were found in the final ranking of the alternatives of each team due to the significant differences in weights assigned to each sub-criterion based on experts' preferences. The developed DSS is designed to be generic in nature, can be used by any group of industry practitioners and is expected to enhance objectivity and consistency of the decision-making process as a step towards achieving sustainable construction.

PREFACE

This thesis is an original work by *Mohammad Masfiqul Alam Bhuiyan* under the supervision of Dr. Ahmed Hammad, Associate Professor of Construction Engineering and Management, Department of Civil and Environmental Engineering, Faculty of Engineering, University of Alberta. Two conference papers related to this thesis have already been accepted and are under publication. The list of those papers is given below:

Alam Bhuiyan, Mohammad Masfiqul, Sulle, Anthony, and Hammad, Ahmed, 2022. Application of Choosing by Advantage (CBA) to Select Most Sustainable Project, Metro Extension Case Study, *Proceedings of Structural Engineering and Construction*, Vol 9 (1). https://doi.org/10.14455/10.14455/ISEC.2022.9(1).CPM-03

Alam Bhuiyan, Mohammad Masfiqul, Karim, Mohammad Rezaul, and Hammad, Ahmed, 2022. Sustainability Analysis of Structural Materials Used in Multistoried Building Construction: A Cradle to Grave Approach. *Proceedings of Canadian Society of Civil Engineering Annual Conference*, British Columbia (under publication).

DEDICATION

I dedicate this thesis to the **Bangladesh Army**, which is the source of my dignity and granted me for two years leave to obtain this degree. I would like to give a small share to my parents (*Mohammad Shamsul Alam Bhuiyan* and *Mrs Fazilatun Nessa*) too, who would be proud to see their son graduating from one of the leading universities in the world if they were still around.

ACKNOWLEDGEMENT

At the outset, all praise to Almighty ALLAH. I express my sincerest thanks to ALLAH for giving me everything; including but not limited to knowledge, good health, life, and the ability to finish this work. Accomplishing a thesis is by no means an easy endeavour. Completing it without the unswerving support of the supervisor, academic and industry experts, university staff, family, and friends was a next-to-impossible task. Hence, I wish to register my heartfelt appreciation to a few individuals who have played a pivotal role in my completing this assignment. Firstly, my appreciation goes out to my supervisor, Dr. Ahmed Hammad; without his guidance, I would have been lost on this long road to my thesis: thank you for all the meetings, so many emails, for answering my many queries, and for all your valuable insight. Second, I would like to thank my wife, Parvin Shahina Haque, and my little son, Sharfan Mahrush, whose contribution is not directly visible from the outcome but who consistently supported me while I worked: without your patience, love, and support, I could not have completed this. Third, I always remain indebted to my family members, those from my little village, Bishnupur, and those who have travelled out to many parts of the world, who are always proud of my little accomplishments and stand by me in every step of the trail. Fourth, my appreciation goes out to Dr. Ying Hei Chui, Dr. Carlos A. Cruz-Noguez and Virginia Pow from the University of Alberta: your knowledge and time have been most valuable in preparing my thesis. Fifth, I would like to thank Dr. Mark D. Hagel, Mr. Jerry Calara, Mr. Rory Koska, Mrs. Jen Hancock, Mr. Kent Love, Mr. Tracy Didluck, Mrs. Danielle Zauscher, Mr. Richard Blouin, Mr. Creag Vogel, Mr. Paul Rasmussen, and Mr. Peter Osborne for finding time out of their busy schedules to sit in on meetings and participating in my research: without your input, my research would have remained incomplete. Sixth, I would like to extend my gratitude to Md. Rifat and Md. Rashedul Alam for providing me technical support in developing the DSS desktop application and preparing the 3D drawings: your expertise and time are highly appreciated. Finally, I would like to extend to my friend Mohammad Rezaul Karim for his unwavering assistance throughout the research, and Suddho Ukil for reviewing my final paper.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
BREEAM	Building Research Establishment Assessment System
CBA	Choosing by Advantage
CLT	Cross-laminated Timber
CM	Confined Masonry
CMR	Construction Manager at Risk
CO_2	Carbon Dioxide
COP	Conference of the Parties
DBB	Design Bid Build
DEMATEL	Decision-Making Trial and Evaluation Laboratory
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen
DM	Decision-maker
DSS	Decision Support System
ELECTRE	ELimination Et Choix Traduisant la REalité
FAHP	Fuzzy Analytic Hierarchy Process
FES	Fuzzy Expert System
GBRS	Green Building Rating System
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IPD	Integrated Project Delivery
ISO	International Organization for Standards
kg	Kilogram
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Assessment
LCSA	Life Cycle Sustainability Assessment

LEED	Leadership in Energy and Environmental Design
MADM	Multi-attribute Decision-making
MCDM	Multi-criteria Decision-making
MCS	Monte Carlo Simulations
MODM	Multi-objective Decision-making
PDM	Project Delivery Method
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
RC	Reinforced Concrete
RM	Reinforced Masonry
SLCA	Social Life Cycle Assessment
SO_2	Sulfur Dioxide
SS	Structural Steel
TOPSIS	Technique for Order Performance by Similarity to Ideal Solution
VIKOR	VIseKriterijumska Optimizacija I Kompromisno Resenje
WCED	World Commission on Environment and Development
$	United States Dollar
%	Percentage

CHAPTER 1: INTRODUCTION

1.1 Background

Over time, the construction industry's development has been constantly questioned due to the issues like low productivity, high energy consumption, generation of wastes, and greenhouse gas emission. Buildings and associated construction industries account for 36% of global energy use and 37% of energy-related carbon dioxide (CO_2) and greenhouse gas emissions, as elucidated in Figure 1.1 (UNEP, 2021). Constructions user's roundtable (2022) reports that productivity of construction works has significantly reduced in the last 50 years compared to other sectors (CURT, 2022). Another report shows that construction-related spending accounts for 13% of the world's GDP, but its annual productivity growth has increased by 1% over the past 20 years. It also presented that $1.6 trillion of additional value-added could be created through higher productivity, meeting half the world's infrastructure needs (CURT, 2022). Therefore, the construction industry desperately needs better resource efficiency, improved productivity, less waste, and increased value.

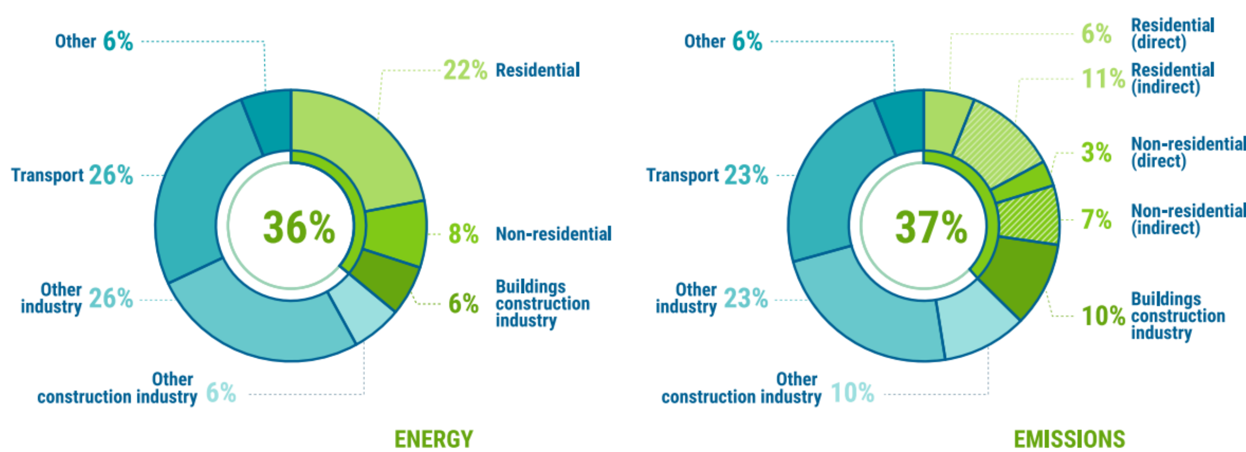


Figure 1.1. Buildings and construction's share of global energy and energy-related CO_2 emissions (extracted from *2021 Global Status Report for Buildings and Construction*, UN Environment Program)

During the 'UN Climate Change Conference UK 2021,' all the participating nations of COP (Conference of the Parties) 26 collectively agreed to work to reduce greenhouse gas emissions to limit the rise of global average temperature by 1.5 degree Celsius. For the first time, nations are pushed to phase down unabated coal power and inefficient fossil fuel subsidies (COP26, 2021). In response, The Canadian government is acting boldly and expeditiously to cut greenhouse gas emissions and combat climate change while strengthening the economy with long-term employment opportunities and clean urban sprawl. The 2030 Emissions Reduction Plan lays out a sector-by-sector plan for Canada to attain its emissions reduction target of 40% below 2005 levels by 2030 and net-zero emissions by 2050. Building and construction sectors need to reduce greenhouse gas emissions to 52 megatons of carbon dioxide equivalent (Mt CO_2 eq) by 2030 compared to 91 Mt CO_2 eq emissions in 2019 (Canada, 2022).

The World Commission on Environment and Development (WCED) published a report in 1987 termed 'Our Common Future' that outlined the concepts of sustainable development (Hill and Bowen, 1997). The report is also known as the 'Brundtland Report,' and it defined sustainable development as "the use of environment and resources to meet the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). Sustainable construction aims to achieve 'maximum value with minimum harm,' ensuring the balance between economic, social, and environmental factors in a project, commonly known as the pillars of sustainability (Farzanehrafat et al., 2015; Purvis et al., 2019; Schoolman et al., 2012). These pillars of sustainability were introduced by the World Summit on Social Development of the United Nations held in 2005 ("II.5 2005 World Summit Outcome United Nations World Summit, 16 September 2005," 2006). 'The biophysical environment impacts a community's economic and social harmony. While the economy is essential, it is not everything; instead, everything is dependent on the environment, including the economy, social structure, and equity.' This idea is the core concept of sustainability and states that all members of society, from the individual to the global community, must be taken into consideration in any decision-making process to improve current and future human well-being (Sakalasooriya, 2021).

Sustainable construction is a holistic process that promotes harmony between nature, humanity and the built environment by creating settlements that suit humans and support economic equality (Yılmaz and Bakış, 2015). It applies sustainable development principles to a building life cycle from planning the construction, mining and preparing the raw materials to production and creating construction material, usage, destruction of construction, and management of wastes (Yılmaz and Bakış, 2015). Sustainability is expected to achieve a win-win situation where competitive market gains and economic benefits for construction companies are pursued in addition to promoting environmental benefits for society (Shen et al., 2010).

1.2 Problem Statement

Structural elements of a building generally consist of beams, columns, tension members and their connections. The selection of structural material in the case of building construction plays a vital role as it acts as the backbone of the structure and demands vast resources. In general, concrete, timber, steel, masonry, composite (timber-steel, timber-concrete, steel-concrete), etc., are used to construct multistory buildings. Reinforced concrete is the most often used structural material for building construction. However, ironically, concrete is one of the leading sources of environmental degradation and is harmful to the ecosystem and environment (Stephan and Stephan, 2016). Steel may be used to replace concrete due to its numerous advantages, including strength and flexibility. Nevertheless, it needs a lot of energy during manufacturing and might be expensive in some situations (Oldfield, 2019). Masonry is a time-tested alternative to concrete construction. However, burned bricks may emit significant levels of carbon during the manufacturing process, and masonry construction requires a substantial amount of cement (Cowan, 1977). As a building material, timber has better energy-saving and carbon reduction performance than other traditional materials. However, lack of design standards and fire resistance issues are commonly highlighted as impediments, inhibiting timber for multi-story buildings, unlike masonry, concrete, or steel (Laguarda Mallo and Espinoza, 2015). This phenomenon has led the concern to rethink alternatives in building construction materials to achieve sustainability.

Though technical and economic aspects are always considered while selecting the structural components, other elements like social and environmental are mostly ignored. Making a sustainable decision is always critical as it combines all technical, social, economic and environmental factors. Although it seems crucial during the planning and conceptual development phase and costly while designing and constructing, a sustainable choice is always more economical, eco-friendly, and convenient considering the entire life cycle of any construction work. So far, several studies have been conducted on timber, concrete, masonry, steel, etc., as structural materials in isolation or combination. However, most of the previous research in this area focused on three pillars of sustainable construction. Although several researchers argued that the technical pillar is an essential analytic element of sustainability assessment for civil infrastructure, there is hardly any work that systematically integrates the technical pillar with economic, social, and environmental considerations to analyze the overall sustainability aspects. As such, there is still room to analyze and compare their performance from the sustainability point of view, combining technical aspects with other commonly used sustainability pillars in the IPD (Integrated Project Delivery) framework.

In the case of traditional Project Delivery Methods, contractors and manufacturers are involved in the project after the project's design phase. Thereby traditional construction processes tend to incur more costs from rework resulting from miscoordination, quality issues, the inefficiency of project delivery times, poor performance and client dissatisfaction with the delivered product. In contrast, IPD contributes more towards sustainability by integrating all stakeholders from the initial stage of the project. It is more sustainable as it seeks to improve the triple constraint (cost, time, and quality) outcomes by aligning the project team goals and applying a shared risk and reward system (AIA, 2007).

Compared to single houses, multistory residential buildings are gaining popularity and contributing more to sustainable construction (Government of Canada, 2022). A hypothetical 8-story building has been considered in this study for calculation, development, validation and verification of the Decision Support System. The primary reason for selecting an 8-story building is that all options of structural materials considered in this study (Reinforced Concrete, Structural Steel, Reinforced Masonry and Timber) remain acceptable alternatives for this height.

1.3 Research Objectives

This research aims to promote sustainable construction and forward-thinking by developing a decision support system to help determine the most sustainable structural material for multistory building construction from several alternatives.

1.4 Research Scopes

In this study Reinforced Concrete, Structural Steel, Timber and Reinforced Masonry were kept as alternatives to the structural elements discarding any other composites. The height of the building was decided so that all options of structural materials could remain acceptable alternatives. The following activities were conducted to achieve the research objectives:

a. Identification of structural materials in use for multistory building construction through literature review, industry practices and expert opinion.

b. Sustainability analysis (technical, economic, social, and environmental aspects) of structural materials in use with the help of tools available (LCC, LCCA, etc.) and expert opinion.

c. Review of the selection process of the structural materials from the point of sustainable construction practices. Several interview sessions with industry experts, project owners, design teams, and constructors were conducted in addition to the literature review to know the details of existing practices.

d. Development of sub-criteria for all the pillars of sustainable construction primarily through the literature review and then validating and finalizing with feedback from industry and academic experts.

e. Development of a decision matrix, in addition to using Fuzzy AHP to assign weightage of criteria.

f. Development of the DSS using MCDM techniques to aid the selection of the most sustainable structural material for multistory building construction.

1.5 Research Methodology

This research was conducted in four phases. The stages of the research methodology are shown in Figure 1.2, and details of each step are summarized below:

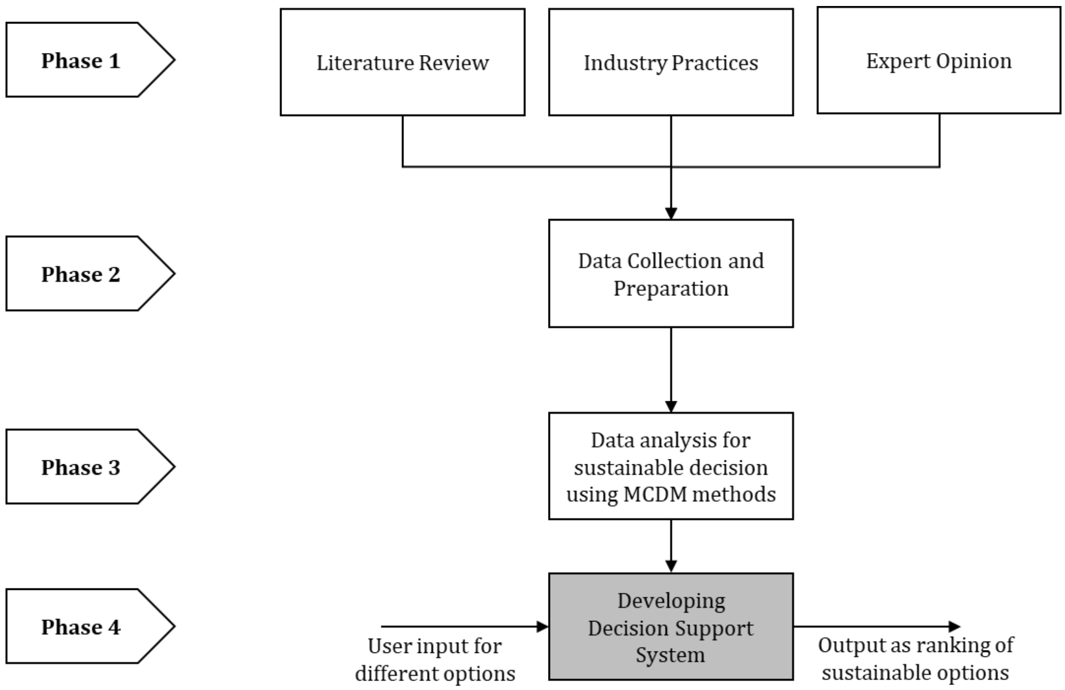


Figure 1.2. Research methodology

The first phase of this research aimed to identify structural materials in use for multistory building construction and review the selection process followed by the industries from the point of sustainable construction practices. An extensive literature review was conducted at the initial stage of this phase to gather the required information and identify the research gap. Later, a series of interviews and discussion sessions were conducted with industry and academic experts to learn about the selection process, preferences of structural materials, sustainability options considered, etc.

In phase two, collected data and information were organized. The most appropriate decision-making technique for solving this problem was selected through studying different research papers. The list of most appropriate sub-criteria, in this case, was chosen primarily through the literature review and then validated and finalized with expert feedback.

The third phase of this research aimed to conduct a sustainability analysis (technical, economic, social, and environmental aspects) of all alternative structural materials and choose MCDM methods to select the most sustainable option. The data for quantitative sub-criteria were obtained through structural analysis, market survey and use of *Athena Impact Estimator for Buildings* software. The information for the qualitative sub-criteria was collected from industry and academic experts. They were also requested to assign weightage for each of those. Next, Fuzzy AHP was used to calculate the weightage of all sub-criteria and Fuzzy TOPSIS and Fuzzy VIKOR were used for ranking the alternatives.

The fourth phase of this research aimed to develop a decision support system to help determine the most sustainable option from several viable alternatives. Earlier it was identified that there is no structured system to combine the opinion of all stakeholders to make a sustainable decision on selecting the structural material. Therefore, most importance was given to developing a system to work in an IPD framework where all stakeholders could give their input. The developed decision support system can also integrate qualitative and quantitative data to decide on the most sustainable option. Finally, the model was validated through a case study and expert opinion.

1.6 Expected Contribution

1.6.1 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 of sustainable structural materials.

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

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

d. Developing a decision support system that can assist in evaluating the sustainability of structural materials in the IPD framework.

1.6.2 Industrial Contribution

The industrial contributions of this research are:

a. Developing an application that can store required project information.

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

c. Developing a DSS that shall assist the decision-makers in choosing evaluation criteria and assign relative importance to those using a combination of qualitative and quantitative methods in an IPD framework for selecting the most sustainable structural material.

d. Providing more scope for the owners to participate in the decision-making process.

1.7 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, expected outcomes, and 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 is the application of the methodologies explained in Chapter three. The Microsoft Excel templates and DSS are utilized here with the case study data for obtaining 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 2: LITERATURE REVIEW

2.1 Introduction

A review of previous research and journal articles is essential to establish the foundation of new work. This chapter reviewed literature from areas pertinent to selecting sustainable structural materials for multistory building construction. The discussion of this chapter began with the need for sustainability and sustainable construction and gradually covered the topics of green building initiatives and rating systems, structural materials commonly used for multistory building construction, multi-criteria decision-making (MCDM) in construction, life cycle assessments relevant to sustainable constructions, and project delivery methods. The review of sustainability and sustainable construction aimed at reiterating its importance in construction. Next, the choice of structural materials available for multistory building construction and their essential properties are discussed. The section on MCDM reviewed a few most relevant techniques used in construction and explained the methods chosen for this research. Appropriate life cycle assessment systems are discussed next to review their applications in construction. Since the selection of project delivery method directly impacts sustainability, this aspect was reviewed next. Finally, findings from the literature are summarized, and the research gap has been identified in this chapter.

2.2 Sustainability and Sustainable Construction

The concept of sustainability was primarily presented in the United Nations Conference on the Human Environment (1972) in "eco-development" and termed as 'an approach to development aimed at harmonizing social and economic objectives with ecologically sound management' (Farzanehrafat et al., 2015). The meaning of sustainability implies maintaining ecological systems' capacity to support and enhance the quality of social systems (Sakalasooriya, 2021). Sustaining this capacity requires analysis and understanding of feedback and, more generally, the dynamics of the interrelations between ecological and social systems. Some researchers have defined social-ecological systems as complex systems that incorporate human societies, economic systems, ecosystems, and their interactions. Furthermore, there have been arguments pushing researchers to consider both human communities and natural resources, along with their modification by human actions across time, when studying social-ecological systems (Holling, 2001; Cumming, 2010).

Various institutions and organizations have adopted the sustainability concept (Cato, 2009; Elkington, 1998), illustrated in Figure 2.1, as a common basis for sustainability standards and environmental certification systems to preserve the Earth's natural ecosystem for future generations (Manning et al., 2012; Reinecke et al., 2012). Purvis et al. (2019) reported that many researchers have also termed these factors or goals as 'dimensions' (Stirling, 1999; Moir and Carter, 2012), 'components' (Du Pisani, 2006; Zijp et al., 2015), 'stool legs' (Vos, 2007), 'aspects' (Lozano, 2008; Tanguay et al., 2010), and 'perspectives' (Arushanyan et al., 2017). In addition, a few other researchers have also mentioned and utilized the fourth pillar, 'technical' factors, to support sustainable development (Hill and Bowen, 1997; Zabihi et al., 2012; Sahlol et al., 2021).

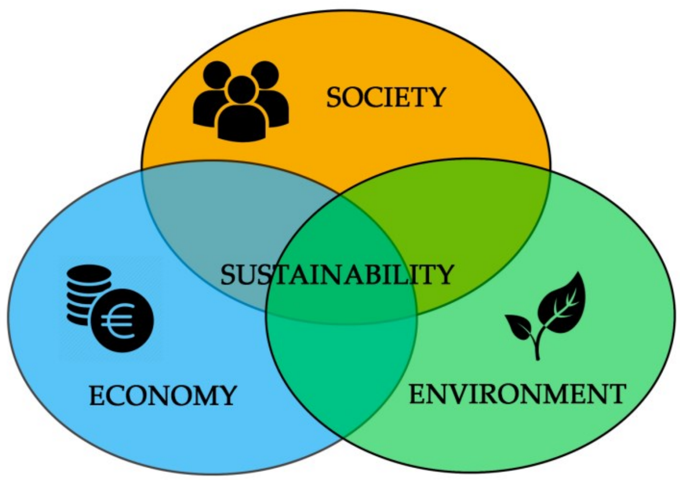


Figure 2.1. Three Common Pillars of Sustainability (Cato, 2009; Elkington, 1998)

Many researchers have defined sustainability and sustainable development from different perspectives. The core concept of sustainable development includes prudent use of natural resources, ensuring increasing economic growth levels, reducing unemployment rates, adequate protection of the environment, and increased social progress that recognizes the needs of everyone (Zabihi et al., 2012). Young (1997) defined sustainability as a measure of how well people live in harmony with the environment, considering the well-being of the people with respect to future generations' needs and environmental conservation (Young, 1997). He described sustainability as a three-legged stool, with each leg representing the ecosystem, society, and economy. Any leg missing from the ‘sustainability stool’ is supposed to cause instability in the community, ecosystem and economy, as all three are intricately linked together (Young, 1997). Indeed, Young (1997) indicated that a measurement of sustainability must combine the individual and collective action of all factors to sustain the environment as well as improve the economy and satisfy social needs (Ding, 2008). Elkington (1997) developed the triple bottom line principles and expanded the concept of sustainability in the corporate community (Ding, 2008). The triple bottom line refers to the three prongs of social, environmental, and financial performance, which provides a framework in alignment with sustainable development goals. The triple bottom line concept focuses not only on the economic value, as do most of the single criterion technique, but equally on development's environmental and social values (Elkington, 1998).

Sustainable development is gradually getting more attention in construction due to the growing resource constraints, involvement of an increased number of stakeholders, and the balanced requirements of environmental, economic and social objectives (Martens and Carvalho, 2017; Schröpfer et al., 2017). Many regard the construction industry as a non-sustainable sector due to its energy-intensive activities, coupled with greenhouse gas (GHG) emissions and low productivity (Yu et al., 2018). A review of the literature on construction project management, sustainability, and sustainability in construction project management reveals a disjointed development of categories and concepts that are more concerned with selective financial and traditional project success factors, in contrast to focusing on sustainability (Kiani Mavi et al., 2021). According to the finding of different studies, building and construction account for 36% of global energy use and 37% of energy-related CO_2 emissions over their lifespan (construction, operation, maintenance and demolition) (Energy Policies, 2017; Hill and Bowen, 1997; IPCC, 2013; UNEP, 2021). While 57% of input resources are wasted in the production process, compared to a mere 26% in other industries (Kiani Mavi et al., 2021). Evidently, the poor performance offers the construction industry a severe concern to reduce negative environmental impacts, thereby improving global sustainability (Yu et al., 2018). However, matters related to economic (e.g., competition, costs, and construction time), social (e.g., health and safety, local community needs), and technical factors must be addressed alongside environmental factors when working towards sustainable construction (Hill and Bowen, 1997; Kiani Mavi et al., 2021). The final pillar, "technical sustainability," is concerned with matters related to the performance, quality, and service life of a building or structure (Hill and Bowen, 1997).

Sustainable construction typically introduces a focus on reducing harm to the environment. It might incorporate elements such as the prevention, reuse, and management of waste, with direct benefits to society and less focus on profitability (Shen et al., 2010). As such, the nature of sustainable construction poses a conflicting dichotomy between long-term environmental benefits and short-term economic goals; thus, Kiani Mavi et al. (2021) suggested a balance between the two to achieve a mutually beneficial equilibrium. To achieve a harmonious outcome, Shen et al. (2010) recommended carrying out a feasibility study including the components of sustainability that should be undertaken as an antecedent to project initiation, as this activity would directly impact overall project success. In order to improve construction sustainability, standard criteria for assessing project technical, economic, social, and environmental impacts, as well as the consequences of various design and construction methodologies on those criteria, must be worked out (Farzanehrafat et al., 2015). Sustainability is essential at all stages of the construction process. Apart from the planning and building phases, sustainability should be considered during the renovation and deconstruction phases. Since construction goods have a limited lifetime, renovation and deconstructing are associated with environmental sustainability. The materials obtained through demolition can be recycled and reused, reducing the demand for new materials and resources (Petzek et al., 2016). As a result, the circular economy can play an essential role in the building industry and the built environment. Circularity begins with smart urban planning that maximizes transportation networks and land use. The circular economy concept could have considerable technical, economic, social, and environmental benefits when applied to building, operation, and deconstruction. For example, designing and moving toward zero-energy buildings, adopting greywater recycling systems in buildings, and any other sustainability-related innovations should consider deconstruction, reuse, and reassembly of construction materials from the beginning (Iyer-Raniga et al., 2019).

2.2.1 Technical Sustainability

Technical sustainability deals with the factors related to a building's or structure's performance, quality, and service life (Hill and Bowen, 1997). Commonly the local authority of any city or municipality outlines the design standards, floor limits, building codes, etc., of any structures. Factors like feasibility, durability, maintainability, constructability, material availability, ease of removal and replacement, disassembly and deconstruction, etc., are not directly related to the building codes. However, appropriate choices from these factors have considerable positive consequences in sustainable construction and can be addressed under technical sustainability.

A literature review of many papers on sustainable construction shows that economic, social, and environmental pillars are combined to express sustainable construction in most cases. The triple bottom line concept also refers to the three prongs of social, environmental, and financial performance directly tied to the concept and goal of sustainable development (Elkington, 1998). Levitt (2007) presented technical performance as the fourth pillar of infrastructure sustainability theory and showed meaningful relationships between technical design and the three pillars (Levitt, 2007). The researcher argued in his work that technical performance should be explicitly included as a pillar of infrastructure sustainability theory and proposed four pillars (environmental, technical, economic, and social) as the essential analytic elements of sustainability theory for civil infrastructure. Furthermore, several industry experts and academic researchers commented that the technical pillar is an essential part of sustainable construction in addition to the economic, social, and environmental pillars. They also expressed their concern about including technical pillar with the existing system in the case of sustainable construction (Levitt, 2007). A list of technical sub-criteria obtained through the literature review, which is utilized in the sustainability assessment of different construction works, is presented in Table 2.1.

Table 2.1. List of technical sub-criteria utilized in the sustainability assessment

Criteria	Sub-criteria	Reference
Technical	Feasibility	(Solangi et al., 2019)
	Durability (life expectancy)	(Akadiri et al., 2013; Josiah Marut et al., 2020; Kamali and Hewage, 2015; Li and Froese, 2017; Minhas and Potdar, 2020; Pearce et al., 1995; Yang and Ogunkah, 2013)
	Maintainability (ease of maintenance)	(Akadiri et al., 2013; Minhas and Potdar, 2020; Pearce et al., 1995; Sahlol et al., 2021; Yang and Ogunkah, 2013)
	Buildability/ Constructability (ease of construction)	(Akadiri et al., 2013; Fazeli et al., 2019; Minhas and Potdar, 2020; Sahlol et al., 2021; Yang and Ogunkah, 2013)
	Performance	(Josiah Marut et al., 2020)
	Efficiency	(Kaya and Kahraman, 2011; Solangi et al., 2019)
	Energy saving and thermal insulation	(Akadiri et al., 2013; Kaya and Kahraman, 2011; Minhas and Potdar, 2020)
	Material availability	(Fazeli et al., 2019; Pearce et al., 1995; Sahlol et al., 2021; Yang and Ogunkah, 2013)
	Thermal insulation	(Sahlol et al., 2021)
	Construction time	(Kamali and Hewage, 2015)
	Heat island effect	(Sahlol et al., 2021)
	Resistance to water and weather	(Kappenthuler and Seeger, 2020)
	Geographic location	(Kamali and Hewage, 2015; Yang and Ogunkah, 2013)
	Resistance to decay	(Sahlol et al., 2021), 27, 109, 116
	Resistance to weather	(Yang and Ogunkah, 2013)
	Knowledge in design and construction	(Yang and Ogunkah, 2013)
	Ease to remove, reaffix, replace	(Yang and Ogunkah, 2013)
	Disassembly and deconstruction	(Sahlol et al., 2021)
	Resistance to horizontal load	(Sahlol et al., 2021)

2.2.2 Economic Sustainability

From the perspective of the economic pillar, sustainability concerns a wide range of local and global aspects (Gloet, 2006). Improved building performance and durability resulting in lower maintenance and operating costs throughout the life cycle of a construction project, are the primary economic reasons for implementing sustainable principles (Roufechaei et al., 2014). The construction industry needs to shift from non-renewable to renewable resources, from waste production to reuse and recycling, first costs to life cycle costs, and full-cost accounting to achieve economic sustainability (Zhong and Wu, 2015). According to

Abidin and Pasquire (2007), economic sustainability improves profitability by maximizing the use of resources (human, material, and financial) (Abidin and Pasquire, 2007). On the other hand, the construction industry must consider housing affordability, building life cycle costs, renovation and development expenditures, business enhancement, law compliance, profitability, and risk management for economic sustainability (Bennett and James, 2017).

There has been a wide range of existing and established tools for estimating economic sustainability through calculating costs and revenues (Heinzle et al., 2006). Complementary to environmental life cycle analysis, life cycle cost refers to assessing all expenses connected with a product system's life cycle that is monetarily reimbursed by one or more entities involved in the product life cycle (Finkbeiner et al., 2010; Hunkeler, 2006). According to British Standards Institution (2008), life cycle cost is the cost associated with owning an asset that fulfills its performance requirements from the beginning until the termination of its usability. The components in life cycle costs include construction costs, maintenance costs, operational costs, occupancy costs, end-of-life costs, and non-construction costs (BSI, 2008). Economic analysis typically includes time by resorting to life cycle costing methods, which in their complete incarnation include costs from cradle to cradle or from resource extraction to reuse phase (Kaminsky, 2015). A list of economic sub-criteria obtained through the literature review, which is utilized in the sustainability assessment of different construction works, is presented in Table 2.2.

Table 2.2. List of economic sub-criteria utilized in the sustainability assessment

Criteria	Sub-criteria	Reference
Economic	Life cycle cost	(Akadiri et al., 2013; Figueiredo et al., 2021; Josiah Marut et al., 2020; Kamali and Hewage, 2015; Rahim et al., 2014; Sahlol et al., 2021)
	Material cost	(Akadiri et al., 2013; Figueiredo et al., 2021; Josiah Marut et al., 2020; Kamali and Hewage, 2015; Rahim et al., 2014; Sahlol et al., 2021)
	Construction cost	(Danso, 2018; Fallahpour et al., 2020; Fazeli et al., 2019; Kamali and Hewage, 2015; Minhas and Potdar, 2020)
	Initial acquisition cost	(Akadiri et al., 2013; Kappenthuler and Seeger, 2020; Kaya and Kahraman, 2011; Solangi et al., 2019; Yang and Ogunkah, 2013)
	Initial investment cost	(Danso, 2018; Fallahpour et al., 2020; Fazeli et al., 2019; Minhas and Potdar, 2020; Thirunavukkarasu et al., 2021)

	Operation cost	(Akadiri et al., 2013; Danso, 2018; Fazeli et al., 2019; Kamali and Hewage, 2015; Kappenthuler and Seeger, 2020; Kaya and Kahraman, 2011; Minhas and Potdar, 2020; Solangi et al., 2019; Yang and Ogunkah, 2013)
	Maintenance cost	(Akadiri et al., 2013; Danso, 2018; Fazeli et al., 2019; Kamali and Hewage, 2015; Kappenthuler and Seeger, 2020; Kaya and Kahraman, 2011; Minhas and Potdar, 2020; Solangi et al., 2019; Yang and Ogunkah, 2013)
	Fair wage potential	(Figueiredo et al., 2021)
	Labor and installation cost	(Yang and Ogunkah, 2013)
	Long term savings	(Danso, 2018)
	Payback period	(Fazeli et al., 2019)
	Disposal, end of life cost	(Kamali and Hewage, 2015; Minhas and Potdar, 2020)

2.2.3 Social Sustainability

Since the publication of the Brundtland Report in 1987, there has been a growing concern that the construction industry must support a sustainable development goal by including social considerations. The concept focuses on the impacts of the construction project on people, both within and outside the project, from inception to project end-of-life. Hill and Bowen (1997) defined that social sustainability in construction aims to improve the quality of human life (Hill and Bowen, 1997). With the evolution of concepts and scope of expansion in construction, the focus was shifted towards developing social sustainability assessment frameworks and, consequently, creating a reliable set of indicators based on which the assessment or implementation can be pursued (Farzanehrafat et al., 2015). Farzanehrafat et al. (2015) also reported a lack of a well-defined set of social sustainability indicators across the entire life cycle of a construction project. They presented a list of social sustainability indicators for use in different project phases. They concluded that stakeholder engagement and public accessibility, health, and safety were vital for all project phases. However, the end-of-life phase indications were the least important compared to the other stages. Although there was considerable consistency in the importance of each indicator among different respondents' viewpoints, indicators that were visible in practice, such as "health and safety considerations," were given more weight in industry professionals' opinions. In contrast, this attitude was balanced among respondents from academia (Sahlol et al., 2021).

Table 2.3. List of social sub-criteria utilized in the sustainability assessment

Criteria	Sub-criteria	Reference
Social	Health and safety	(Akadiri et al., 2013; Josiah Marut et al., 2020; Kamali and Hewage, 2015; Minhas and Potdar, 2020; Sahlol et al., 2021; Yang and Ogunkah, 2013)
	Fire resistance and safety	(Akadiri et al., 2013; El khouli et al., 2015; Kappenthuler and Seeger, 2020; Minhas and Potdar, 2020; Sahlol et al., 2021; Yang and Ogunkah, 2013)
	Skilled labor availability	(Akadiri et al., 2013; Minhas and Potdar, 2020; Sahlol et al., 2021)
	Job opportunity creation	(Danso, 2018; Fallahpour et al., 2020; Kaya and Kahraman, 2011)
	Aesthetics	(Akadiri et al., 2013; Danso, 2018; Josiah Marut et al., 2020; Minhas and Potdar, 2020; Sahlol et al., 2021)
	Acceptance and satisfaction	(Kamali and Hewage, 2015; Kaya and Kahraman, 2011; Solangi et al., 2019)
	Adaptability	(Danso, 2018)
	Safety and security	(El khouli et al., 2015; Fallahpour et al., 2020; Kamali and Hewage, 2015; Li and Froese, 2017)
	Thermal comfort	(Danso, 2018; El khouli et al., 2015; Fazeli et al., 2019; Kamali and Hewage, 2015; Li and Froese, 2017)
	Acoustic comfort	(El khouli et al., 2015; Fazeli et al., 2019; Kamali and Hewage, 2015; Li and Froese, 2017; Solangi et al., 2019)
	Indoor air quality	(El khouli et al., 2015; Fazeli et al., 2019; Kamali and Hewage, 2015; Li and Froese, 2017)
	Use of local material	(Akadiri et al., 2013; Kamali and Hewage, 2015; Minhas and Potdar, 2020; Pearce et al., 1995; Sahlol et al., 2021)
	Influence on local economy	(Kamali and Hewage, 2015)
	Compatibility with heritage	(Josiah Marut et al., 2020; Kamali and Hewage, 2015; Yang and Ogunkah, 2013)
	Use of local material	(Akadiri et al., 2013)

Social sustainability issues need to be addressed during building projects' design, planning, and construction. The construction industry provides many job opportunities and significant contributions to the national GDP. While construction works' environmental and economic effects have been extensively investigated, social impacts such as traffic congestion and delays are often overlooked (Valdes-Vasquez and Klotz, 2013). Project stakeholders should give more attention to social sustainability-related aspects that influence project social performance, such as community quality of life, health and safety, security, training, and educational opportunities (Zuo et al., 2012). To avoid disparity, health concerns, and other high-priority social issues in the value creation process, social needs and community perceptions should prioritize project development decisions based on traditional cost-benefit analyses (Almahmoud and Doloi, 2015). A list of social sub-criteria obtained through the literature review, which is utilized in the sustainability assessment of different construction works, is presented in Table 2.3.

2.2.4 Environmental Sustainability

Environmental sustainability is using natural resources efficiently, encouraging renewable resources, and protecting the land, water, and air from contamination to prevent severe and permanent environmental consequences (Abidin and Pasquire, 2007). The influence of the construction industry on the environment is enormous, as it is responsible for 36% of global energy consumption, 37% of global greenhouse gas emissions, 12% of global potable water usage and 40% of solid waste generation in developed countries (Mohammad et al., 2020; UNEP, 2021).

There has been remarkable development in analyzing the environmental sustainability of buildings for the last two decades (Bernardi et al., 2017). Life cycle assessment (LCA) and building assessment systems or tools have been widely used to determine the environmental sustainability of buildings (Crawley and Aho, 1999; Todd et al., 2001). For example, the Leadership in Energy and Environmental Design (LEED) uses sustainable sites, water efficiency, energy and atmosphere, material, resources, and indoor air quality as indicators. In contrast, The Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) uses energy efficiency, water management, economic development, life cycle cost, technical and planning quality as the indicators (Zhong and Wu, 2015). Section 3 of this chapter covers a detailed explanation of widely accepted green building rating systems. In all cases, an environmental building assessment method's primary function is to comprehensively evaluate a building's environmental features using a standard and reliable set of criteria and goals for building owners and designers to reach better environmental standards (Cole, 1999). Regarding environmental sustainability, housing construction should consider renewable energy, energy efficiency, water efficiency, ecology, conservation, material efficiency, air pollution, pollution control, indoor environmental quality, sustainable site and land utilization and management (Roufechaei et al., 2014). A list of environmental sub-criteria obtained through the literature review, which is utilized in the sustainability assessment of different construction works, is presented in Table 2.4.

Table 2.4. List of environmental sub-criteria utilized in the sustainability assessment

Criteria	Sub-criteria	Reference
Environmental	Impact during raw material extraction	(Minhas and Potdar, 2020; Sahlol et al., 2021; Yang and Ogunkah, 2013)
	Method of raw material extraction	(Josiah Marut et al., 2020)
	Impact during manufacturing	(Kappenthuler and Seeger, 2020; Minhas and Potdar, 2020)
	Wastage in production	(Minhas and Potdar, 2020)
	Embodied energy	(Josiah Marut et al., 2020; Kappenthuler and Seeger, 2020; Sahlol et al., 2021)
	Life cycle assessment	(El khouli et al., 2015; Fallahpour et al., 2020)
	Use of Reused material	(Sahlol et al., 2021)
	GHG emission	(Josiah Marut et al., 2020; Kamali and Hewage, 2015; Kappenthuler and Seeger, 2020; Miller and Ip, 2013; Ren et al., 2015; Sahlol et al., 2021; Solangi et al., 2019)
	Global warming potential	(Fazeli et al., 2019; Figueiredo et al., 2021; Kappenthuler and Seeger, 2020; Kaya and Kahraman, 2011; Yang and Ogunkah, 2013)
	Impact during construction	(Akadiri et al., 2013; Fallahpour et al., 2020; Kappenthuler and Seeger, 2020; Minhas and Potdar, 2020; Sahlol et al., 2021; Solangi et al., 2019; Yang and Ogunkah, 2013)
	Impact on air quality	(Akadiri et al., 2013; Fallahpour et al., 2020; Kappenthuler and Seeger, 2020; Minhas and Potdar, 2020; Sahlol et al., 2021; Solangi et al., 2019; Yang and Ogunkah, 2013)
	Ozone depletion probability	(Akadiri et al., 2013; Fallahpour et al., 2020; Kappenthuler and Seeger, 2020; Miller and Ip, 2013; Minhas and Potdar, 2020; Sahlol et al., 2021; Solangi et al., 2019; Yang and Ogunkah, 2013)
	Acidification potential	(Danso, 2018; Fazeli et al., 2019; Figueiredo et al., 2021; Gale, 1998; Josiah Marut et al., 2020; Kaya and Kahraman, 2011; Yang and Ogunkah, 2013)
	Eutrophication potential	(Fazeli et al., 2019; Figueiredo et al., 2021; Josiah Marut et al., 2020; Miller and Ip, 2013; Ren et al., 2015)
	Smog potential	(Fazeli et al., 2019; Tazikova, 2017)

	Toxicity	(Akadiri and Olomolaiye, 2012; Danso, 2018; Fallahpour et al., 2020; Miller and Ip, 2013; Minhas and Potdar, 2020; Pearce et al., 1995)
	Minimize pollution (air, land)	(Akadiri et al., 2013; Minhas and Potdar, 2020; Solangi et al., 2019)
	Recycle and reuse potential	(Akadiri et al., 2013; Kappenthuler and Seeger, 2020; Minhas and Potdar, 2020; Pearce et al., 1995; Solangi et al., 2019)
	Eco friendly disposal option	(Minhas and Potdar, 2020; Pearce et al., 1995)
	Energy saving	(Li and Froese, 2017; Sahlol et al., 2021)
	Recycling cost	(Kappenthuler and Seeger, 2020; Solangi et al., 2019)

2.2.5 Selection of Sub-Criteria based on Literature Review and Expert Opinion

There can be a variety of sub-criteria (i.e., sustainability evaluation criteria) for assessing the technical, economic, social, and environmental criteria of sustainable construction. From the literature review, it is observed that researchers have used different sets of sub-criteria based on the type and nature of the construction projects. The selection of sub-criteria also depends on the user's preferences. Therefore, to finalize the list of sub-criteria in selecting the most sustainable structural material, we seek the opinion of several industry experts and academic researchers.

According to most experts, the technical criteria come first since any material which is not technically feasible cannot be used despite having overwhelming benefits in other considerations. They commented that building codes define the essential components of the design standards. There can be several options that building codes may permit for a particular project. That is the case to utilize technical criteria to determine the most sustainable choice from several available alternatives. Durability, constructability, maintainability, resistance to horizontal load, resistance to water and weather, knowledge in design and construction, etc., are the essential technical sub-criteria mentioned by the experts. The durability of a material is its life expectancy. Constructability or buildability is the ease of construction using that material, and maintainability is the need for maintenance throughout the material's life cycle. The material's earthquake and wind load resistivity are measures of resistance to horizontal load. The resistance to water and weather is the withstanding and behaviour of the material once exposed. The knowledge of design and construction of other materials may result in the overuse of some particular materials. Besides, lack of knowledge also results in inappropriate design and construction, resulting in less durability and more maintainability.

Similarly, industry and academic experts gave their opinion on other sustainability pillars, and a summary of sub-criteria based on overall findings are shown in the following Table 2.5.

Table 2.5. Summary of sustainability evaluation criteria (pertinent to this research)

Criteria	Sub-Criteria	Type
Technical	Durability (life expectancy)	Qualitative
	Constructability (Ease of construction)	Qualitative
	Maintainability (Ease of maintenance)	Qualitative
	Resistance to water and weather	Qualitative
Economic	Material cost	Quantitative
	Construction cost	Quantitative
	Maintenance cost	Qualitative
	End of life cost	Quantitative
Social	Job opportunity creation	Qualitative
	Fire resistance and safety	Qualitative
	Skilled labor availability	Qualitative
	Compatibility with local heritage	Qualitative
Environmental	Greenhouse gas emission	Quantitative
	Impact during manufacturing	Qualitative
	Impact during construction	Qualitative
	Recycle and reuse potential	Qualitative

2.3 Structural Materials Commonly used for Multistory Building Construction

Construction projects are classified into three broad categories: (a) building construction projects like residential and commercial buildings and schools; (b) infrastructure construction projects like highways; (c) industrial construction projects such as manufacturing plants (Safa et al., 2015). The structural members of a building comprise beam, column, tension members and their connections (Ochshorn, 2020). The commonly used structural materials in building construction practices are steel, concrete, masonry, and timber (Gharehbaghi, 2015). The selection of sustainable construction materials requires a detailed investigation of materials' environmental impacts, fire performance, structural performance (strength and durability), and available functionality (load-bearing capacity and stress-strain potentials) (Gharehbaghi, 2015). The primary source of environmental impacts of greenhouse gas emissions is mining raw materials and their production (Goodhew, 2016). Concrete, in particular, is responsible for approximately 10% of global CO_2 emissions. In addition to concrete, steel and its manufacturing processes also produce CO_2 emissions, but not as much as concrete (Jang et al., 2015). However, timber is considered the most emission-free material since it does not produce much pollution during production (El khouli et al., 2015). A comparison of energy and material required for making a three-meter high similar column is shown in Figure 2.2 (Buck et al., 2015).

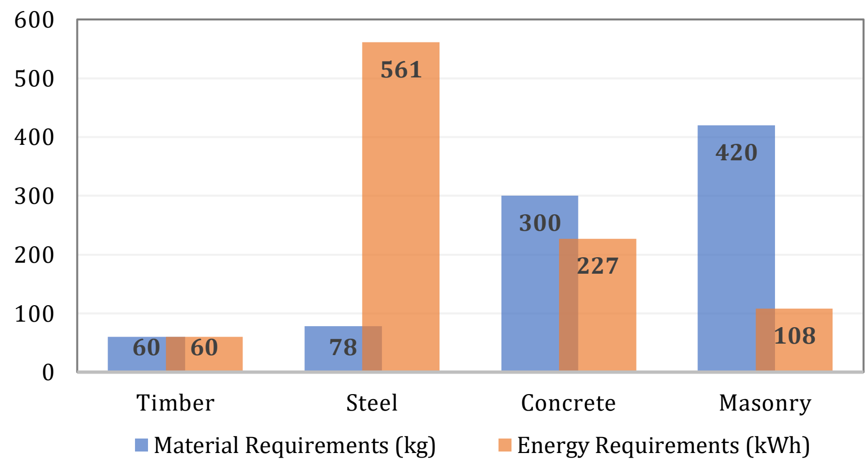


Figure 2.2. Material and energy requirements for producing similar 3-m height column (Buck et al., 2015)

A building's total energy consumption consists of embodied energy, operational energy and demolition energy during the construction stage, service life and at the end of life, respectively (Gavali and Ralegaonkar, 2019). Operating energy refers to the energy required for building operations, such as heating, cooling, and illumination. Embodied energy refers to the energy required to produce construction materials, including all upstream energy for extracting raw materials and the energy needed to construct the building (Cabeza et al., 2013). The embodied energy of a building mainly depends on the materials used for its construction, and it consists of energy required for raw material extraction, processing, production, and transportation. Approximately 80% of the total embodied energy is due to conventional construction materials such as concrete, steel and masonry (Debnath et al., 1995). According to a study comparing the environmental impacts of steel and concrete, steel buildings produce fewer materials stage emissions, and concrete structures cause a higher use phase of emissions (Xing et al., 2008). An LCA study of wooden products in buildings reveals that timber offers better environmental performance in reducing emissions and construction waste (Werner and Richter, 2007).

Reinforced concrete is the most often used structural material for building construction. It is a widely used material for various construction applications due to its strength, durability, reflectivity, and adaptability (Opon and Henry, 2019). These features make it a durable and long-lasting alternative for various residential and industrial building construction. However, ironically, concrete is one of the leading sources of environmental degradation and is harmful to our ecosystem and environment. Concrete manufacturing emits 2.8 billion tons of carbon dioxide, accounting for 4-8% of global greenhouse gas emissions (Stephan and Stephan, 2016). Concrete consumes a tenth of all industrial water around the globe (Halloran, 2019). This phenomenon has led to the concern of looking for alternatives in building construction materials to achieve sustainability. Steel may be used to replace concrete in structural construction due to its numerous advantages, including high strength, high tensile, ductile, flexibility, and cost-effectiveness (Oldfield, 2019). On the other hand, steel needs a lot of energy in its manufacturing process and might be expensive in some situations. Masonry is also a time-tested alternative to concrete construction, albeit burned bricks may emit significant levels of carbon during the manufacturing process, and masonry construction requires a substantial amount of cement (Cowan, 1977). So, architects, builders, and sustainability advocates have recently been buzzing about timber as a building material. They believe that timber can significantly reduce greenhouse gas (GHG) emissions in the building sector and bring down waste, pollution, and construction costs, simultaneously creating a more physically, psychologically, and aesthetically healthy built environment (Švajlenka and Kozlovská, 2018).

As a building material, timber has better energy-saving and carbon reduction performance than other traditional materials, such as bricks, RC, and steel (Guo et al., 2017). RC-framed buildings consume approximately 80% more energy during material production and are responsible for 100-200% more net

GHG emissions than wood-framed buildings (Börjesson and Gustavsson, 2000). On the other hand, wood can store about 1.10 tons of CO_2 per cubic meter, and much of the carbon trapped in forest products may not be released decades after harvesting (Ek et al., 2019). As a result of comparing concrete and timber frame materials in various scenarios, the researchers found that concrete frames consume 30% more energy than timber (Gong et al., 2012). Compared to a concrete building in its operating stage, a seven-story Cross Laminated Timber building might save 29.4 percent energy, equivalent to a 24.6 percent carbon reduction (Guo et al., 2017).

2.3.1 Reinforced Concrete (RC)

Globally, concrete is the most utilized substance after water (Goggins et al., 2010). In terms of volume, twice as much concrete is used worldwide in construction as all other building materials combined, including timber, steel, aluminum, and plastic (Gharehbaghi, 2015). Approximately three tons of concrete are used each year globally per capita, making it the most widely used material in construction (Nassar et al., 2013). A study by Bribian et al. (2011) indicates that the contribution of primary energy demand to concrete manufacturing, excluding aggregate and additives, is 11%; it appears to rise to 30% when CO_2 emissions associated with concrete manufacturing are included (Gharehbaghi, 2015).

Concrete production increased from 40 million cubic meters in 1900 to 6.4 billion cubic meters in 1997 around the world (Yeo and Gabbai, 2011). Manufacturing 1 kg of OPC results in between 0.76 and 1.37 kg of carbon dioxide equivalents released into the atmosphere, depending on the region and manufacturing method used (Dahmen et al., 2018). Studies acknowledge that the global production of ordinary cement causes 5-8% of global anthropogenic GHG emissions (Oss and Padovani, 2003). Extracting raw materials (e.g., cement and steel production) and manufacturing chemicals also considerably impact CO_2 emissions (Worrell et al., 2001). According to Rodríguez et al. (2015), the European Union produced approximately 530 million tons of construction and demolition waste from concrete use, accounting for 25-30% of the total solid waste generated.

Concrete and steel are two of the most common construction materials with high embodied energy (Zhong and Wu, 2015). The appropriate selection from these two construction materials may help the industry minimize environmental impacts (Zhong and Wu, 2015). A reduction in embodied energy for reinforced concrete structures can be achieved not only by utilizing novel building materials, such as low-carbon cement and clinker alternatives, and recycling but also through more efficient use of other construction materials resulting from the optimization of RC structural designs (Gartner, 2004; Thormark, 2002; Yeo and Gabbai, 2011).

2.3.2 Structural Steel (SS)

In construction, steel is widely used primarily due to its tensile strength (Gharehbaghi, 2015). Moreover, steel usage in sustainable construction practices is due to its adaptability, ductility, and durability (Gharehbaghi and Georgy, 2019). Steel can be modified for a variety of requirements, for example, I-beams, continuous beams, structural joints, etc. The ability to adapt to changes facilitates easier development, which extends the life of the structure (Gharehbaghi, 2015). Steel structurally does not distort, rotate, clink, warp, or splinter. Additionally, it can be rolled or cut into various shapes and sizes without changing its composition or physical properties. Steel can endure extreme forces, such as sturdy winds, earthquakes, hurricanes, and heavy snow. With the appropriate coating, steel also resists rust, and unlike timber, it is not affected by termites, bugs, mildew, or fungi. Besides, steel is more fire-resistant with cement coating than timber (Gharehbaghi, 2015).

About 1500 million tons of steel are produced yearly, accounting for 9% of world CO_2 emissions from energy and processes (Allwood et al., 2010). Construction of buildings accounts for over one-quarter of steel production each year. Steel demand is expected to quadruple in the next 37 years, according to Allwood et al. (Allwood et al., 2010). On the other hand, experts on climate change recommend halving carbon dioxide emissions from steel manufacturing by 2050. One approach to do this is to design and construct buildings more effectively while maintaining the same level of service by using less steel (Moynihan and Allwood, 2014).

2.3.3 Reinforced Masonry (RM)

Due to its availability, cost-effectiveness, durability, and excellent weather resistance, masonry is one of the most preferred construction materials for low-to-medium rise buildings (Jayasinghe et al., 2016). It also provides excellent thermal and sound insulation for the structures compared to other construction materials (Hendry, 2001). Therefore, masonry remains a competitive building option due to its inherent material properties and simplicity in the construction process. However, masonry has low tensile strength and ductility (like concrete). Alternative construction systems such as reinforced masonry (RM), confined masonry (CM), post-tensioned masonry and thin layer mortared masonry were introduced in the past to overcome these limitations (Thamboo, n.d.).

RM is widely used in North America, Europe, and Australasia. Generally, the masonry units used for RM are hollow to incorporate reinforcement and grout. Depending on the size and shape of the hollow unit, it may have one or several cavities. The RM has proven adequate structural behaviour on par with RC structures, even under higher load demands such as earthquake and cyclonic actions (da Porto et al., 2010; Dhanasekar, 2011; El-Dakhakhni and Ashour, 2017). As a result, RM construction may be more cost-effective than RC construction, particularly in low- to medium-rise structures. The main features of a hollow masonry unit are shown in Figure 2.3.

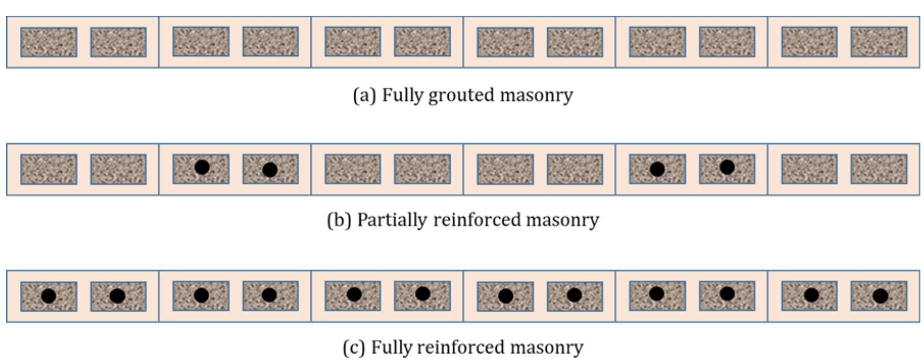


Figure 2.3. Reinforcing options in masonry (Thamboo, n.d.)

CM is an improved masonry structural system where the unreinforced masonry walls are confined with nominally reinforced concrete tie-elements (tie-columns and tie-beams) at the perimeter and other salient locations. The structure's flexibility under lateral stress improves due to these small tie members, resulting in enhanced seismic performance than an unreinforced masonry building (Borah et al., 2019).

2.3.4 Timber

Timber is considered one of the most eco-friendly building materials available and has been used as a basic construction material for millennia (Guo et al., 2017). Timber as a construction material may be regarded as a highly sustainable solution. It is a renewable natural substance that will sequester carbon throughout its life if managed appropriately. In addition, at the end of its useful life as a building material, it may be reused or recycled, burnt as a fuel, or decompose naturally in the landfill (Miller and Ip, 2013). Trees release oxygen and absorb CO_2 from the atmosphere, resulting in biomass and a reduction in CO_2 levels. Carbon is 'locked' inside a tree during its growth and the life of its usage in wood products, and the carbon can only escape when the wood is finally disposed of, either by natural decomposition or burning. When forests and woods are adequately maintained and new trees are planted to replace those that are cut, the use of timber in the building offers a long-term environmental benefit. It is estimated that the average tree absorbs approximately 55 kg of CO_2 and gives off 40 kg of oxygen when growing 2 kg of wood (Gale, 1998). Therefore, during its growth period, a tree positively impacts the environment by reducing GHG (Miller and Ip, 2013).

Compared to steel and concrete, timber building has a smaller environmental footprint (Buck et al., 2015). Steel has a nine-fold higher energy consumption than timber, while reinforced concrete has a three-fold higher energy consumption (Kolb, 2008). Wood is a material that requires lower processing power to be prepared for building construction compared to most common construction materials like concrete (Kaziolas et al., 2017). Wood buildings use less fossil fuels, emit lower greenhouse gas emissions, and produce less solid waste than buildings made of other materials (Werner and Richter, 2007). A timber building also has lower environmental burdens than buildings made of different materials (Lippke and Bowyer, 2007). Since wood possesses excellent thermal conductivity, timber structures have higher energy efficiency (Buchanan and Levine, 1999).

A comparison of the construction time shows that the wooden house construction time is 48% shorter than the masonry variant (Švajlenka and Kozlovská, 2018). This is significant not only for the investor, who can have a much faster return on his financial investment, but also for the environment. The shorter construction time proportionally reduces the environmental impact concerning noise, dust, and waste (Švajlenka and Kozlovská, 2018). The comparison of selected environmental parameters showed that wooden buildings consume 54% less embodied energy and generate 35% less SO_2-equivalent emissions (acidification potential). Additionally, the production of CO_2 emissions (global warming potential) reaches a negative value; hence, reducing emissions for wooden constructions versus a high of 156% in masonry constructions. The negative value of CO_2 emissions is that wood, as a naturally renewable material, absorbs more CO_2 during growth than it generates during the processing of a wood product (Švajlenka and Kozlovská, 2017).

Timber construction systems have several advantages over steel and concrete (Buck et al., 2015). Timber has a higher ratio of load-carrying capacity to weight, and its lower weight reduces soil load by 30 to 50%. Lifts are accomplished with smaller cranes, and more manageable handling allows for faster installation. Increasing the prevalence of timber construction is one strategy for reducing the global climate change rate (Stehn, 2008). However, knowledge about timber construction is still lacking, which can create skepticism and preconceptions about the features and costs of timber construction (Buck et al., 2015).

2.4 Multi-Criteria Decision-Making (MCDM) in Construction

Decision-making is an integral part of every human activity, regardless of professional or personal work (Filho et al., 2022). Some decisions may be relatively simple, especially if the consequences of a wrong decision are minor, while others can be very complex and have significant effects. Multi-criteria decision making (MCDM) is a technique for aiding decision-makers in analyzing information to make an informed decision (Belton and Stewart, 2002). Real-life decision problems will generally involve several conflicting points of view (criteria) that should be considered conjointly to arrive at a reasonable decision (Filho et al., 2022). MCDM is fundamentally a systematic approach to solving problems of varying degrees of structure (Eom, 1999). Ultimately, it provides decision-makers with an informed recommendation from a finite list of alternatives (also known as actions, objects, solutions, or candidates) while being evaluated from multiple viewpoints, called criteria (also known as attributes, features, or objectives) (Chai et al., 2013). The MCDM technique generates alternative scenarios, establishes criteria, assesses alternatives, weighs the criteria, and ranks the alternatives (Bouyssou, 1994).

As with most MCDM approaches, the weights of criteria reflect their relative importance in the decision-making process (Wang and Lee, 2009). Since the evaluation of criteria involves a variety of opinions and meanings, each evaluation criterion is not of equal importance (Mei-Fang Chen et al., 2003). Subjective (qualitative) methods and objective (quantitative) methods are the two types of weighing techniques. The subjective methods determine weights according to the preference or judgments of decision-makers. On the other hand, objective techniques, such as the entropy method, multiple objective programming, etc., determine weights by solving mathematical models without considering the decision maker's preferences (Deng et al., 2000). Besides, the purpose of Decision Support Systems (DSS) is to facilitate problem-solving by integrating quantitative data and qualitative knowledge; comparing and ranking various alternatives; and selecting the alternative that mostly fits the predefined criteria (Lu et al., 2007).

MCDM methods range from a single approach (such as AHP and Fuzzy Sets) to a combination of the methods, also known as the hybrid approach (Jato-Espino et al., 2014). Hybrid systems to MCDM involve an extension or combination of the single processes with other techniques such as: AHP + Fuzzy sets, AHP + Delphi + Fuzzy sets, ANP + MCS (Monte Carlo Simulations), Fuzzy sets + TOPSIS, AHP + TOPSIS in Fuzzy environment, AHP + ELECTRE + Fuzzy sets, GST + TOPSIS, etc. (Nwodo and Anumba, 2019). Over the last decades, several MCDM methods have been developed, the most popular of which are AHP, ANP, TOPSIS, ELECTRE, VIKOR, and PROMETHEE (Brans et al., 1986; Brans and Mareschal, 1995; Brans and Vincke, 1985; Hwang and Yoon, 1981; Olson, 2004; Opricovic and Tzeng, 2004; Saaty, 2006, 1988). Short descriptions of several widely accepted MCDM methods are discussed in the subsequent paragraphs.

2.4.1 Fuzzy Expert System

The Fuzzy set theory effectively reflects human thought and aids decision-making by utilizing fuzzy membership functions to handle uncertainties, imprecision, or a lack of information about some aspects and vagueness (Akadiri et al., 2013; Dwi Putra et al., 2018). This theory can improve the comprehensiveness and rationality of decision-making (Chen et al., 2006). Zadeh first developed the Fuzzy theory to describe complex or ill-defined systems with imprecise or uncertain knowledge (Ahmadi-Nedushan et al., 2008; Zadeh, 1965). Through a gradual shift from a member to a non-member, the Fuzzy set creates vagueness by decreasing the sharp boundary separating set members from non-members. It is opposite to the traditional crisp set theory, which states that elements are either in or out of the set (Krause, 1995). The membership function of a fuzzy set is a curve that shows how each point in the input space can be assigned a membership value between 0 and 1, indicating the degree of that element's membership (Kishk and Al-Hajj, 1999). Figure 2.4 shows three widely used Fuzzy membership functions (MF): triangular, trapezoidal, and gaussian.

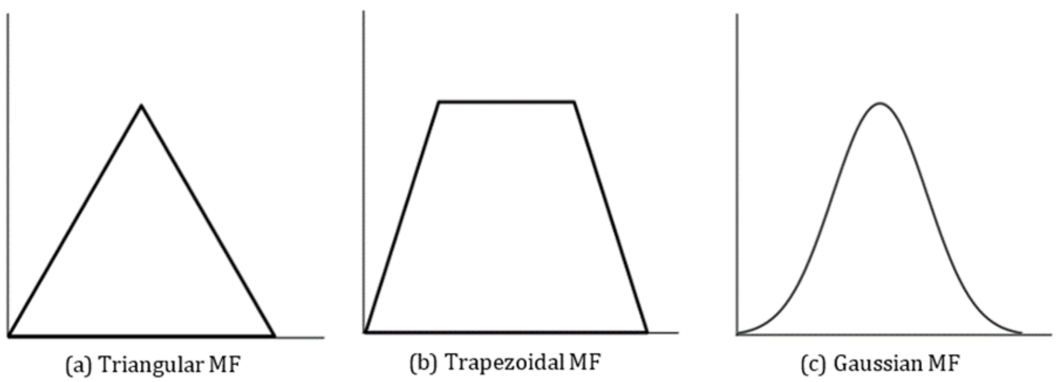


Figure 2.4. Fuzzy membership functions (Triangular, Trapezoidal and Gaussian)

In fuzzy logic, general linguistic concepts like "bad," "good," or "fair" are employed to represent numerical intervals that are not well defined (Kishk and Al-Hajj, 1999). Triangular membership functions are commonly utilized in decision-making due to their ease of usage and calculation, which can be defined as (x, y, z) where $x \le y \le z$. The parameters x, y, and z reflect the lowest possible, the most expected, and the highest possible value, respectively (Kannan et al., 2013). Besides, the trapezoidal function is considered to handle uncertainties, imprecision, or a lack of information in a better way (Mocq et al., 2013).

In two cases, fuzzy logic is most appropriate: highly sophisticated models with limited or judgmental understanding and processes that are inextricably linked to human reasoning, perception, or decision-making (Krause, 1995). Some of its advantages include simple mathematical fundamentals, matching input-output data sets, and ease of combination with traditional methods. This logic has generated outstanding results in many engineering and science disciplines (Kishk and Al-Hajj, 1999).

2.4.2 AHP

Analytic Hierarchy Process (AHP) is one of the most widely used MCDM tools that can be used to analyze, measure, and synthesize decision problems (Danso, 2018). There have been numerous applications of the AHP, including selecting among competing alternatives in multi-objective environments, allocating scarce resources, and forecasting (Forman and Gass, 2001). AHP is one MCDM method that allows decision-makers to make choices when evaluating several competing criteria (Ishizaka and Labib, 2009). Developed by Saaty (1980), it deals with determining the relative importance of a set of activities in a multi-criteria decision-making issue. According to AHP, multiple pairwise comparisons are conducted according to a standard comparison scale with nine levels, as shown in Table 2.6 (Dağdeviren et al., 2009).

Table 2.6. The nine-point intensity of importance scale and its description (Dağdeviren et al., 2009)

Definition	Intensity of importance
Equally important	1
Moderately more important	3
Strongly more important	5
Very strongly more important	7
Extremely more important	9
Intermediate values	2, 4, 6, 8

In AHP, individual preferences are transformed into ratio-scale weights, which are then combined into linear additive weights for the alternatives. Based on these weights, the decision-maker (DM) can rank the alternatives and forecast the outcome more effectively (Forman and Gass, 2001). For determining the relative priorities of different selection criteria and sub-categories, Fuzzy AHP uses fuzzy numbers as a pairwise comparison scale. This approach can adequately handle the inherent uncertainty and imprecision of human decision-making processes and offer an appropriate level of flexibility and robustness so that a decision-maker can comprehend and understand a decision problem (Akadiri et al., 2013).

2.4.3 TOPSIS

Chen and Hwang first proposed TOPSIS (Technique for Order Performance by Similarity to Ideal Solution) in 1992 as an MCDM technique to identify solutions from a finite set of alternatives (Büyüközkan and Çifçi, 2012). This method is widely used for solving ranking problems in real situations (Dağdeviren et al., 2009). The fundamental concept of TOPSIS is that the chosen alternative should be closest to the positive ideal solution (PIS) and the furthest away from the negative ideal solution (NIS) (Ertuğrul and Karakaşoğlu, 2008). TOPSIS defines an index called similarity (or relative closeness) to the PIS and the remoteness from the NIS. Then, the method chooses an alternative which has maximum similarity to the PIS (Kahraman et al., 2007). The classical TOPSIS method uses a precise weighting of the criteria and crisp values for rating the alternatives. Even though it is popular and simple in concept, the classical technique has often been criticized for its inability to adequately deal with the inherent uncertainty and imprecision involved in mapping the decision maker's perception into crisp values (Dağdeviren et al., 2009). The human preference model is often uncertain, making decision-makers reluctant or unable to provide crisp judgments on comparisons (Chan and Kumar, 2007). In order to address the shortcoming of traditional TOPSIS, several fuzzy TOPSIS methods and applications have been developed in recent years that utilize linguistic variables expressed by fuzzy numbers to determine how to evaluate criteria and alternatives (Chen and Tsao, 2008; Ertuğrul and Karakaşoğlu, 2008; Gligoric et al., 2010). Using fuzzy sets theory with TOPSIS enables decision-makers to incorporate uncertainty, a lack of information, and partial ignorance into the decision process (Kulak et al., 2005).

2.4.4 ANP

ANP (Analytic Network Process) is a modified form of the AHP introduced by Saaty in 1990 (Büyüközkan and Çifçi, 2012). It extends the AHP method, allowing for interactions among criteria (Zaim et al., 2014). Theoretically, the ANP consists of a structure with clusters (main criteria), sub-criteria, alternatives, and the inter-relationships and dependencies between them (Saaty and Vargas, 2013). AHP uses a one-way hierarchical relationship between decision levels and more comprehensive interrelationships between decision levels and attributes. Instead of a hierarchy, the ANP-based system is a dependent and feedback-based network that replaces single-direction relationships (Büyüközkan and Çifçi, 2012). The ANP uses ratio scale measurements created on pairwise comparisons; however, it does not impose a strict hierarchical structure as in AHP. It models a decision problem to deal with dependency and feedback among decision criteria and incorporates varied types of criteria (Amiri Fard et al., 2021).

2.4.5 DEMATEL

The Decision-Making Trial and Evaluation Laboratory (DEMATEL) is an MCDM technique used to assess cause-and-effect relationships between variables (Yadegaridehkordi et al., 2018). This system effectively identifies the indirect and direct linkages between a system's criteria and interdependencies, allowing decision-makers to analyze how these criteria influence the output (Yadegaridehkordi et al., 2020). Developed at the Geneva Research Centre of Battelle Memorial Institute, this approach is comprehensive for creating and analyzing models incorporating complicated causal linkages (Zhang et al., 2019). Despite the common use of the crisp version of DEMATEL in MCDM problems, fuzzy logic can be a more effective way to deal with concerns of ambiguity, vagueness, and information leakage (Mardani et al., 2019). Many researchers employed the fuzzy DEMATEL approach to overcome the difficulty of measuring by exact numerical values (Chang et al., 2011; Chen et al., 2008; Wang and Lee, 2009).

2.4.6 PROMETHEE

The PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) is an outranking-based MCDM technique developed by Brans et al. (Brans et al., 1986; Brans and Vincke, 1985). It is well suited for problems in which a finite number of substitutes are ranked according to several, sometimes contradictory criteria (Albadvi et al., 2007). The application of PROMETHEE requires two essential types of information: (1) The relative importance of the evaluation criteria, that is, the weights of the criteria; (2) The preference function of the decision-makers, that is, the influence of the alternatives in terms of each discrete criterion (Mergias et al., 2007; Nijkamp et al., 1990). Brans et al. presented PROMETHEE I for a partial ranking of the alternatives and PROMETHEE II for the complete ranking of the alternatives in 1982 at a conference in University Laval, Quebec, Canada (Brans et al., 1986). A few years later, researchers introduced several versions of the PROMETHEE methods, such as the PROMETHEE III for ranking based on an interval, for complete or partial ranking when the set of viable solutions is continuous, the PROMETHEE IV, for problems with segmentation constraints, the PROMETHEE V (Brans and Mareschal, 1992), for the human brain representation the PROMETHEE VI (Brans and Mareschal, 1995), and for group decision-making the PROMETHEE GDSS (Macharis et al., 1998).

2.4.7 ELECTRE

ELECTRE (ELimination Et Choix Traduisant la REalité or ELimination and Choice Expressing the REality) is another outranking MCDM method used in the field of construction (Roy, 1991). Benayoun, Roy, and Sussman presented the ELECTRE method for the first time in 1966 while reporting on the works of the European consultancy company SEMA concerning a specific real-world problem. However, the first published article did not appear until 1968, when Roy explained the method in detail (Figueira and Roy, 2002). This technique comprises two phases: aggregation and exploitation. The concordance and non-discordance concepts are employed in the aggregation phase of a Multi-Criteria Aggregation Procedure (MCAP) to make pairwise comparisons of the alternatives, which are defined by their performance on the various criteria. Depending on the method in question, these pairwise comparisons of the alternatives lead to forming one or more outranking relations. A performance model based on outranking relation considers three situations: preference, indifference, and incomparability (Figueira and Roy, 2002). The exploitation process (EP) relevant to the ELECTRE technique in consideration is the second step. The EP is used to take advantage of the MCAP's earlier outranking relationship constructed by the MCAP. Its goal is to create and illustrate the expected outcomes for a given situation (Figueira and Roy, 2002).

2.4.8 VIKOR

Opricovic developed the VIKOR (VIsekriterijumska Optimizacija I Kompromisno Resenje) method in 1998 for multi-criteria optimization of complex systems (Opricovic and Tzeng, 2002). VIKOR focuses on ranking and sorting a set of alternatives against various or possibly conflicting and non-commensurable decision criteria (Shemshadi et al., 2011). Similar to other MCDM methods like TOPSIS, VIKOR uses an aggregating function to express closeness to the ideal. However, unlike TOPSIS, where the ranking introduces an index considering closeness to the ideal solution, this technique employs linear normalization to eliminate units of criteria functions (Opricovic and Tzeng, 2004). In VIKOR, the decision-makers are anticipated to accept the option that is closest to the ideal, and the alternatives are evaluated (fuzzy or crisp) against all established criteria. The decision-makers can accept the generated compromise solution since VIKOR provides the highest group utility (denoted by min S) of the majority and the lowest of individual regret (denoted by min R) of the opponent (Shemshadi et al., 2011). In many instances, an extension of VIKOR, like Fuzzy-VIKOR, is utilized to generate a fuzzy compromise solution for MCDM cases (Opricovic, 2011). More details and calculation steps of this method are discussed in Chapter 3.

2.4.9 CBA

CBA (Choosing by Advantage) is an MCDM technique developed by Suhr (1999) and used to select alternatives based on their advantages. CBA's fundamental concept is to identify only the advantages of alternatives first, rather than the typical approach of weighing both advantages and disadvantages of alternatives to eliminate double-counting and omissions (Suhr, 1999). The second rule is to differentiate between cost and value. Cost is a constraint, not a factor, and should be considered carefully before deciding (Suhr, 1999). Most importantly, CBA determines the importance of differences between advantages of alternatives rather than merely selecting the significance of factors, as in most DSS tools (Suhr, 1999). CBA promotes transparency in the decision-making process and explicitly considers multiple alternatives based on various influencing factors (Parrish and Tommelein, 2009; Arroyo et al., 2012; Espinoza et al., 2021). The CBA method also generates a database that expresses in a clear and organized manner how and why a decision was taken, and this can serve as a valuable point of reference for future projects (Parrish and Tommelein, 2009).

2.4.10 Application of MCDM in Construction

X Zhu et al. (2021) studied a total of 530 civil engineering construction articles published from 2000 to 2019 and analyzed the application of MCDM in construction (Zhu et al., 2021). The authors reported the use of 29 single methods and 94 hybrid methods. Among single methods, AHP (used in 60 papers), Fuzzy theory (used in 52 papers), Generic Algorithm (used in 24 papers), Data Envelopment Analysis (used in 16 papers), and Analytical Neural Process (used in 14 papers) are the top five. At the same time, Fuzzy-AHP (used in 53 papers), Fuzzy-TOPSIS (used in 28 papers), AHP-Fuzzy-TOPSIS (used in 8 papers), Fuzzy-ANP (used in 8 papers), ANP-DEMATEL (used in 7 papers), Fuzzy-DEMATEL (used in 7 papers) are the top hybrid methods used in construction. The two largest hybrid categories are hybrid methods that include fuzzy logic (used in 159 articles; 30.00 percent) and hybrid methods that include AHP (used in 104 papers; 19.62 percent) (Zhu et al., 2021).

The search result in the 'Scopus' database with the keywords 'mcdm' and 'construction' for 2020-2021 shows that an additional 136 journal articles have been published that comprise the use of both single and hybrid methods of MCDM. The fuzzy theory was used in 37 papers, out of which six papers utilized a single method, and the other 31 used Fuzzy in combination with TOPSIS, ANP, AHP, PROMETHEE, CORPAS, GIS, VIKOR, etc. AHP alone was used in three papers, and in combination with other methods, it was used in another four articles. TOPSIS was also used in 7 articles, whereas twice it was a single method, and the remaining five were a hybrid. PROMETHEE and VIKOR were used twice each, along with other techniques.

2.4.11 Method Chosen for this Research with Justification

As discussed above, AHP and TOPSIS are the most widely used MCDM techniques in construction. Except few, these methods were combined with Fuzzy theory to eliminate crisp values and introduce vagueness to handle uncertainties, imprecision, or a lack of information. Fuzzy AHP (FAHP) is one of the most powerful and extensively used tools to assign weightage to criteria in MCDM. Therefore, it was used in this research to assign weightage to the sixteen chosen criteria. Though the triangular membership function is most widely used in FAHP for its simplicity, the trapezoidal function is considered to handle uncertainties, imprecision, or a lack of information in a better way. Therefore, the trapezoidal membership function was used in this research. Besides, as an experiment, a simple decision matrix was used to assign the weightage of the criteria as inconsistency of data increases in FAHP with more numbers of criteria. Fuzzy

TOPSIS was chosen to rank the alternatives as it is a widely used, familiar and easy tool for decision-making that has acceptance by both industry and academia.

Besides, a relatively new and less familiar tool, Fuzzy VIKOR, was used in parallel to rank the alternatives. Fuzzy VIKOR was used to compare the results with a different technique and validate its reliability. It is expected that a comparison of results through Fuzzy TOPSIS and Fuzzy VIKOR is likely to enhance the acceptance of the Fuzzy VIKOR in construction.

2.5 Green Building Rating Systems and Sustainability

Sahlol et al. (2021) defined sustainable or green buildings as high-quality buildings that last longer and cost less to operate and maintain. They are the optimal solution to reduce resource consumption, minimize environmental damage, diminish waste, reduce energy loss, and escalate renewable energy use (Sahlol et al., 2021; Wong and Zhou, 2015). In another definition, buildings planned, constructed, and run according to the principles of energy efficiency, climatic aspects, and water consumption can be termed green buildings. Those unite a high comfort level with user quality, minimal energy and water expenditure, and a means of energy generation that is as easy as possible on both climate and resources, all these under economical aspects with a pay-back span of 5 to 15 years (Bauer et al., 2009). By design, construction, or operation, a green building reduces or eliminates adverse impacts on our natural environment and climate while also having the potential to create positive ones (Sherif and Carmela, 2019). The definition of green building has changed over time. However, the widely accepted definition is "a building with healthy, pertinent, efficient space and harmonious natural architecture with the maximum possible savings on resources, environmental protection, and reduced pollution throughout its entire lifecycle" (Wen et al., 2020). Although green buildings and sustainable buildings are mostly used interchangeably, they have significantly different connotations in practice (Sinha et al., 2013). The primary focus of green building is on the environment, whereas sustainable buildings consider the technical, economic, social, and environmental pillars of sustainability during all phases of the building's lifecycle (Omer and Noguchi, 2020). Green building emphasizes its requirements in resource conservation, environmental protection, and pollution reduction in each step of construction, often neglecting the social and economic aspects, which is also significant for long-term sustainability (Sev, 2009). The Green Building Rating System (GBRS) is a tool to assess and recognize buildings that meet predefined green and sustainability requirements or standards. Presently numerous tools or grading systems are available to certify the greenness or sustainability of any structure, predominantly for business purposes keeping sustainability in consideration. Many of these evaluation systems have been criticized for emphasizing environmental factors and ignoring the importance of the other sustainability pillars (Khodadadzadeh, 2016; Wen et al., 2020). Fundamental aspects of a few widely accepted GBRS have been discussed in successive paragraphs.

Leadership in Energy and Environmental Design (LEED) is the most widely used green building rating system globally. LEED certification is a worldwide recognized mark of achievement and leadership in sustainability. The United States Green Building Council (USGBC) developed the LEED rating system in 1994 to assess design and construction performance from a sustainability aspect. It provides a whole framework for green building design, construction, operation, and performance. The approach focuses on employing low-emitting or recycled materials, conserving energy, reusing land resources, and collaborating with other sustainable infrastructure initiatives. LEED helps investors emphasize building efficiency, reduce operational costs, increase asset value, and assure occupant productivity, comfort, health, and well-being (USGBC, 2022). According to a 2014 UC Berkeley research, buildings constructed to LEED standards generated 50% fewer GHGs due to water usage, 48% fewer GHGs due to solid waste, and 5% fewer GHGs due to transportation than conventionally constructed buildings. They are essential in combating climate change and achieving environmental, social, and governance (ESG) goals and strengthening resilience and promoting more equitable societies. 35% of LEED credits are related to climate change, 20% of credits have a direct impact on human health, 15% of credits have an impact on water resources, 10% of credits have an impact on biodiversity, 10% of credits have an impact on the green economy, 5% of credits have an impact on the community, and 5% of credits have an impact on natural resources. In LEED v4.1, most of the LEED credits are related to operational and embodied carbon. The Green Building Certification Institute (GBCI) validates and reviews projects and awards points according to the LEED certification level the project has achieved. These levels of certification include: Certified (40-49 points), Silver (50-59 points), Gold (60-79 points) and Platinum (80+ points) (USGBC, 2022).

The Building Research Establishment (BRE) in the United Kingdom developed and maintains BREEAM (Building Research Establishment Assessment System), which is widely regarded as the world's first green building rating system (Alyami and Rezgui, 2012; Lee, 2013). It was first introduced in 1990 and updated in 1993 for commercial use (Chen et al., 2015; Lee, 2013). BREEAM is well recognized for its influence on nearly all subsequent major green rating systems, including LEED, Green Star, and CASBEE. It evaluates local regulations and conditions and permits use in international structures (Marjaba and Chidiac, 2016). BREEAM also allows for evaluating a building's lifecycle in terms of design, construction, operation, and refurbishment. BREEAM certificates account for 80% of the sustainable building certification industry in Europe (Collins et al., 2018). Although BREEAM can assess all sustainability pillars, the environmental factor remains the most significant, with eight primary categories: management, energy, transportation, water, materials, waste, land use and ecology, and pollution (Doan et al., 2017). The ranking systems are as follows: pass ≥ 30%, good ≥ 45%, very good ≥ 55%, excellent ≥ 70%, and outstanding ≥ 85% (Wu et al., 2016).

The Green Globes rating system was first developed in Canada by ECD Energy and Environment using the BREEAM as the guidelines (Reeder, 2010). Although the grading system for new construction began in 1996, the Green Globes development process was completed in 2002. The Building Owners and Manufacturers Association of Canada adopted Green Globes for Existing Buildings in 2004, and it is presently termed as *Go GreenPlus* (GBI, 2022). Green Globes were first introduced to the United States in 2004 when the nonprofit organization Green Building Initiative® (GBI) acquired the license to promote and develop Green Globes in the United States. Since 2004, the development of Green Globes for both new and existing buildings in the United States has been independent of the development of Green Globes-based programs in Canada (Reeder, 2010). The system comprises 1000 points, and the certification is based on the percentage of the applicable points that any project can obtain (Wu et al., 2016). Seven areas are included in this rating system, namely project management (100 points), site (120 points), energy (300 points), water (130 points), material and resources (145 points), emission (45 points), and indoor environment (160 points). There are four levels of certification: four globes for 85% to 100%, three globes for 70% to 84%, two globes for 55% to 69% and one globe for 35% to 54% of the available points (GBI, 2022; Reeder, 2010).

The Green Building Council of Australia launched the Green Star rating system in 2003, and the latest version of it was released in 2016. South Africa and New Zealand use a different version of Green Star, which is customized according to their national standards (Mattoni et al., 2018). The Green Star rating system evaluates a project's long-term sustainability at all phases of its life cycle in the built environment. The highest number of achievable points is 100, distributed among eight different areas. The accreditation is expressed as a number of stars: Minimum Practice, Average Practice, and Good Practice are represented by 1–3 stars (from 10 to 19, 20 to 29, and 30 to 44 points respectively); Best Practice is represented by 4 stars (from 45 to 59 points). The Australian Excellence Level is 5 stars (from 60 to 75), and more than 75 points earn the 6 stars rating, which is the world leadership ranking (Mattoni et al., 2018).

The *Deutsche Gesellschaft für Nachhaltiges Bauen* (DGNB) is the most recent rating system developed in 2009 by German Sustainable Building Council (GSBC), following German codes and standards. Subsequently, a global version was released in 2014 (Bernardi et al., 2017). Later, GSBC released the most recent international version in November 2020. This system considers buildings' life-cycle assessment and follows a performance-based approach for assigning the weightage (Doan et al., 2017). It has the most detailed analysis and specifications among all available systems for the life cycle assessment category, having 9.5% of the overall credits (Sartori et al., 2021). DGNB includes environmental, economic, sociocultural, and technical aspects of sustainability, giving due weightage to each, which are known as the pillars of sustainable construction (Bernardi et al., 2017; Doan et al., 2017; Keeble, 1988; Mattoni et al., 2018). In this system, environmental, economic, sociocultural and functional quality account for 22.5% each, technical quality accounts for 15%, process quality accounts for 12.5%, and site quality accounts for 5% of total weightage. Certification levels include DGNB Bronze (≥ 35 points), DGNB Silver (≥ 50 points), DGNB Gold (≥ 65 points), and DGNB Platinum (≥ 80 points) (Sánchez Cordero et al., 2019).

Over the last twenty years, green construction practices have got popular in most countries to minimize the adverse impacts of construction. Different green building rating systems were introduced to ensure and encourage such initiatives. These assessment modules include criteria like passive design aspects, energy efficiency, life cycle assessment, site planning, renewable energy utilization, post-occupancy evaluation, resource conservation aspects in most of the cases (Chodnekar et al., 2021). Among the most prominent rating systems, DGNB can be identified as the most prominent to sustainable construction, which gives due importance to other factors besides the environmental qualities. The sustainability aspects covered in some widely accepted GBRS are given in Table 2.7.

Table 2.7. Sustainability aspects covered in some widely accepted GBRS

Rating System	**LEED (BD+C)**	**Green Globe**	**BREEAM**	**Green Star**	**DGNB**
Country of Origin	USA	Canada	UK	Australia	Germany
Year of Initiation	1994	2002	1990	2003	2007
Total Points	110	100%	130	100	100%
Rating Categories	Platinum: 80+ Gold: 60-79 Silver: 50-59 Certified: 40-49	Four globes: 85% - 100% Three globes: 70% - 84% Two globes: 55% - 69% One globe: 35% - 54%	Outstanding: ≥ 85% Excellent: ≥ 70% Very Good: ≥ 55% Good: ≥ 45%	1 Star: (10-19) 2 Star: (20-29) 3 Star: (30-44) 4 Star: (45-59) 5 Star: (60-74) 6 Star: (75-100)	Platinum: ≥ 80% Gold: ≥ 65% Silver: ≥ 50% Bronze: ≥ 35%
Sustainability Aspects Considered					
Water Efficiency	√	√	√	√	
Material and Resources	√	√	√	√	√
Energy and Atmosphere	√	√	√	√	√
Indoor Environment	√	√		√	
Site Selection/ Location	√	√			
Land Use and Ecology			√	√	
Waste Management			√	√	√
Health and Wellbeing	√		√		√
Transport	√		√		
Quality of Service					
Pollution			√		
Economic Development					√
Lifecycle Cost					√
Functionality					√
Design Quality					√
Technical Quality					√
Planning Quality					√
Construction Quality					√
Regional Priority	√				

2.6 Life Cycle Sustainability Assessment (LCSA)

The Life Cycle Sustainability Assessment (LCSA) is an interdisciplinary framework that simultaneously evaluates the impacts associated with products and processes from an environmental, social, and economic perspective (Onat et al., 2017). Traditionally material selection in projects is based on satisfying technical requirements or economic aspects, such as material strength and price, respectively, without considering the life cycle impact associated with the material (Ijadi Maghsoodi et al., 2019). LCSA aims to evaluate and combine three main processes: Life Cycle Assessment (LCA), representing the environmental dimension (Nwodo and Anumba, 2019); Social Life Cycle Assessment (SLCA), representing the social dimension (Ramos Huarachi et al., 2020); and Life Cycle Cost Assessment (LCCA), describing the economic dimension (Illankoon and Lu, 2019). As such, LCSA can be represented in an equation form as follows (Guinée, 2016; Llatas et al., 2020):

$$\mathrm{LCSA} = \mathrm{LCA} + \mathrm{LCCA} + \mathrm{SLCA} \tag{2.1}$$

Zhou et al. (2007) primarily introduced LCSA, where he discussed climate change, resource depletion, and integration with LCCA (Zhou et al., 2007). LCSA is still a comparatively new system and needs further development with case studies and methodological developments (Guinée, 2016). One of the main challenges in using LCSA is the difficulty of integrating the interrelationships between the three dimensions (environmental, economic, and social dimensions) of LCSA, resulting in decision-making toward proposing sustainability improvements for existing product systems (Hannouf and Assefa, 2018). Integrating the three pillars of sustainability in LCSA is still an emerging field. It needs additional case-study-based contributions in advancing it further (Sala et al., 2012a), and 'integrated assessment' may be utilized in a different context (Sala et al., 2012b). Various knowledge-based decision support systems (KBDSS) have been used with LCSA to evaluate the sustainability performance of different alternatives and select the most suitable option (Hannouf and Assefa, 2018).

2.7 Life Cycle Assessment (LCA)

The term 'life cycle assessment' (LCA) refers to a broad technique for quantitatively evaluating a product's material, energy inputs and outputs, and environmental impacts over its entire life cycle (Sharma et al., 2011). It considers all building stages' cradle-to-grave and life cycle contributions from manufacturing, construction, operation, maintenance, disposal, and end-of-life (Islam et al., 2015a; Marszal and Heiselberg, 2011; Ramesh et al., 2010; Stazi et al., 2012). In the standards ISO 14040 and ISO14044, LCA is defined as 'a technique for assessing the environmental aspects and potential impacts associated with a product, by: compiling an inventory of relevant inputs and outputs of a product system; evaluating the potential environmental impacts; and interpreting the results of the inventory analysis and impact assessment phases' (ISO 14040, 2006; ISO, 2006; ISO 14044, 2006; Klüppel, 2005).

LCA considers all phases in a process, product, or system's life, from raw material extraction, processing, transportation to site, installation, use, removal, and recycling or disposal (Russell-Smith and Lepech, 2015). The system boundary of a whole life-cycle analysis is known as 'cradle to grave,' and analysis including the impacts beyond end-of-life is known as the 'cradle to cradle' approach. In the case of building construction, these different stages include the raw material extraction for the various assembly components of the building (i.e., limestone mining and calcination for cement), the manufacturing, transport to site, construction and installation, the building's operational life, maintenance and retrofitting, and at the end of life, its demolition (Russell-Smith and Lepech, 2015). Figure 2.5 shows the system boundary of different LCA stages of the building.

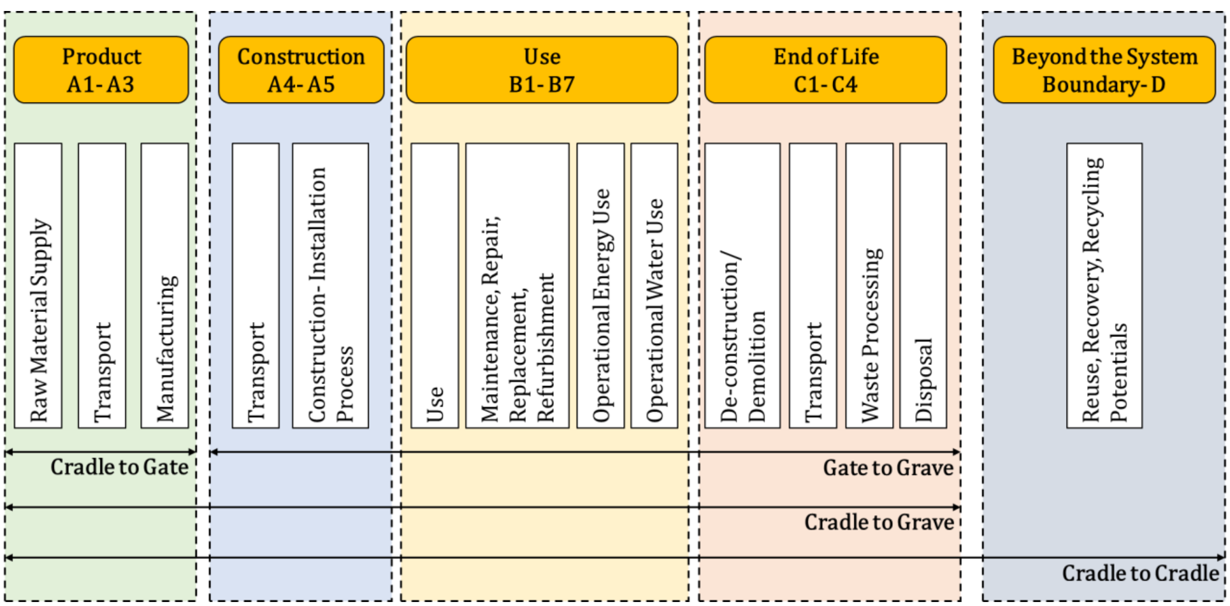


Figure 2.5. LCA stages of building (Sartori et al., 2021)

2.8 Life Cycle Cost Analysis (LCCA)

Life cycle cost analysis (LCCA) is a tool that helps the owner and stakeholders determine the most cost-effective solution (Hajare and Elwakil, 2020). Life cycle costing has been used in many studies to assist decision-making in building construction (AbouHamad and Abu-Hamd, 2019). In the ISO 15686-5 standard, LCCA is defined as ‘a methodology for the systematic economic evaluation of life-cycle costs over a period of analysis, as defined in the agreed scope. Life-cycle costing can address a period of analysis that covers the entire life cycle or (a) selected stage(s) or periods of interest thereof’ (ISO 15686, 2017). Life cycle cost analysis is also defined as 'a method of determining the entire cost of a structure, product, or component over its whole life' (Hajare and Elwakil, 2020).

LCCA considers all costs associated with the life cycle building stages, including initial costs, operating costs, maintenance costs, and end-of-life costs, as well as any residual value (removal, resale, and salvage value) throughout the life period (AbouHamad and Abu-Hamd, 2019; Islam et al., 2015b). It performs economic assessments by comparing the relative cost-effectiveness of various building construction methods. LCCA is particularly beneficial for comparing the costs and advantages of several alternative designs to determine which has the lowest life cycle cost and is more cost-effective in the long run (AbouHamad and Abu-Hamd, 2019).

The aim of LCCA on buildings is to estimate costs throughout their whole life cycle, which may then be utilized as input into a decision-making or evaluation process. However, because of the variable time value of money, charges incurred during different stages of the building's lifetime cannot be directly combined. Economic assessment tools, such as the Net Present Value (NPV) technique, are commonly used for LCC studies on buildings that are required to achieve this goal (Schade, 2006). Despite the increase of LCC assessments on constructions, which are largely connected to the cost-optimal approach, the building sector's acceptance and use of this technique are still limited (Marszal and Heiselberg, 2011; Uygunoğlu and Keçebaş, 2011).

2.9 Social Life Cycle Assessment (SLCA)

Social Life Cycle Analysis (SLCA) is a social (existing and potential) impact analysis technique that aims to evaluate the social and socio-economic aspects and their positive and negative impacts throughout the life cycle of a product. That includes raw material extraction and processing, manufacturing, distribution, use, re-use, maintenance, recycling, and final disposal (Macombe et al., 2011; Sonnemann and Valdivia, 2014). With the publication of the Guidelines for SLCA for Products and Services in May 2009, the field of SLCA has developed rapidly in recent years (UNEP, 2009). The proposed framework follows the ISO 14040 and 14044 standards for Life Cycle Assessment but has been modified to account for social aspects. According to the Guidelines, SLCA is defined as a "method that tries to examine the social and socio-economic elements of products, as well as their potential positive and negative consequences throughout their life cycle" (UNEP, 2009).

Since many social indicators are not quantifiable, qualitative ranking and scoring are utilized with quantitative data (Kloepffer, 2008). The question of generic versus site-specific data collection and variability in the perception of social impacts make this system complex to assign weightage and integrate into a decision support tool (Jørgensen et al., 2008). Kloepfffer (2008) also argued that quantifying the indicators is the most challenging part of SLCA. Other problems of SLCA seem to be correctly quantifying the impacts, quantitatively relating existing indicators to the system's functional units, choosing appropriate indications from many options and determining a way to measure that, etc. (Jørgensen et al., 2008; Kloepffer, 2008).

Petti et al. (2018) conducted a systematic literature review and examined 35 case studies on SLCA and concluded that local employment was considered to have the most significant positive impact with a percentage of 21%, followed by 13% for improved health and safety; 11% for increased economic development; 5% for better working conditions, increased consumer privacy, and technology development; and 3% for decreased child labour and increased freedom of incorporation. Increased revenue, cooperative contracts, diversity, psychological working conditions, social acceptability, enhanced physical area reputation, improved environmental impacts, and access to information accounted for the remaining 24% of positive effects (Petti et al., 2018).

2.10 Project Delivery Methods and Integrated Project Delivery (IPD)

The term "Project Delivery Method" refers to all contractual relationships, roles, and responsibilities between the parties participating in a project (Touran et al., 2009). According to the Texas Department of Transportation, "a project delivery method equates to a procurement method and defines the relationships, roles, and activities of project team members, as well as the sequences of activities required to complete a project. A contracting strategy is a specialized procedure used to give tools for bidding, managing, and specifying a project under the broader banner of a procurement method" (El Wardani et al., 2006). A delivery method identifies the primary parties taking contractual responsibility for the performance of the work. Thus, different project delivery methods are distinguished by how the owners, designers, and builders are formed and the technical relationships among parties within those contracts (Touran et al., 2009).

Design Bid Build (DBB) is the traditional project delivery method. In this method, an owner retains a designer to furnish complete design services and then advertises and awards a separate construction contract based on the designer's completed construction documents (Touran et al., 2009). The owner is responsible for the design details and warrants the quality of the construction design documents to the construction contractor. DBB is associated with superior understanding in the design and construction fields. All qualified designers are eligible to compete for the design. Furthermore, all constructors who can provide the necessary bonds and meet regulatory prequalification conditions are eligible to compete. Subcontractors in the design and construction sectors can compete with few constraints (Ibbs et al., 2003).

CMR (Construction Manager at Risk) projects are defined by a contract between an owner and a construction manager responsible for the project's final cost and duration. The owner permits the construction manager to conduct the construction phase and provide feedback during design development in this agreement. CMR's goal is to provide expert management of all stages of a project's life cycle to an owner whose company may lack those capabilities (Touran et al., 2009). Typically, CMR contracts include a clause specifying a guaranteed maximum price (GMP) above which the owner is not responsible for payment. These contracts frequently include incentive provisions allowing the CMR and the owner to split any cost savings below the GMP (Wiss et al., 2000).

Design-build is a project delivery method where the owner contracts for design and construction services from a single legal entity designated as the design-builder under one contract. Instead of DBB invitation-forbid procedures, this technique often uses request for qualifications (RFQ)/ request for proposal (RFP) procedures. The DB process has several types, but they all have three fundamental elements in common. First, the owner creates an RFQ/ RFP that outlines the project's most essential performance requirements. Secondly, proposals are scrutinized. Finally, the owner needs to go through some procedures to award contracts for both design and construction services once the review is complete. The DB entity provides a firm, fixed price in its proposals and is responsible for all design and construction expenditures (El Wardani et al., 2006; Ibbs et al., 2003). DB method has several variations. Design-build-operate-transfer, design-build-operate-own (sometimes called lease-back), and DBOM (design-build-operate-maintain) require the DB contractor to remain with the project after completion (Touran et al., 2009; Wiss et al., 2000).

Integrated Project Delivery (IPD) is a relatively new project delivery method. IPD aims to improve efficiency, reduce risks and waste through the collaborative construction process (AIA, 2007). In this method, all project stakeholders are involved from the beginning to align their goals and incentives through shared risk and rewards, which ultimately leads to the increased efficiency of this PDM. Since IPD is a team-based approach, it requires all parties to be open, trustful, and collaborative. Unlike other traditional project delivery methods where there is a linear and distinct process, IPD is concurrent and multi-level, with all the information openly shared. Despite being around for years, it was not till recently that the IPD method started receiving recognition in the construction industry. The merging of innovative technology allows information to be shared and received instantly by all stakeholders. In addition, different media platforms and new software enable all team members to meet whenever and wherever. Advanced technology has made the concept of IPD to be feasible. In IPD, all parties, including the owner, the designer, and the contractor, are bound together through a joint agreement. Each party is compensated through one or a combination of three methods: cost reimbursement to cover costs, the incentive for reducing project costs, and rewards for accomplishing project goals. A project team under IPD can only be imagined as members of one entity. The best available person fills each position in this specific IPD project team from any primary parties (AIA, 2007).

Compared to other traditional project delivery methods, IPD contributes more towards sustainability by integrating all stakeholders from the initial stage of the project. In the case of conventional PDMs, contractors and manufacturers are involved in the project after the project's design phase. Thereby traditional construction processes tend to incur more costs from rework resulting from miscoordination, quality issues, the inefficiency of project delivery times, poor performance and client dissatisfaction with the product delivered (Elghaish et al., 2020). Each of these conditions creates more waste during the work's execution phase, causing a negative impact on sustainability. Many researchers have proved that the IPD is a more effective project delivery system than others, and it is designed to better team integration in project delivery. IPD is more sustainable as it seeks to improve the triple constraint (cost, time, and quality) outcomes by aligning the project team goals and applying a shared risk and reward system (Hall and Scott, 2019). Elghaish et al. (2020), in their paper, focused on the cost management component of IPD projects. Their team identified that one of the major benefits of using IPD is establishing a sustainable relationship among built environment practitioners (Jones, 2014). Researchers also proved that IPD has been successful in minimizing defects associated with dimensional and geometric variations, improving the energy efficiency of the structures, bridging the gap between client expectations and the final product, and reducing costs through the collaboration of all parties since the initial stage. Each of the factors adds value to achieving more sustainability in construction.

2.11 Summary of Literature Review

The core concept of sustainable development includes prudent use of natural resources, ensuring increasing economic growth levels, reducing unemployment rates, providing adequate protection of the environment, and assuring increased social progress that recognizes the needs of everyone. The triple bottom line concept focuses not only on the economic value, as do most of the single criterion technique, but also on the environmental and social values of development. Several researchers argued that technical performance should be explicitly included as a pillar of infrastructure sustainability theory and proposed four pillars (environmental, technical, economic, and social) as the essential analytic elements of sustainability theory for civil infrastructure. Technical sustainability, the fourth pillar, deals with the factors related to a building's or structure's performance, quality, and service life. Sustainable development is gradually getting more attention in construction due to the growing resource constraints, involvement of an increased number of stakeholders, and the balanced requirements of environmental, economic and social objectives. According to different studies, building and construction account for 36% of global energy use and 37% of energy-related CO_2 emissions over their lifespan (construction, operation, maintenance and demolition). This poor performance warns the construction industry of extreme concern about reducing negative impacts and improving global sustainability.

There can be different sets of sub-criteria for assessing the technical, economic, social, and environmental pillars of sustainable construction based on the type and nature of the construction projects. The selection of sub-criteria also depends on the user's preferences. To finalize the list of sub-criteria appropriate for this research, we seek the opinion of several industry experts and academic researchers. The ultimate list of sub-criteria for assessing the most sustainable structural material for multistory building construction, along with the evaluation method, is given in Table 2.8. However, this list is not applicable for all cases, and users can modify it according to the location and nature of the projects and the preferences of the stakeholders.

Table 2.8. List of sub-criteria, including the evaluation methods

Criteria	Sub-Criteria	Type	Evaluation Method
Technical	Durability (Life expectancy)	Qualitative	User input
	Constructability (Ease of construction)	Qualitative	User input
	Maintainability (Ease of maintenance)	Qualitative	User input
	Resistance to water and weather	Qualitative	User input
Economic	Material cost	Quantitative	Market Analysis/ ATHENA
	Construction cost	Quantitative	Market Analysis/ ATHENA
	Maintenance cost	Qualitative	User input
	End of life cost	Quantitative	LCCA/ ATHENA
Social	Job opportunity creation	Qualitative	User input
	Fire resistance and safety	Qualitative	User input

	Skilled labor availability	Qualitative	User input
	Compatibility with local heritage	Qualitative	User input
Environmental	Greenhouse gas emission	Quantitative	LCA/ ATHENA
	Impact during manufacturing	Qualitative	User input
	Impact during construction	Qualitative	User input
	Recycle and reuse potential	Qualitative	User input

In building construction practices, the commonly used structural materials are RC, SS, RM, and timber. RC is the most often used for its strength, durability, reflectivity, and adaptability. However, ironically, concrete is one of the leading sources of environmental degradation and is harmful to the ecosystem and environment. This phenomenon has led to concerns about looking for alternatives in building construction materials to achieve sustainability. Steel may replace concrete in structural construction; however, it needs a lot of energy in its manufacturing process and might be expensive in some situations. Masonry is a time-tested alternative to concrete construction, albeit burned bricks may emit significant levels of carbon during the manufacturing process, and masonry construction requires a substantial amount of cement. Architects, builders, and sustainability advocates have recently been buzzing about timber as a building material. They believe that timber can significantly reduce greenhouse gas (GHG) emissions in the building sector and reduce waste, pollution, and construction costs.

Although green buildings and sustainable buildings are commonly used interchangeably, they have significantly different connotations in practice. The primary focus of the green building is on the environment, whereas sustainable buildings consider the technical, economic, social, and environmental pillars of sustainability during all phases of the building's lifecycle. Green building emphasizes its requirements in resource conservation, environmental protection, and pollution reduction in each step of construction, often neglecting the social and economic aspects, which is also significant for long-term sustainability. The Green Building Rating System (GBRS) is a tool to assess and recognize buildings that meet predefined green and sustainability requirements or standards. Many of these evaluation systems have often been criticized for emphasizing environmental factors and ignoring the importance of the other sustainability pillars.

Traditionally, material selection in projects is based on satisfying technical requirements or economic aspects, such as material strength and price, without considering the life cycle impact associated with the material. The Life Cycle Sustainability Assessment (LCSA) aims to evaluate and combine three main processes: Life Cycle Assessment (LCA), representing the environmental dimension; Social Life Cycle Assessment (SLCA), representing the social dimension; and Life Cycle Cost Assessment (LCCA), describing the economic dimension.

Multi-criteria decision-making (MCDM) has been extensively used in construction to select the best possible option from several alternatives. The MCDM techniques generate alternative scenarios, establish criteria, assess alternatives, weigh the criteria, and rank the alternatives. Since the evaluation of criteria involves a variety of opinions and meanings, each criterion is not of equal importance. The weights of criteria reflect their relative importance in the decision-making process. MCDM methods range from a single approach (such as AHP or Fuzzy Sets) to a combination of the methods, also known as the hybrid approach (such as Fuzzy sets + TOPSIS, AHP + TOPSIS in Fuzzy environment, AHP + ELECTRE + Fuzzy sets, AHP + VIKOR, etc.).

In the case of traditional Project Delivery Methods, contractors and manufacturers are involved in the project after the project's design phase. Thereby traditional construction processes tend to incur more costs from rework resulting from miscoordination, quality issues, the inefficiency of project delivery times, poor performance and client dissatisfaction with the product delivered. In contrast, IPD (Integrated Project Delivery) contributes more towards sustainability by integrating all stakeholders from the initial stage of the project. It is more sustainable as it seeks to improve the triple constraint (cost, time, and quality) outcomes by aligning the project team goals and applying a shared risk and reward system.

2.12 Identification of Research Gap and Area Chosen for this Research

From the findings of the literature reviews, it is identified that numerous works have been done on the selection of building materials, sustainability indicators of materials, sustainability analysis of energy efficiency of green buildings, etc. Construction of buildings is one of the most significant works in this sector, among which low to mid-rise multistory buildings are the most prominent. So far, none of the works integrated the inputs of all stakeholders, i.e., owner, design team and constructions in the IPD framework from the project's inception to decide on the most preferred sustainable option. Besides, although several researchers argued that the technical pillar is an essential analytic element of sustainability assessment for civil infrastructure, there is hardly any work that systematically integrates the technical pillar with economic, social, and environmental pillars to analyze the overall sustainability aspects. From the interview with several industry experts, it was also identified that the decision on selecting structural material is commonly taken considering technical and economic factors. There is no structured tool to integrate all stakeholders' opinions or assess the overall aspects of sustainable construction in the selection process.

Therefore, developing an MCDM model (i.e., DSS) that combines the preferences of all stakeholders for choosing the most sustainable structural material and assessing the four pillars of sustainable construction is still lacking. This research aims to develop an MCDM model that will integrate all stakeholders' preferences into an IPD framework for selecting the most sustainable structural material from the technical, economic, social, and environmental sustainability points of view. The academia shall benefit from integrating technical aspects with the commonly used three pillars in a methodic approach. The industry shall be benefited from the MCDM model, helping to select the most sustainable alternative.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter discussed the methodologies and calculation sequences used in this research. It started with the research framework and afterward discussed the hierarchy of decision problems, calculation methodologies associated with Fuzzy AHP, decision matrix, Fuzzy TOPSIS and Fuzzy VIKOR. Subsequently, it highlighted the use of computer applications for computation and the development of DSS software.

3.2 Research Framework

The details of the research framework are shown in Figure 3.1.

3.3 Assumptions and Considerations

This study considered four alternative options of structural materials (reinforced concrete, structural steel, reinforced masonry, and timber) and sixteen evaluation criteria taking four from each pillar of sustainable construction as mentioned in Table 2.8. The weightage of criteria was calculated using Fuzzy AHP with a trapezoidal membership function. Fuzzy TOPSIS and Fuzzy VIKOR were used to rank the alternatives using the weightage obtained through Fuzzy AHP.

During data collection, it was felt that for Fuzzy AHP, inconsistency in pairwise comparison increases once the number of criteria is more. In most cases, users had to modify their responses several times to bring consistency of inputs. Therefore, a decision matrix was developed to assign the weightage of criteria and to rank the alternatives using the similar techniques mentioned above. This step aimed to compare the results obtained through two different approaches.

Fuzzy TOPSIS was used to develop the DSS software out of two ranking methods. Comparing the weightage of criteria derived through Fuzzy AHP and the decision matrix, the software used the decision matrix to compute the weightage.

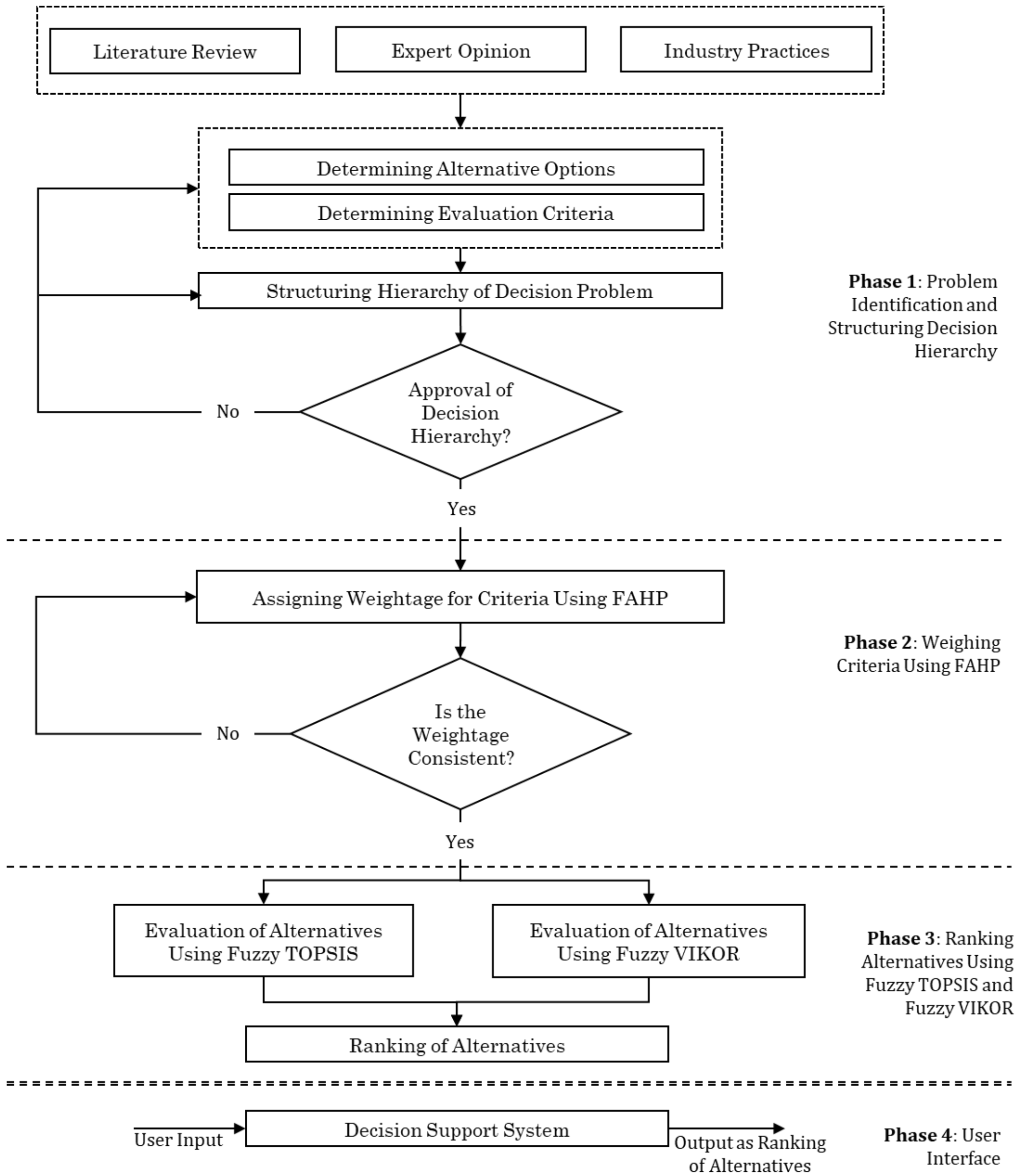


Figure 3.1. Research framework

3.4 Hierarchy of Decision Problem

The hierarchy of the decision problem is shown in Figure 3.2.

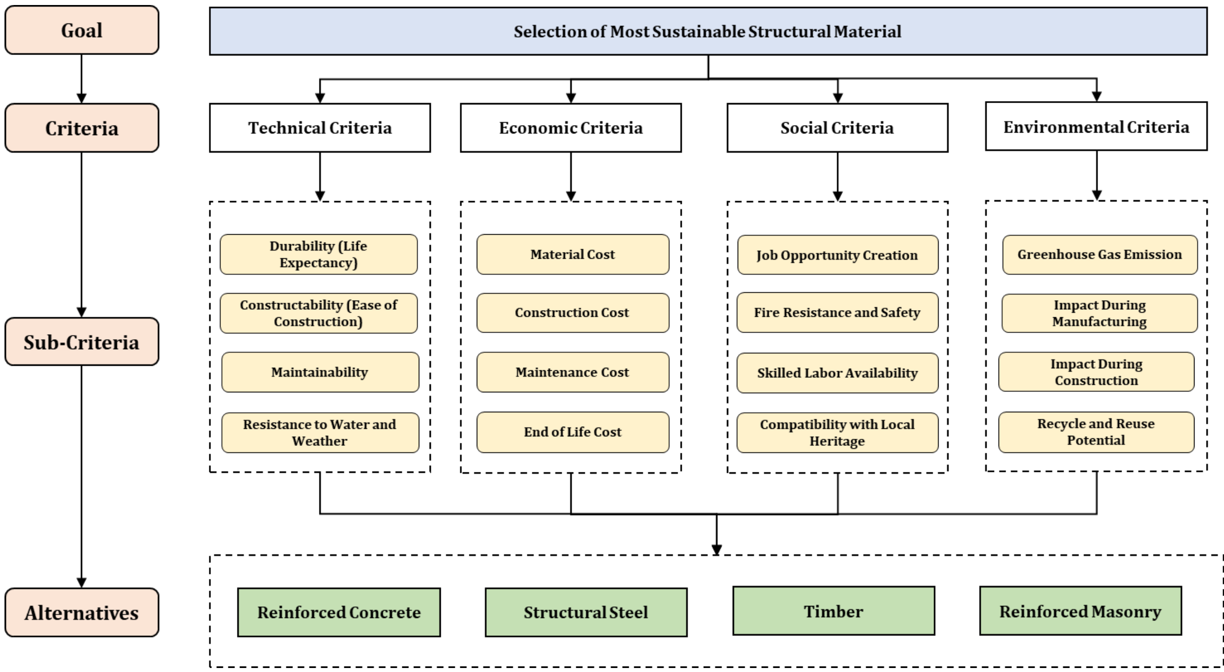


Figure 3.2. Hierarchy of decision problem

3.5 Description of Selected Criteria and Measurement Techniques

From the literature review, it is observed that researchers have used different sets of sub-criteria (i.e., sustainability evaluation criteria) based on the type and nature of the construction projects. The user's preferences also influence the choice of evaluation criteria. Therefore, we consulted with several industry experts and academic researchers to finalize the list of sub-criteria for choosing the most sustainable structural material. Details of that process have been discussed in Section 2 of Chapter 2. Finally, a total of 16 evaluation criteria were selected for the sustainability assessment of this study, which are explained below:

3.5.1 Durability (Life Expectancy): With proper maintenance, a structure's durability is described as its capacity to stay fit for its intended or anticipated usage over its design working life (Akadiri et al., 2013; Minhas and Potdar, 2020). For different structural materials, it may be measured at a specific time. However, this is a qualitative beneficial assessment derived from user input based on their experience and research.

3.5.2 Constructability (Ease of Construction): "Constructability" refers to how easily and efficiently structures can be built. The more simply a construction can be built, the less expensive it will be. Ease of construction equates to higher cost-effectiveness, which is always desirable from an economic standpoint (Fazeli et al., 2019; Sahlol et al., 2021). In this study, it is also referred to as qualitative beneficial feedback based on user input.

3.5.3 Maintainability (Ease of Maintenance): Maintainability is a factor that goes into the design of a building system, ensuring that maintenance tasks are simple, accurate, safe, and cost-effective. The goal of maintainability is to make maintenance more effective and efficient. It is often contrary to construction costs (Sahlol et al., 2021; Yang and Ogunkah, 2013). Over its life cycle, a less expensive building material may incur higher maintenance costs. This criterion is also considered qualitative beneficial information and is based on user input.

3.5.4 Resistance to Water and Weather: It is usually desirable for a structure to be strongly resistant to water and other weather effects. Weather resistance refers to a material's capacity to withstand corrosion, material loss, or further degradation due to extended exposure to extreme environmental and weather conditions (Kappenthuler and Seeger, 2020). Water and weather effects may substantially impact a building's structure, reducing its life cycle and increasing maintenance costs. It is a qualitative beneficial criterion that is evaluated qualitatively based on user input.

3.5.5 Material Cost: The cost of the material is a significant consideration when choosing structural material for a building. The expenses of purchasing the materials required for building construction are known as material costs. This criterion includes the cost of purchasing essential raw materials and semi-finished goods (Akadiri et al., 2013; Figueiredo et al., 2021). It may be quantified and included in the building's Life Cycle Cost Analysis (LCCA). The cost of materials is estimated quantitatively in this study using Alberta, Canada rates using ATHENA software for estimating.

3.5.6 Construction Cost: The cost of construction includes both the cost of materials and the cost of labor (Danso, 2018; Minhas and Potdar, 2020). Here, a general estimate is made to determine the cost of building for each of the various materials. It is a quantitative cost criterion that's part of the LCCA and measured based on the research location, i.e., Alberta, Canada, using ATHENA software.

3.5.7 Maintenance Cost: Any cost required to keep the structural materials in good working order is referred to as maintenance cost. These costs might be utilized for general item maintenance or material degradation remedies. These costs are in addition to the structures' actual construction costs and are subject to growth exponentially (Akadiri et al., 2013; Kaya and Kahraman, 2011). It is also an essential component of the LCCA assessing the total cost of the structure over its total life cycle. It is assessed subjectively and evaluated using user feedback based on their knowledge and expertise.

3.5.8 End of Life Cost: It is also a part of the LCCA process. The materials must be disposed of when the structure's life cycle has concluded, which incurs costs. The materials can subsequently be reused or recycled, resulting in revenue. The net cost at the end of life is calculated and utilized as a positive criterion in this study (Kamali and Hewage, 2015; Minhas and Potdar, 2020). If the value is high, the structures are likely to produce more revenue after the end of the life of the structure. It is a quantitative beneficial input.

3.5.9 Job Opportunity Creation: It refers to creating jobs that support long-term development goals. Another way, it can be defined as creating jobs that support economic growth, social inclusion, and environmental protection (Danso, 2018; Kaya and Kahraman, 2011). It is a crucial social beneficial criterion for long-term growth, and this is assessed qualitatively based on user feedback.

3.5.10 Fire Resistance and Safety: Fire safety is crucial and necessary for building structures to avoid and safeguard against damage caused by fire. Fire safety lowers the danger of harm and property damage caused by fires. It is a social criterion that gives residents a sense of security and dependability (Akadiri et al., 2013; Sahlol et al., 2021; Yang and Ogunkah, 2013). It also applies to other threats such as earthquakes, tornadoes, and other natural disasters. It can be determined through qualitative feedback based on user input.

3.5.11 Skilled Labor Availability: Sustainable construction depends on skilled labour. Various studies show that the inclusion of skilled labor works positively toward sustainability by indirectly achieving economic, social justice and environmental protection. It is measured from the user input from their experience (Akadiri et al., 2013; Sahlol et al., 2021).

3.5.12 Compatibility with Heritage: Culture and cultural heritage can help achieve inclusive and long-term development. Tradition, which is built on long-term or time-tested practices consistent with the environment, economy, and society, is required to ensure social sustainability (Josiah Marut et al., 2020; Yang and Ogunkah, 2013). It is a qualitative beneficial criterion that relies on user input from experiences.

3.5.13 Greenhouse Gas Emission: The building sector must cut greenhouse gas emissions to safeguard the environment. The construction industry is a significant source of CO_2 emissions into the atmosphere, and it ought to be as low as feasible (Josiah Marut et al., 2020; Miller and Ip, 2013; Solangi et al., 2019). The ATHENA program is used to quantify it in this study.

3.5.14 Impact During Manufacturing: The manufacturing process of construction materials for building structures significantly impacts the environment locally and worldwide. The mining processes used to get materials, the transportation of these resources from around the world to the construction site, and the waste collection and disposal procedure that follows the project's completion all have clear environmental consequences (Kappenthuler and Seeger, 2020; Minhas and Potdar, 2020). With the world changing so quickly, it is more vital than ever to understand how construction projects influence the environment and how we can measure and prevent that impact in the future. It is a qualitative cost criterion based on user feedback.

3.5.15 Impact During Construction: The construction of a new building structure can impact the environment in various ways. CO_2 emissions, for example, have a detrimental influence on the environment. Construction pollutes the air and water, and construction-related chemicals can be hazardous to employees and the environment. The construction of new infrastructure generates a great deal of waste, which ends up in landfills. The building process necessitates the combustion of fossil fuels, which emits greenhouse gases and affects the environment (Akadiri et al., 2013; Sahlol et al., 2021; Yang and Ogunkah, 2013). Newly erected structures use energy, which contributes to the negative environmental effect. It is a qualitative cost criterion that relies on user input from experiences.

3.5.16 Recycle and Reuse Potential: Buildings have a lifespan that may be separated into three phases: building, operation, and destruction (ATHENA, 2022). Since much of a large variety of materials is necessary for building construction, the construction phase of a structure necessitates a lot of energy and expenditure. During a structure's construction and demolition phases, a large amount of garbage is created. As a result of the numerous environmental consequences, dumping waste materials in landfills is neither cost-effective nor environmentally benign. As a result, it is critical to think about how a building's waste may be reused once it has served its purpose. Recycling and reusing waste materials minimizes the need for fresh new building materials and virgin, which positively influence the environment (Akadiri et al., 2013; Sahlol et al., 2021). It can be quantified; however, in this study, it is used as qualitative beneficial input based on the user's discretion.

3.6 LCA and LCCA

For the life cycle effect evaluation, this study used *Athena Impact Estimator (IE) for Buildings*, version 5.4. While other LCA tools are available for different parts of the world, ATHENA IE is the only North American tool for whole-building life-cycle assessment based on globally recognized LCA methodology (ATHENA, 2022; Reza et al., 2014). This technique has been used in LCA studies in Canada to evaluate the environmental implications of different building types and their structural systems (Reza et al., 2014; Van Ooteghem and Xu, 2012). The LCA technique employed in these investigations is based on ISO 14044

(ISO, 2006), which is a standard on LCA. Environmental footprint data is reported by Athena using the TRACI approach created by the US Environmental Protection Agency (ATHENA, 2022).

The system boundary is constructed for this study to assure the completeness of input and output variables of unit processes (Dara et al., 2019). Figure 3.3 depicts the study system's boundaries and fluxes. Raw materials and energy are examples of primary inputs. The ATHENA program offers a cradle-to-grave LCA of structures, which includes resource extraction, manufacture, construction, related transportation, maintenance, replacement impacts, building operation destruction, and disposal (ATHENA, 2022). The input parameters and other details are discussed in Chapter 4.

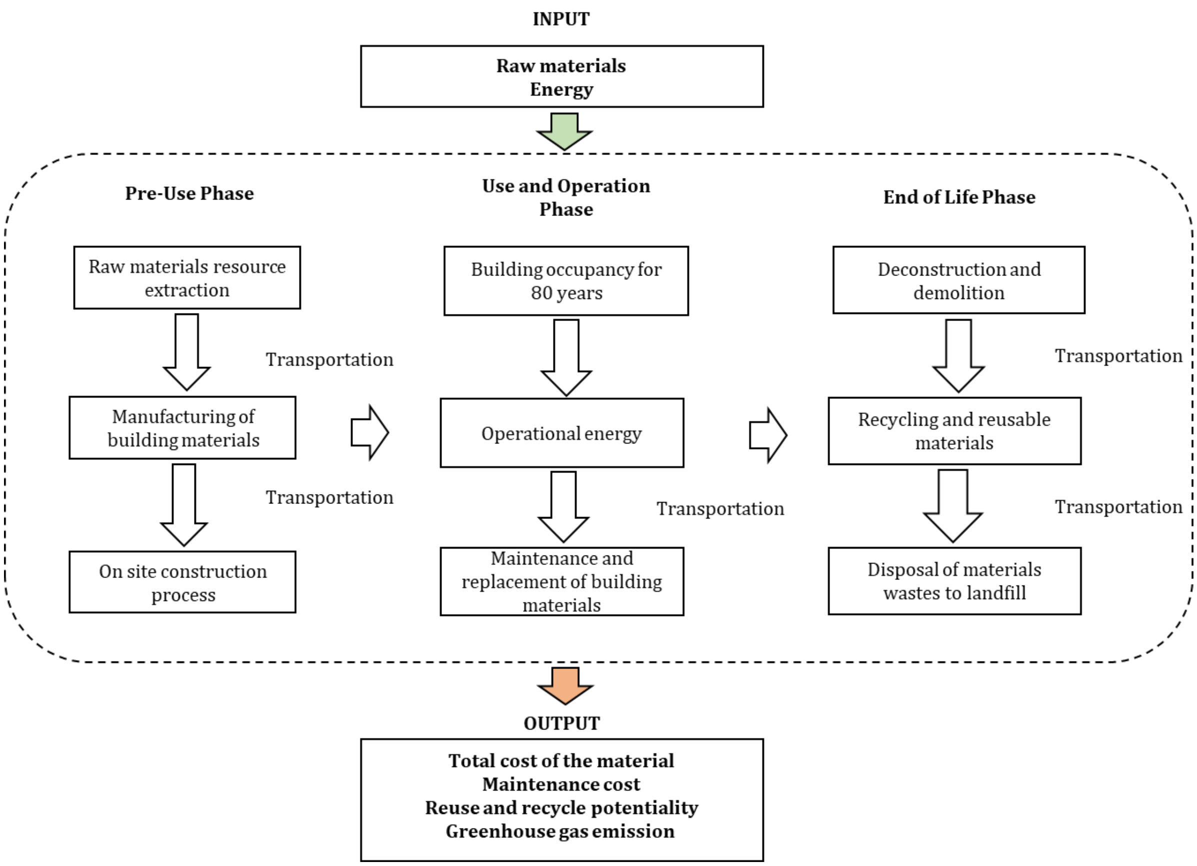


Figure 3.3. LCA and LCCA study system's boundaries and fluxes

3.6.1 Converting Objective Values into Subjective Inputs

This study generated a TOPSIS extension that integrates subjective and objective weight. The advantage of the developed approach is that it uses decision makers' experience and the tangible (numerical input) information from end users throughout the decision-making process. In addition to subjective weights determined by decision-makers, this study derived subjective weights from objective values using Shannon's entropy as a basis (Jost, 2006; Wang and Lee, 2009). The idea of information entropy demonstrates the significance of an evaluating characteristic that may successfully offset the impacts of subjective components. The creative method might offer a more comprehensive decision-making strategy.

Step 1: In order to determine objective weights by the entropy measure, the decision matrix needs to be normalized for each criterion ($C_j, j = 1,2 \ldots n;\ n$ =is the criteria number), to obtain the projection value p_{ij} of each criterion:

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

Step 2: After normalizing the decision matrix, we can calculate the Shannon diversity index as

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

Step 3: Now, the following equation is used to find out the Shannon Equitability Index or the entropy to measure the evenness of the values in particular criteria. The entropy value is denoted as e_j.

Where,

$$e_j = H/\ln(m), \tag{3.3}$$

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

Step 4: Now, the degree of divergence can be calculated as $d_j = 1 - e_j$. Higher the value of d_j higher the degree of divergence. Within the matrix, the criteria values containing a higher degree of divergence are considered for the range distribution of subjective values. Where maximum value is considered is very high and minimum value is considered very low. All other subjective values are distributed equally within the range. These range values are considered to transform all other criteria values of the matrix from objective to subjective one.

3.7 Fuzzy AHP (FAHP)

3.7.1 Background and Details

The Fuzzy Analytic Hierarchy Process is a fuzzy logic-based Analytic Hierarchy Process (AHP) approach. The fuzzy AHP approach is comparable to the AHP method. The Fuzzy AHP approach simply converts the AHP scale into a fuzzy triangular or trapezoidal scale that may be accessed directly for analysis purposes.

3.7.2 Analytic Hierarchy Process (AHP)

Saaty (1980) created a powerful and practical tool for handling qualitative and quantitative multi-criteria elements in decision-making. This approach included a variety of alternatives in the decision-making process and the ability to do sensitivity analysis on the following criteria and benchmarks. Furthermore, the paired comparisons facilitate judgements and computations and display the compatibility and incompatibility conclusions that result from multi-criteria decision-making (Lee, 2013). The AHP breaks down problems, groups them, and then arranges them in a hierarchical framework to solve them. This approach combines a comparison of criteria with a pre-determined measuring scale to identify priority criteria. The perception of experts or experts is the key input of the AHP approach; hence subjectivity plays a role in retrieval decisions. This technique also considers data consistency with inconsistent limitations (Reza et al., 2014).

3.7.3 Methodology for Calculating Criteria Weight with Fuzzy AHP

3.7.3.1 Define the Problem and Determine the Desired Solution

In the first stage, the hierarchical decision-making problem is organized. This stage is the same as it is in the conventional AHP technique. In this case, the problem must be described in terms of the criteria to choose the most sustainable structural material. The pillars of consideration for determining the most sustainable structural materials were technical, economic, social, and environmental. These four pillars of sustainability analysis were grouped into four criteria each, for a total of sixteen criteria to be compared, which are explained in Paragraph 3.5. The steps of the calculations are shown in Figure 3.4 and explained subsequently (Dağdeviren et al., 2009; Sirisawat and Kiatcharoenpol, 2018).

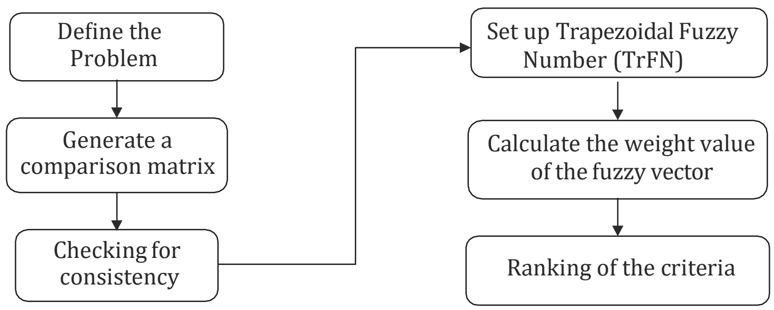


Figure 3.4: Fuzzy AHP process

Step 1: Generate a Comparison Matrix

We need to develop a comparison matrix once we have the details on the alternatives and the criteria by which they are to be assessed for the selection of sustainable materials. The matrix employed is simple, has a strong position for the consistency framework, acquires additional information as needed with all potential comparisons, and can assess the overall priority sensitivity for changes in consideration. The equations that define pairwise comparisons are given below:

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

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 of the i and j criteria.

$$
\begin{array}{l}
 \\
\text{Criteria 1} \\
\text{Criteria 2} \\
\text{Criteria 3} \\
\vdots \\
\text{Criteria n}
\end{array}
\begin{array}{c}
\begin{array}{ccccc}
\text{Criteria 1} & \text{Criteria 2} & \text{Criteria 3} & \cdots\cdots & \text{Criteria n}
\end{array} \\
\left|\begin{array}{ccccc}
1 & a_{1-2} & a_{1-3} & \dots & a_{1-n} \\
a_{2-1} & 1 & a_{2-3} & \dots & a_{2-n} \\
a_{3-1} & a_{3-1} & 1 & \dots & a_{3-n} \\
\dots & \dots & \dots & 1 & \dots \\
a_{n-1} & a_{n-2} & a_{n-3} & \dots & 1
\end{array}\right|
\end{array}
$$

Table 3.1. Pairwise comparison of criteria

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

After knowing the comparison of its criteria in Table 3.1, the next thing is to normalize the matrix. It is done by dividing each cell by the summation of that column value. Here,

$$x_{ij} = \frac{a_{ij}}{\sum a_{ij}} \tag{3.5}$$

Step 3: Developing Criteria Weightage

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

$$\tilde{a}_{ij} = \frac{1}{n}\sum x_{ij} \tag{3.6}$$

Step 4*: Checking for Consistency*

Saaty listed the values in a set to compare the consistency index (CI) with a random generator (RI) value (Saaty, 1977). This value is variable with the matrix order n. Consistency is expected to be close to perfect for one selection to be considered almost accurate. The formula used to determine consistency's value is shown below. The value of the eigenvector, the weighted value of the criteria, must first be determined. The following equation is used to calculate the eigenvector:

$$w_{cri-i} = \frac{1}{n}\sum \tilde{a}_{ij},\ \forall_i \tag{3.7}$$

Here, w_{cri-i} is the eigenvector, which is the sum of the matrix normalization values and is divided by the number of criterion (n). Now we have to find out the λ (lambda) value:

$$\lambda_{maks} = \frac{1}{n}\left[\frac{1}{w_{cri-i}} \sum w_{cri-i} \text{x}\, w_i\right] \tag{3.8}$$

After obtaining the maximum lambda value, the value of the Consistency Index (CI) can be determined.

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

Here, CI is the consistency index, and λ_{maks} is the largest eigenvalue of the n-order matrix. The matrix is consistent if CI equals zero (0). Suppose the calculated CI value is more than zero (CI> 0). In that case, it is necessary to evaluate Saaty's limit of inconsistency, utilizing the Consistency Ratio (CR), also known as the index value (i.e., comparison between CI and RI) (Table 3.2).

Table 3.2. Relative Index Value (Saaty, 1977)

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 chosen RI value complies with the order n matrix. It is acceptable to tolerate the inconsistency of each opinion if the CR of a matrix is smaller than 10% (0.1).

Step 5: Fuzzification

The given weights need to be fuzzified based on Table 3.3 given below:

Table 3.3. 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	$l_{12,}m_{12,}n_{12,}p_{12}$	$l_{13,}m_{13,}n_{13,}p_{13}$	...	$l_{1n,}m_{1n,}n_{1n,}p_{1n}$
Criteria 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: Fuzzified Normalized Weight and Global Ranking

Finally, Normalized Fuzzy weight are calculated as:

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,

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

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

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

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

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

3.8 Ranking of Alternatives with Fuzzy TOPSIS (Using Fuzzy AHP Weightage)

3.8.1 Outline

Multiple alternatives can be evaluated against the selected criteria using the fuzzy TOPSIS technique. The TOPSIS method selects the alternative closest to the Fuzzy Positive Ideal Solution (FPIS) and the farthest from the Fuzzy Negative Ideal Solution (FNIS). The best performance numbers for each alternative make up an FPIS, while the poorest performance values make up the FNIS. Details of calculations are explained in Paragraph 3.8.3, following the procedures explained by Dağdeviren et al. and Sirisawat and Kiatcharoenpol (Dağdeviren et al., 2009; Sirisawat and Kiatcharoenpol, 2018).

3.8.2 Subjective and Objective Weight

In this study, we present a TOPSIS modification that considers both subjective and objective weight. The suggested technique can utilize decision-makers' knowledge while involving end-users in the decision-making process. We use Shannon's entropy as a basis for normalizing the subjective weights of the criteria assigned by the decision-makers (Jost, 2006; Wang and Lee, 2009).

3.8.3 Details of Steps of Calculation

Step 1: Input Parameter (Preferences) from User

In this step, a matrix is formed comprising the preferences given by the users.

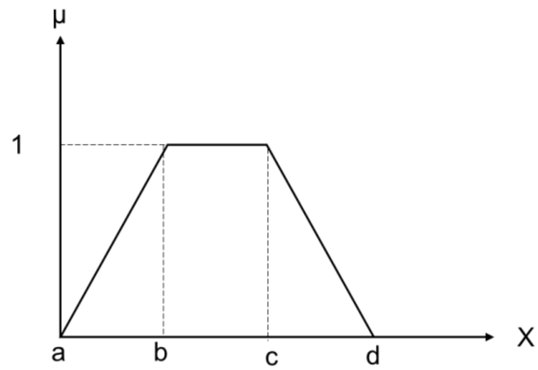
$$
\begin{array}{r c c c c}
 & \text{Alternative 1} & \text{Alternative 2} & \ldots\ldots\ldots\ldots\ldots & \text{Alternative n} \\
\begin{array}{r}\text{Criteria 1}\\ \text{Criteria 2}\\ \text{Criteria 3}\\ \vdots\\ \text{Criteria n}\end{array} &
\multicolumn{4}{l}{\left|\begin{array}{cccc}
High & High & \ldots & Medium \\
Low & Very\ Low & \ldots. & Low \\
Medium & Medium & \ldots\ldots & Medium \\
\ldots & \ldots & & \ldots \\
Very\ High & High & \ldots.. & \text{Very } Low
\end{array}\right|}
\end{array}
$$

Step 2: Set up Trapezoidal Fuzzy Number (TrFN) and Transform the User Input into Fuzzy Decision Matrix

In the FAHP scale, Trapezoidal Fuzzy Number (TrFN) has four boundary values a, b, c and d: the degree of membership increases between a and b, flattens between b and c with a degree of 1 (i.e., values between c and d fully belong to the category), then decreases between c and d (Figure 3.5). Each fuzzy set representing the categories described in Table 3.4 was represented by trapezoidal membership functions (Table 3.3 and Figure 3.6).

Table 3.4. 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



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

Figure 3.5. Four parameters describing the trapezoidal membership function

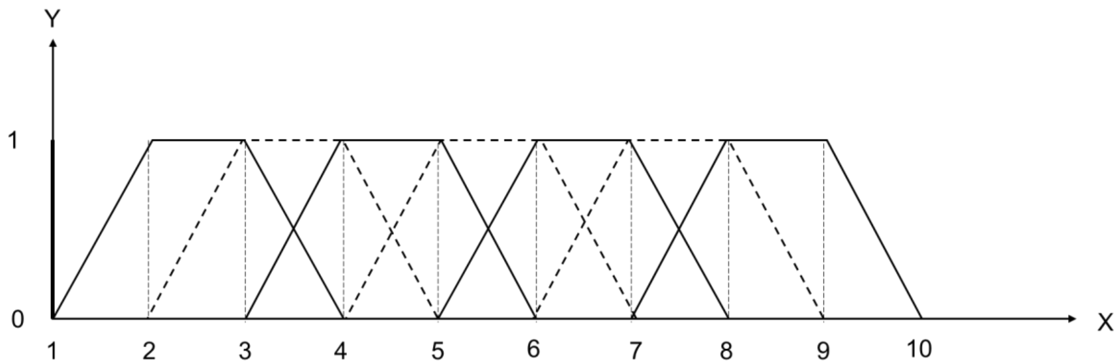


Figure 3.6. Trapezoidal membership functions

	Alternative 1	Alternative 2	....	Alternative m
Criteria 1	$a_{11},b_{11},c_{11},d_{11}$	$a_{12},b_{12},c_{12},d_{12}$	...	$a_{1m},b_{1m},c_{1m},d_{1m}$
Criteria 2	$a_{21},b_{21},c_{21},d_{21}$	$a_{22},b_{22},c_{22},d_{22}$	...	$a_{2m},b_{2m},c_{2m},d_{2m}$
Criteria 3	$a_{31},b_{31},c_{31},d_{31}$	$a_{32},b_{32},c_{32},d_{32}$	...	$a_{3m},b_{3m},c_{3m},d_{3m}$
:	...	...		...
Criteria n	a_{n1},b_{n1},c_{n1},d	$a_{n2},b_{n2},c_{n2},d_{n2}$	...	$a_{nm},b_{nm},c_{nm},d_{nm}$

Step 3: Calculation of the Combined Fuzzy Decision Matrix

After the AHP comparison value is transformed into the F-AHP scale value, a combined decision matrix is formed. The process of getting a fuzzy combined decision matrix value is shown using the equation of the following formula:

$$\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}, d_{ij}) \quad (3.11)$$

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

Step 4: Calculation of the Normalized Fuzzy Decision Matrix Based on Beneficial (Positive) and Cost (Negative) Criteria

Now we need to identify the benefit (positive) and cost (negative) criteria and compute 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 decision matrix is normalized using the following equation:

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

Step 5: Normalized Fuzzy Decision Matrix Based on Single User's Input

Then the matrix value is multiplied by the fuzzy normalized weight of each criterion obtained from Fuzzy AHP.

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

Step 6: Deriving Fuzzy Ideal Solution; Fuzzy Positive Ideal Solution (FPIS), and Fuzzy Negative Ideal Solution (FNIS)

Now from the matrix, Fuzzy ideal solutions are obtained by:

Fuzzy Positive Ideal Solution (FPIS):

$A^* = (\tilde{u}^*{}_1, \tilde{u}^*{}_2, \tilde{u}^*{}_3, \ldots\ldots \tilde{u}^*{}_n)$, where $\tilde{u}^*{}_j = \max_i\{u_{ij(4)}\}$ (3.16)

Fuzzy Negative Ideal Solution (FNIS):

$A^- = (\tilde{u}^-{}_1, \tilde{u}^-{}_2, \tilde{u}^-{}_3, \ldots\ldots \tilde{u}^-{}_n)$, where $\tilde{u}^*{}_j = \min_i\{u_{ij(1)}\}$ (3.17)

Step 7: Distance from FPIS and FNIS

Now the distance from each alternative is calculated using the following formula:

$$d(\tilde{x},\tilde{y}) = \sqrt{\frac{1}{4}[(a_1-a_2)^2 + (b_1-b_2)^2 + (c_1-c_2)^2 + (d_1-d_2)^2]} \tag{3.18}$$

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

$$CC_i = \frac{d_i^-}{d_i^- + d_i^*}\ ;\ d_i^* = \sum_{j=1}^{n} d(\tilde{u}_{ij}, \tilde{u}^*_j) \text{ and } d_i^- = \sum_{j=1}^{n} d(\tilde{u}_{ij}, \tilde{u}^-_j) \tag{3.19}$$

The higher value of the CC_i gets the higher ranking order.

Step 9: Ranking and Selection of Decisions

For the number of members (N) in a team, the combined decision is calculated as

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

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

3.9 Ranking of Alternatives with Fuzzy VIKOR (Using Fuzzy AHP Weightage)

3.9.1 Outline: Fuzzy VIKOR

VIKOR method includes a multi-criteria optimization of complex systems that focuses on ranking and selecting from a set of alternatives among conflicting criteria. Its role is to find a multi-criteria ranking index based on a particular measure of closeness to the ideal solution (Opricovic and Tzeng, 2004). It helps solve MCDM problems with two advantages: it provides a maximum group utility of the majority and a minimum of the individual regret of the opponent (Opricovic and Tzeng, 2002). The compromise ranking of VIKOR has several steps, which are discussed below (Opricovic and Tzeng, 2004; Shemshadi et al., 2011).

3.9.2 Steps of Calculation

Step 1: The input parameters are assessed, and weighted beneficial (positive) and cost (negative) criteria are chosen.

	Alternative 1	Alternative 2	....	Alternative n	Positive/Negative	Weightage
Criteria 1	*High*	*High*	...	*Medium*	Positive	X1
Criteria 2	*Low*	*Very Low*	....	*Low*	Positive	X2
Criteria 3	*Medium*	*Medium*	......	*Medium*	Negative	X3
:	...	...		...	......	
Criteria n	*Very High*	*High*	.....	Very *Low*	Negative	Xn

Step 2: Linguistic terms are converted into Fuzzy Scale as shown in Table 3.5 below:

Table 3.5. Linguistic expression vs quantitative scale

Linguistic Expression	Quantitative Scale
Very High	7,8,9,10
High	5,6,7,8
Medium	3,4,5,6
Low	1,2,3,4
Very Low	1,1,1,1

Step 3: The importance of the decision makers' judgement is determined, and their weights for each criterion are computed.

	Importance Factor	Criteria 1	Criteria 1	....	Criteria m
DM 1	X_1	$S1$	$T1$	...	$Z1$
DM 2	X_2	$S2$	$T2$	...	$Z2$
:		...	...		...
DM n	X_n	Sn	Tn	...	Zn

Step 4: Generation of combined decision matrix of the team.

The process of getting a fuzzy combined decision matrix value is shown using the equation of the following formula:

$$\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}, d_{ij}) \tag{3.21}$$

Where, $a_{ij} = \min_k\{a^k{}_{ij} \text{x } importance\ factor^k\}$,

$$b_{ij} = \frac{1}{K}\sum_{k=1}^{k} b^k{}_{ij} \text{x } importance\ factor^k,$$

$$c_{ij} = \frac{1}{K}\sum_{k=1}^{k} c^k{}_{ij} \text{x } importance\ factor^k,$$

$d_{ij} = \max_k\{d^k{}_{ij} \text{ x } importance\ factor^k\}$,

Step 5: Now, both the benefit (positive) and cost (negative) criteria are identified, and the normalized fuzzy decision matrix is computed as:

$$\tilde{r}_{ij}= (\frac{a_{ij}}{c^*{}_j}, \frac{b_{ij}}{c^*{}_j}, \frac{c_{ij}}{c^*{}_j}, \frac{d_{ij}}{c^*{}_j});\ c^*{}_j=\max_i\{c_{ij}\}, \text{ benefit criteria} \tag{3.22}$$

$$\tilde{r}_{ij}= (\frac{a^-{}_j}{a_{ij}}, \frac{a^-{}_j}{b_{ij}}, \frac{a^-{}_j}{c_{ij}}, \frac{a^-{}_j}{d_{ij}});\ a^-{}_j=\min_i\{a_{ij}\}, \text{ cost criteria} \tag{3.23}$$

Step 6: Defuzzification: The normalized fuzzy decision matrix is normalized as

$$\tilde{x}_{ij}=\frac{1}{n}\sum \tilde{r}_{ij}. \tag{3.24}$$

Step 7: The Best Element of Criteria (X_i^*) and Worst Element of Criteria (X_i^-) are calculated as:

For beneficial criteria, $(x_{ij})_{max}$ and for non-beneficial criteria $(x_{ij})_{min}$

$$X_i^* = \max\,[(x_{ij}) \mid i = 1,2,3 \ldots m] \tag{3.25}$$

$$X_i^- = \min\,[(x_{ij}) \mid i = 1,2,3 \ldots m] \tag{3.26}$$

Step 8: The value of Utility Measure (S_i), Regret Measure (R_i) and VIKOR Index (Q_i) is calculated as:

$$S_i=\sum_{i=1}^{n} w_i \frac{x_i^*- x_{ij}}{x_i^*-x_i^-} \tag{3.27}$$

$$R_i=\max[\, w_i(\frac{x_i^*- x_{ij}}{x_i^- -x_{ij}})] \tag{3.28}$$

Where, S_i and R_i denote the utility measure and regret measure for the alternatives x_i, w_i is the weight of each criterion. Now Compute the values of S^* = min (S_i), $S^- = \max\,(S_i)$, $i = 1,2,3 \ldots m$

$$R^* = \min\,(R_i), R^- = max\,(R),\ i = 1,2,3 \ldots m \tag{3.29}$$

Determine the values of $Q_i\ for\ j = 1,2,3 \ldots m$ and rank the alternatives by values of Q_j,

$$Q_i = v\left(\frac{S_i-S^*}{S^- -S^*}\right) + (1-v)\ \left(\frac{R_i-R^*}{R^- -R^*}\right) \tag{3.30}$$

Where v is the weight for the strategy of maximum group utility and $1 - v$ is the weight of the individual regret. Usually, v is 0.5 and when v > 0.5, the index of Q_j will tend to majority agreement, and clearly, when v <0.5, the index of Q_i will indicate a majority of negative attitudes. With the smallest number being the best option, the three values S_i, R_i , and Q_i are ranked from biggest to smallest in ascending order.

3.9.3 Check for Consistency

3.9.3.1 Condition C1: "Acceptance of Benefits"

By comparing the difference between the second rank's alternative value and the first rank's alternative against the DQ value, one may determine if one has met the C1 requirements or accepted benefits (Sasirekha and Ilanzkumaran, 2013; Shemshadi et al., 2011).

Here,

$$Q(a'') - Q(a') \geq DQ, \tag{3.31}$$

$$DQ = \frac{1}{m-1} \tag{3.32}$$

3.9.3.2 Condition C2: "Acceptance of Stability in Decision Support"

Alternatives must also rank first in prioritizing S_i and/ or, R_i values to satisfy C2 conditions. The stability of the compromise solution is accepted in the decision-making process if the C2 conditions are satisfied (Sasirekha and Ilanzkumaran, 2013). The degree of stability obtained takes the following forms:

a. Selected by the "majority rule," when v> 0.5

b. Chosen by "consensus," when $v \approx$ 0.5

c. Vetoed, when v <0.5

There will be some suggested compromise alternatives if one condition is not fulfilled. A reasonable compromise solution can include (Sasirekha and Ilanzkumaran, 2013; Shemshadi et al., 2011):

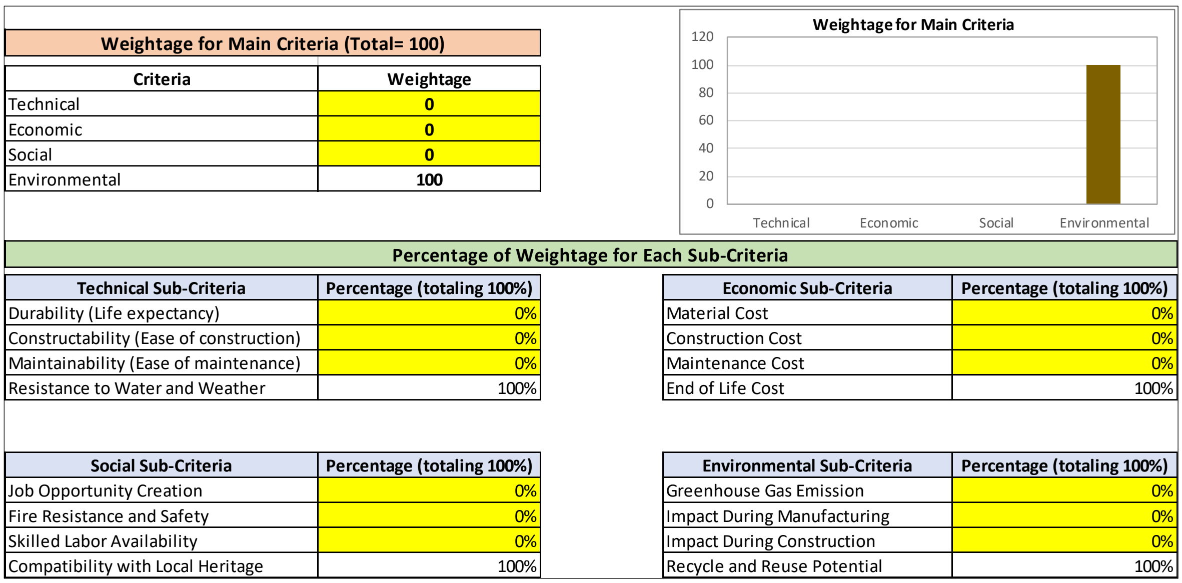
Alternatives, if a'' and a' only if C2 conditions are not met.

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

$$Q(am) - Q(a') < DQ \tag{3.33}$$

3.10 Decision Matrix

This method was used in addition to the Fuzzy AHP for criteria weightage calculations. Assigning the percentage of weightage reflects users' preferences for different options in this technique. It is relatively simple and convenient for users to assign importance to different evaluation criteria. A screenshot of the interface is given in Figure 3.7.



Criteria	Weightage
Technical	0
Economic	0
Social	0
Environmental	100

Technical Sub-Criteria	Percentage (totaling 100%)
Durability (Life expectancy)	0%
Constructability (Ease of construction)	0%
Maintainability (Ease of maintenance)	0%
Resistance to Water and Weather	100%

Economic Sub-Criteria	Percentage (totaling 100%)
Material Cost	0%
Construction Cost	0%
Maintenance Cost	0%
End of Life Cost	100%

Social Sub-Criteria	Percentage (totaling 100%)
Job Opportunity Creation	0%
Fire Resistance and Safety	0%
Skilled Labor Availability	0%
Compatibility with Local Heritage	100%

Environmental Sub-Criteria	Percentage (totaling 100%)
Greenhouse Gas Emission	0%
Impact During Manufacturing	0%
Impact During Construction	0%
Recycle and Reuse Potential	100%

Figure 3.7. The interface of the decision matrix used for criteria weightage calculation

3.10.1 Steps of Calculation

Users assign their preferences in weightage and percentage in two steps in this matrix. In the first step, they assign weightage for four pillars of sustainable construction, making a sum of 100. Next, they need to allot a percentage for each group of evaluation criteria (sub-criteria) under different pillars. The higher the preference or importance, the more would be the percentage of weightage. If the total weightage for the technical pillar is x, and the percentage for any sub-criteria under it is y, the weightage of that evaluation criteria out of all was calculated using the following equation:

$$\text{weightage (w)} = (\text{x} \times \text{y in percentage}) \times 0.01 \tag{3.34}$$

3.11 Computation and Automation of the Sustainable Material Selection Process

3.11.1 Use of Microsoft Excel for Computation

Microsoft Excel 2019 application was primarily used for data computation and developing the DSS model. Several templates with required equations were formulated to calculate the weightage of criteria using Fuzzy AHP and decision matrix and for ranking of alternatives using Fuzzy TOPSIS and Fuzzy VIKOR.

3.11.2 Creation of Decision Support System Software

This desktop application has been developed using the 'Microsoft dot-net framework' and is intended to operate on the Windows platform. C sharp was used in the 'windows form application' for coding this software, and its algorithm is based on the Fuzzy TOPSIS technique for ranking the alternatives. A graphical user interface was also developed using the 'windows form application.' Microsoft Management Studio used 'MySQL' and the 'windows database server' for database management. It is a joint application where user management has been configured as a single project, and there is no separate interface for different entities (owner, constructor, design team). After logging in, users need to create a new project (or retrieve the data of a previously saved project), and three entities need to give their inputs in the same interface. Users can edit or change the evaluation criteria during the initial inputs. Later they need to assign percentages of weightage for evaluation criteria (using text fields) and preferences for different alternatives (using dropdown menu options). Subsequently, they should assign a percentage for each entity (using text fields) stating the importance of stakeholders' opinions in group decision-making. This application shall take the qualitative inputs as the users' preferences and quantitative inputs as computed numerical values. Finally, it shall present the ranking of alternatives as to the output. Other details are discussed in Chapter 4.

3.12 Verification and Validation Technique

Verification of both Excel templates and developed DSS software was done through sensitivity analysis. The model was validated through several expert inputs and opinions in two phases. The first phase was the input validation. In this phase, Excel templates comprising a list of sustainable construction evaluation criteria, pairwise comparison of criteria, weightage distribution for criteria in the decision matrix, and assigning preferences for alternatives were emailed to academic and industry experts. They were requested to check the list of chosen criteria and comment on their relevance. The purpose of their input in the pairwise comparison template was to calculate the weightage of criteria using FAHP. In addition, input for weightage through a decision matrix was taken to compare the results of FAHP. Lastly, the inputs of assigning preferences template were used for ranking the alternatives through Fuzzy TOPSIS and Fuzzy VIKOR. Nine academic and industry experts participated in the first phase and sent their responses through email. The next phase was the output validation which took place through several online meetings. Other details of verification and validation are discussed in Chapter 5.

3.13 Sensitivity Analysis Technique

Saltelli et al. defined sensitivity analysis as "the study of how the uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input" (Saltelli et al., 2002). It is a verification process to check that the system fulfils the intended purpose by analyzing the output results with the variations of input parameters (Bakhoum and Brown, 2015). Researchers used different techniques like Monte Carlo Simulations (AbouHamad and Abu-Hamd, 2019), and the creation of different scenarios (Dara et al., 2019; Sirisawat and Kiatcharoenpol, 2018), and combinations of case studies (Bakhoum and Brown, 2015), etc. for model verifications. Sensitivity analysis was carried out in this research by running the developed model under various scenarios to ensure that it is responsive to changes in its input and that the output makes meaningful results. Details of the sensitivity analysis are discussed in Chapter 5.

CHAPTER 4: APPLICATION AND CASE STUDY

4.1 Introduction

Chapter three outlined the detailed methodology and steps of calculations used in this research. This chapter applied those utilizing multiple sets of data collected from industry and academic experts to develop the multi-criteria DSS ultimately. This chapter initially outlined the details of the case study, MCDM and DSS templates used for data collection and calculations. Next, it described the LCA and LCCA using *Athena Impact Estimator for Buildings* software. Fuzzy AHP and decision matrix were then used to calculate the criteria' weightage. Fuzzy TOPIS and Fuzzy VIKOR were used independently using criteria weightage from Fuzzy AHP and decision matrix in the last step of the calculation for ranking the alternatives. In all steps, the inputs of all stakeholders were integrated, keeping the IPD framework into consideration. Finally, an automated multi-criteria DSS was developed using software applications.

4.2 Details of Case Study, MCDM and DSS Templates

This research used a case study on an eight-story building to validate the theoretical model developed in Chapter 3. Detailed methodology and MCDM techniques used to create the DSS in this research have been discussed in Chapter 3. A practical example with numerical computation of user, project and structural data was essential to derive the model's output in terms of ranking alternatives. The case study also assisted in creating several scenarios to verify the developed system's consistency and sensitivity. Details of the case study are discussed in the subsequent paragraphs.

4.2.1 Details of the Case Study

From the opinion of the experts, it was revealed that compared to single houses, multistory residential buildings are gaining popularity and contributing more to sustainable construction. According to the report of Government of Canada Statistics, from January 2017 to December 2021, among all the residential units completed, 51.8% comprised apartment buildings and types other than single, semi-detached, and row units (Government of Canada, 2022). For development, validation and verification of the DSS, a hypothetical 8-story building is considered in this study. The primary reason for selecting an 8-story building is that all options of structural materials (RC, SS, RM and Timber) remain acceptable alternatives for this height. Experts also informed that previously timber construction was allowed up to 6 stories in Alberta, which has recently been extended up to 12-story construction. The *Athena Impact Estimator for Buildings* has an inbuilt database for Calgary; therefore, the structure's location was chosen for ease of LCA and LCCA calculations. Eighty years of building life expectancy were considered according to the guidelines of Infrastructure Canada for five or more-story apartment buildings (Government of Canada, 2018). Other details of the building are given in Table 4.1.

Table 4.1. Study parameters as input in 'Athena Impact Estimator for Buildings'

Parameters	**Details**
Project location	Calgary, Alberta
Building type	Residential
Building life expectancy	80 years
Building height	26.1 meter (m)
Number of floors	8
Gross floor area	798.66 m^2
Structural components considered	Columns Beams
Options of structural materials	Reinforced concrete Structural steel Reinforced masonry Timber

The architectural view of the building, typical floor plan and structural layout with different material options are shown in Figures 4.1 to 4.6.

Figure 4.1. Architectural view of the 8-story building

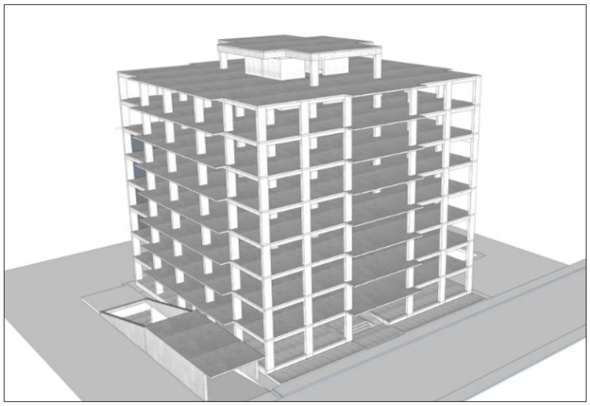


Figure 4.2. Building structure using RC

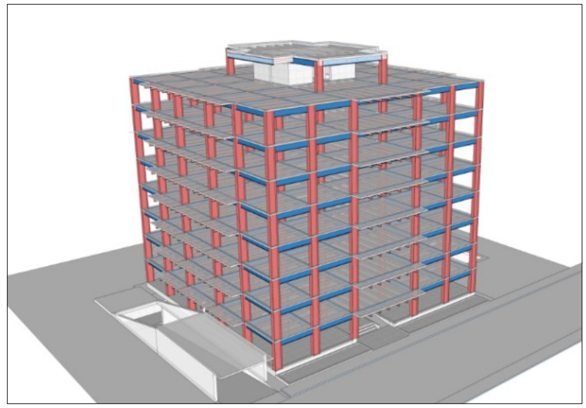


Figure 4.3. Building structure using SS

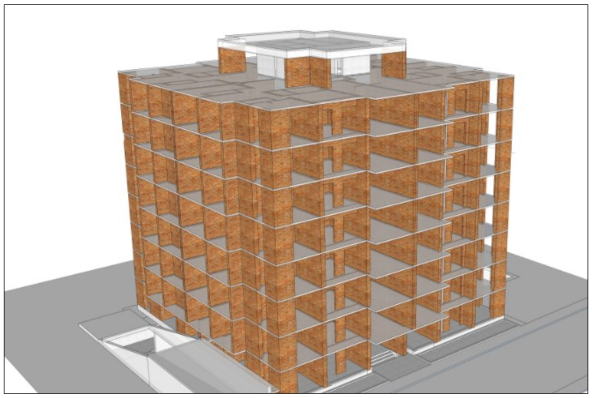


Figure 4.4. Building structure using RM

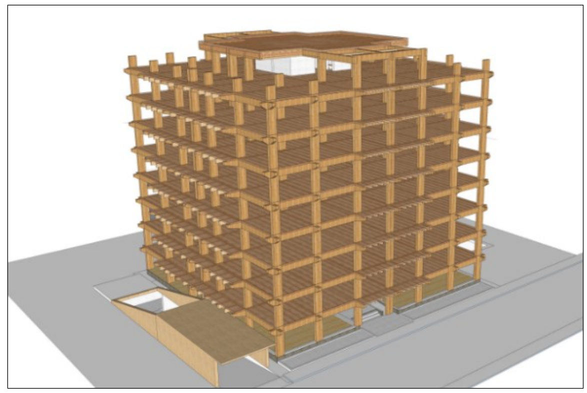


Figure 4.5. Building structure using timber

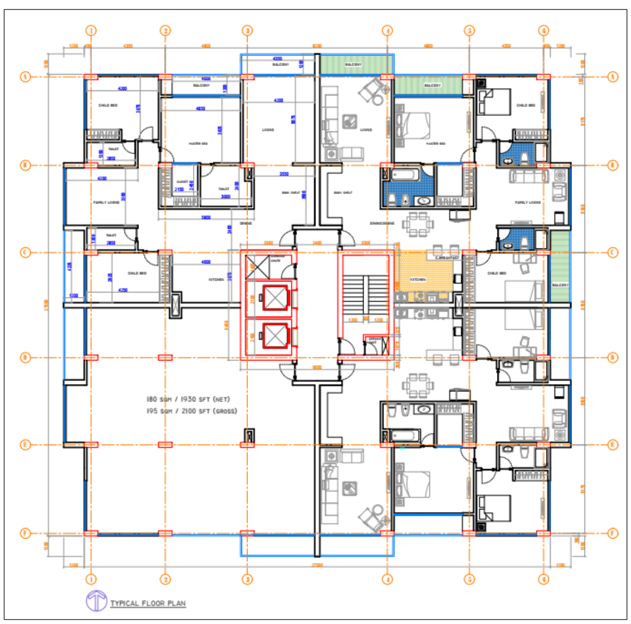


Figure 4.6. Typical floor plan of the building

4.2.2 Details of the Participating Teams of the Case Study

The data from three teams comprising nine members were used in this case study. Each team had a representative from the owner, constructor and design team who are experts in their relevant fields. The members of the study teams were the project owners, prime consultants, chief structural engineers, principal architects, project coordinators, project managers, and academic researchers from Clark Builders, Stantec, GEC Architecture, RJC Engineers, Alberta Masonry Council, Chandos Construction, Wood Works, and the University of Alberta. It is important to note that the members of Team 1 and Team 2 were from several leading construction industries, whereas Team 3 was formed with academic researchers and people who are already practicing sustainable construction.

4.2.3 Details of the MCDM and DSS Templates

A number of templates were used to collect the data from users. Details of those are given in Appendix A.

4.3 Calculation of LCA and LCCA

The *Athena Impact Estimator for Buildings* application was used to determine the quantity of construction materials required to build the model building. The cost criteria were then computed using the local (Alberta) market rate, and the emission rate was calculated using the environmental analysis module of the same application. Detailed calculations of those are given in Appendix B and results are tabulated in Table 4.2.

Table 4.2. The calculated cost of materials and emission rate

Alternatives	Material Cost ($/sqm)	Construction Cost ($/sqm)	End of Life Cost ($/sqm)	Greenhouse Gas Emission (kg CO_2 equivalent/sqm)
Reinforced Concrete	550	152	50	115
Structural Steel	480	115	95	110
Timber	300	85	80	25
Reinforced Masonry	380	180	65	95

4.3.1 Conversion of Quantitative (Objective) User Input to Qualitative (Subjective) Value

To convert the quantitative users' inputs into qualitative data, we followed the methods described in chapter 3. The objective values obtained from Athena Impact Estimator for Buildings software and local market analysis as tabulated in table 4.2 have been used.

Step 1: The inputs of table 4.2 is normalized by dividing each cell value by the sum value of each column (total criteria values for all alternatives). The obtained normalized decision matrix is shown in Table 4.3:

Table 4.3. Converted in Normalized Matrix

Alternatives	Material Cost ($/sqm)	Construction Cost ($/sqm)	End of Life Cost ($/sqm)	Greenhouse Gas Emission (kg CO_2 equivalent/sqm)
Reinforced Concrete	0.3216	0.2857	0.1724	0.3333
Structural Steel	0.2807	0.2161	0.3275	0.3188
Timber	0.1754	0.1597	0.2758	0.0724
Reinforced Masonry	0.2222	0.3383	0.2241	0.2753

Step 2: By adding the column values, where each cell value is multiplied by its logarithm (ln) value, Shannon's diversity index is calculated. The Shannon diversity index measures the diversity of range values for any criterion among the alternatives. The results are shown in Table 4.4, with the lowest greenhouse gas emission value (kg CO_2 equivalent/sqm) factoring in at 1.28.

Table 4.4. Shannon diversity index

Alternatives	Material Cost ($/sqm)	Construction Cost ($/sqm)	End of Life Cost ($/sqm)	Greenhouse Gas Emission (kg CO_2 equivalent/sqm)
Shannon diversity Index	1.36	1.35	1.36	1.28

Step 3: Shannon's equitability index is the value of Shannon's diversity index divided by the logarithm value of the total number of alternatives considered in the decision-making process. It is also termed entropy value.

Table 4.5. Shannon Equitability Index

Alternatives	Material Cost ($/sqm)	Construction Cost ($/sqm)	End of Life Cost ($/sqm)	Greenhouse Gas Emission (kg CO_2 equivalent/sqm)
Shannon's equitability index	0.98	0.97	0.98	0.92

Step 4: The degree of divergence has been calculated by subtracting the Shannon equitability index from the unit value. Within the matrix, the criteria values containing a higher degree of variation are considered for the range distribution of subjective values. In this case, the values of Greenhouse Gas Emission (kg CO_2 equivalent/sqm) are regarded for benchmark distribution. Here, the maximum value is considered very high and the minimum value is considered very low. All other subjective values are distributed equally within the range, as shown in table 4.6. These range values are considered to transform all other criteria values of the matrix from objective to subjective one.

Table 4.6. Determination of range

Linguistic Term	Conversion Scale in Normalized Matrix
Very High	>0.2811
High	0.2289 to 0.2811
Medium	0.1768 to 0.2289
Low	0.1246 to 0.1768
Very Low	<0.1246

Step 5: Finally, the subjective results of table 4.3 values are tabulated in Table 4.7, equalizing with the ranges shown in table 4.6:

Table 4.7: Output subjective result

Alternatives	Material Cost ($/sqm)	Construction Cost ($/sqm)	End of Life Cost ($/sqm)	Greenhouse Gas Emission (kg CO_2 equivalent/sqm)
Reinforced Concrete	Very High	Very High	Low	Very High
Structural Steel	High	Medium	Very High	Very High
Timber	Low	Low	High	Very Low
Reinforced Masonry	Medium	Very High	Medium	High

4.4 Calculation of Weightage for Each Criteria Using Fuzzy AHP

4.4.1 Criteria and Codes

A total of 16 criteria have been selected for evaluating sustainable building structural materials under the four pillars of sustainability discussed in chapter 3. The name of the criteria and codes for them are listed in Table 4.8. The following results are generated based on the input of one stakeholder (Owner of Team 3) using the formula and procedure described in Chapter 3.

Table 4.8. Criteria and Codes

Sustainability Pillars	Evaluation Criteria	Code	Influence
Technical	Durability (life expectancy)	TEC1	Beneficial criteria
	Constructability (Ease of construction)	TEC2	Beneficial criteria
	Maintainability	TEC3	Beneficial criteria
	Resistance to Water and Weather	TEC4	Beneficial criteria
Economical	Material Cost	ECO1	Cost criteria
	Construction Cost	ECO2	Cost criteria
	Maintenance Cost	ECO3	Cost criteria
	End of Life Cost	ECO4	Beneficial criteria
Social	Job Opportunity Creation	SOC1	Beneficial criteria
	Fire Resistance and Safety	SOC2	Beneficial criteria
	Skilled Labor Availability	SOC3	Beneficial criteria
	Compatibility with Heritage	SOC4	Beneficial criteria
Environmental	Greenhouse Gas Emission	ENV1	Cost criteria
	Impact During Manufacturing	ENV2	Cost criteria
	Impact During Construction	ENV3	Cost criteria
	Recycle and Reuse Potential	ENV4	Beneficial criteria

4.4.2 Calculation of Weightage for Each Criterion

Step 1: A pairwise comparison matrix shown in table 4.9 is developed for each user to compute the relative priorities of criteria from the user's point of view. Each criterion is evaluated with others on a 9-point scale, as described in chapter 3.

Table 4.9. 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	1	3	1	3	1	3	3	3	1	1	1	1	1	1
TEC2	1/3	1	1	3	1/3	1	1	3	3	3	3	3	1/5	1/3	1/3	1/3
TEC3	1	1	1	3	1/3	1/3	1	3	3	3	3	5	1/3	1	1	1/3
TEC4	1/3	1/3	1/3	1	1/7	1/5	1/3	1	1	1	3	1	1/5	1/3	1/5	1/3
ECO1	1	3	3	7	1	3	3	5	3	3	3	3	1	1	1	3
ECO2	1/3	1	3	5	1/3	1	3	3	1	3	3	5	1/5	1/3	1/3	1
ECO3	1	1	1	3	1/3	1/3	1	1	1	1	1	1	1/5	1/3	1/3	1
ECO4	1/3	1/3	1/3	1	1/5	1/3	1	1	1/3	1	1/3	1	1/9	1/5	1/3	1
SOC1	1/3	1/3	1/3	1	1/3	1	1	3	1	1	1	3	1/5	1/3	1/3	1/3
SOC2	1/3	1/3	1/3	1	1/3	1/3	1	1	1	1	3	3	1/7	1/3	1/3	1
SOC3	1	1/3	1/3	1/3	1/3	1/3	1	3	1	1/3	1	1	1/5	1/3	1/3	1
SOC4	1	1/3	1/5	1	1/3	1/5	1	1	1/3	1/3	1	1	1/7	1/5	1/5	1/3
ENV1	1	5	3	5	1	5	5	9	5	7	5	7	1	3	5	3
ENV2	1	3	1	3	1	3	3	5	3	3	3	5	1/3	1	3	3
ENV3	1	3	1	5	1	3	3	3	3	3	3	5	1/5	1/3	1	1
ENV4	1	3	3	3	1/3	1	1	1	3	1	1	3	1/3	1/3	1	1
Sum	12	26	19 7/8	45 1/3	8 1/3	23	27 1/3	46	32 2/3	34 2/3	35 1/3	48	5 4/5	10 2/5	15 3/4	18 2/3

Step 2: Each cell is then divided by the column sum to obtain the normalized value from table 4.9. The normalized matrix is shown in table 4.10.

Table 4.10. Normalized pairwise comparison matrix

Criteria	TEC1	TEC2	TEC3	TEC4	ECO1	ECO2	ECO3	ECO4	SOC1	SOC2	SOC3	SOC4	ENV1	ENV2	ENV3	ENV4
TEC1	0.08	0.12	0.05	0.07	0.12	0.13	0.04	0.07	0.09	0.09	0.03	0.02	0.17	0.10	0.06	0.05
TEC2	0.03	0.04	0.05	0.07	0.04	0.04	0.04	0.07	0.09	0.09	0.08	0.06	0.03	0.03	0.02	0.02
TEC3	0.08	0.04	0.05	0.07	0.04	0.01	0.04	0.07	0.09	0.09	0.08	0.10	0.06	0.10	0.06	0.02
TEC4	0.03	0.01	0.02	0.02	0.02	0.01	0.01	0.02	0.03	0.03	0.08	0.02	0.03	0.03	0.01	0.02
ECO1	0.08	0.12	0.15	0.15	0.12	0.13	0.11	0.11	0.09	0.09	0.08	0.06	0.17	0.10	0.06	0.16
ECO2	0.03	0.04	0.15	0.11	0.04	0.04	0.11	0.07	0.03	0.09	0.08	0.10	0.03	0.03	0.02	0.05
ECO3	0.08	0.04	0.05	0.07	0.04	0.01	0.04	0.02	0.03	0.03	0.03	0.02	0.03	0.03	0.02	0.05
ECO4	0.03	0.01	0.02	0.02	0.02	0.01	0.04	0.02	0.01	0.03	0.01	0.02	0.02	0.02	0.02	0.05
SOC1	0.03	0.01	0.02	0.02	0.04	0.04	0.04	0.07	0.03	0.03	0.03	0.06	0.03	0.03	0.02	0.02
SOC2	0.03	0.01	0.02	0.02	0.04	0.01	0.04	0.02	0.03	0.03	0.08	0.06	0.02	0.03	0.02	0.05
SOC3	0.08	0.01	0.02	0.01	0.04	0.01	0.04	0.07	0.03	0.01	0.03	0.02	0.03	0.03	0.02	0.05
SOC4	0.08	0.01	0.01	0.02	0.04	0.01	0.04	0.02	0.01	0.01	0.03	0.02	0.02	0.02	0.01	0.02
ENV1	0.08	0.19	0.15	0.11	0.12	0.22	0.18	0.20	0.15	0.20	0.14	0.15	0.17	0.29	0.32	0.16
ENV2	0.08	0.12	0.05	0.07	0.12	0.13	0.11	0.11	0.09	0.09	0.08	0.10	0.06	0.10	0.19	0.16
ENV3	0.08	0.12	0.05	0.11	0.12	0.13	0.11	0.07	0.09	0.09	0.08	0.10	0.03	0.03	0.06	0.05
ENV4	0.08	0.12	0.15	0.07	0.04	0.04	0.04	0.02	0.09	0.03	0.03	0.06	0.06	0.03	0.06	0.05

Step 3: Criteria weight is the average of each row value weight in the table above (Table 4.10). The results are shown in Table 4.11.

Table 4.11. Criteria weightage

Sustainability Pillars	Criteria	Code	Criteria Weight
Technical	Durability (life expectancy)	TEC1	0.08
	Constructability (Ease of construction)	TEC2	0.05
	Maintainability	TEC3	0.06
	Resistance to Water and Weather	TEC4	0.03
Economical	Material Cost	ECO1	0.11
	Construction Cost	ECO2	0.06
	Maintenance Cost	ECO3	0.04
	End of Life Cost	ECO4	0.02
Social	Job Opportunity Creation	SOC1	0.03
	Fire Resistance and Safety	SOC2	0.03
	Skilled Labor Availability	SOC3	0.03
	Compatibility with Heritage	SOC4	0.02
Environmental	Greenhouse Gas Emission	ENV1	0.18
	Impact During Manufacturing	ENV2	0.10
	Impact During Construction	ENV3	0.08
	Recycle and Reuse Potential	ENV4	0.06

Step 4: Typically, obtaining an acceptable consistency value is complicated once there are many criteria to be evaluated with each other. The users performed a few trials and errors to get consistent values. The sample calculation of the consistency check of one of the users (designer, team 3) has been shown below:

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

=17.95,

Here, n=16. CI= $\frac{17.95-16}{16-1}$ = 0.1306

From Table 3.2, we get RI for n= 16 is 1.59

So, CR= 0.1306/1.59 = 8.25% < 10%, which is an acceptable result.

Step 5: The crisp values of table 4.9 are fuzzified using the fuzzification table of 3.3. The pairwise input comparison matrix is shown in table 4.12 below.

Table 4.12. Fuzzification of the pairwise comparison matrix

Criteria	TEC1	TEC2	TEC3	TEC4	ECO1	ECO2	ECO3	ECO4
TEC1	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
TEC2	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
TEC3	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
TEC4	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
ENV1	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
ENV2	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
ENV3	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
ENV4	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	ENV1	ENV2	ENV3	ENV4
TEC1	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
TEC2	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
TEC3	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
TEC4	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
ENV1	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
ENV2	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
ENV3	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
ENV4	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 in ascending order, as shown in Table 4.13 below. The fuzzy normalized weight criteria values are essential because they are crucial in influencing and formulating decisions by adding weightage to any preference.

Table 4.13. Fuzzified normalized weight and global ranking

Criteria	**Fuzzy Normalized Weight**	**Weight-based Rank of Criteria**
Durability (life expectancy)	0.0696	5
Constructability (Ease of construction)	0.0545	9
Maintainability	0.0631	7
Resistance to Water and Weather	0.0287	14
Material Cost	0.1054	2
Construction Cost	0.0642	6
Maintenance Cost	0.0405	10
End of Life Cost	0.0278	15
Job Opportunity Creation	0.0392	11
Fire Resistance and Safety	0.0382	12
Skilled Labor Availability	0.0356	13
Compatibility with Heritage	0.0256	16
Greenhouse Gas Emission	0.1681	1
Impact During Manufacturing	0.1000	3
Impact During Construction	0.0806	4
Recycle and Reuse Potential	0.0589	8

Depending on the input in the comparison matrix, the result of the fuzzified normalized weightage of the criterion will vary from user to user. Table 4.14 and Figure 4.7 show an overview of the fuzzified normalized weight of the criteria used by all the stakeholders in this study.

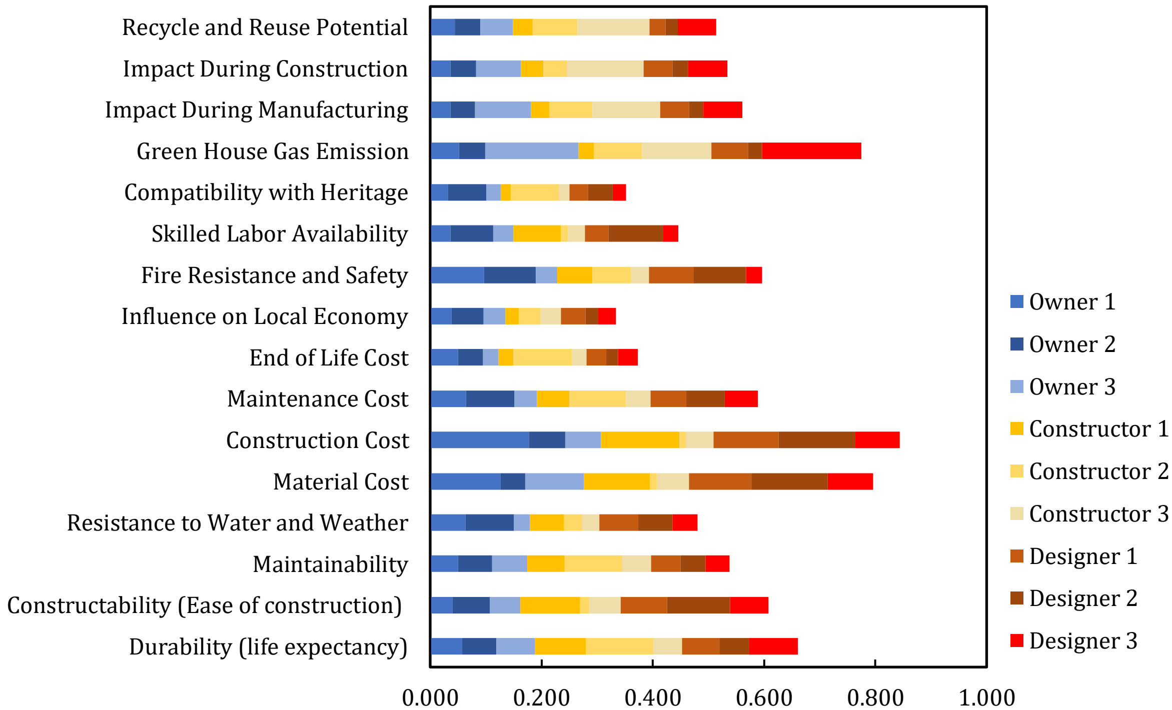


Figure 4.7. Summary of the fuzzified normalized criteria weightage of all stakeholders

Table 4.14. Summary of the fuzzified normalized criteria weightage of all stakeholders

	Owner 1	Owner 2	Owner 3	Constructor 1	Constructor 2	Constructor 3	Designer 1	Designer 2	Designer 3
Durability (life expectancy)	0.06	0.06	0.07	0.09	0.12	0.05	0.07	0.05	0.09
Constructability (Ease of construction)	0.04	0.07	0.05	0.11	0.02	0.06	0.08	0.11	0.07
Maintainability	0.05	0.06	0.06	0.07	0.10	0.05	0.05	0.05	0.04
Resistance to Water and Weather	0.06	0.09	0.03	0.06	0.03	0.03	0.07	0.06	0.04
Material Cost	0.13	0.04	0.11	0.12	0.01	0.06	0.11	0.14	0.08
Construction Cost	0.18	0.07	0.06	0.14	0.01	0.05	0.12	0.14	0.08
Maintenance Cost	0.06	0.09	0.04	0.06	0.10	0.04	0.06	0.07	0.06
End of Life Cost	0.05	0.05	0.03	0.03	0.11	0.03	0.04	0.02	0.03
Job Opportunity Creation	0.04	0.06	0.04	0.02	0.04	0.04	0.04	0.02	0.03
Fire Resistance and Safety	0.10	0.09	0.04	0.06	0.07	0.03	0.08	0.09	0.03
Skilled Labor Availability	0.04	0.08	0.04	0.09	0.01	0.03	0.04	0.10	0.03
Compatibility with Heritage	0.03	0.07	0.03	0.02	0.09	0.02	0.03	0.04	0.02
Greenhouse Gas Emission	0.05	0.05	0.17	0.03	0.09	0.12	0.07	0.03	0.18
Impact During Manufacturing	0.04	0.04	0.10	0.03	0.08	0.12	0.05	0.03	0.07
Impact During Construction	0.04	0.05	0.08	0.04	0.04	0.14	0.05	0.03	0.07
Recycle and Reuse Potential	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)

Step 1 (a): Table 4.15 shows one of the user's inputs while evaluating the alternatives based on different criteria. Five options are available to the user: "Very High, High, Medium, Low, and Very Low." Additionally, a total of 4 criteria are fixed for a specific location and time and have an objective value. However, these values are transformed from objective to subjective using the Shannon entropy method, which is shown in table 4.16.

Table 4.15. Input parameter of stakeholder - Owner of Team 3

Criteria / Alternatives	Reinforced Concrete	Structural Steel	Timber	Reinforced Masonry
Technical				
Durability (life expectancy)	Very High	High	High	Very High
Constructability (Ease of construction)	Medium	High	Very High	Medium
Maintainability (Ease of maintenance)	Very High	Medium	High	High
Resistance to Water and Weather	High	High	High	High
Economic				
Material Cost	550	480	300	380
Construction Cost	152	115	85	180
Maintenance Cost	Very Low	Medium	Medium	Very Low
End of Life Cost	50	95	80	65
Social				
Job Opportunity Creation	High	High	Very High	High
Fire Resistance and Safety	Very High	Medium	Medium	Very High
Skilled Labor Availability	Medium	Medium	High	Medium
Compatibility with Heritage	Low	Low	High	Very High
Environmental				
Greenhouse Gas Emission	115	110	25	95
Impact During Manufacturing	High	High	Very Low	Medium
Impact During Construction	High	Medium	Low	High
Recycle and Reuse Potential	Very Low	High	Very High	Medium

Step 1 (b): Objective values converted into subjective values using Shannon's entropy method (Table 4.16):

Criteria / Alternatives	Reinforced Concrete	Structural Steel	Timber	Reinforced Masonry
Technical				
Durability (life expectancy)	Very High	High	High	Very High
Constructability (Ease of construction)	Medium	High	Very High	Medium
Maintainability (Ease of maintenance)	Very High	Medium	High	High
Resistance to Water and Weather	High	High	High	High
Economic				
Material Cost	**Very High**	**High**	**Low**	**Medium**
Construction Cost	**Very High**	**Medium**	**Low**	**Very High**
Maintenance Cost	Very Low	Medium	Medium	Very Low
End of Life Cost	**Low**	**Very High**	**High**	**Medium**

Social				
Job Opportunity Creation	High	High	Very High	High
Fire Resistance and Safety	Very High	Medium	Medium	Very High
Skilled Labor Availability	Medium	Medium	High	Medium
Compatibility with Heritage	Low	Low	High	Very High
Environmental				
Greenhouse Gas Emission	**Very High**	**Very High**	**Very Low**	**High**
Impact During Manufacturing	High	High	Very Low	Medium
Impact During Construction	High	Medium	Low	High
Recycle and Reuse Potential	Very Low	High	Very High	Medium

Step 2: The user input table is then transformed into a fuzzy decision matrix (Table 4.17) using the trapezoidal membership function described in chapter 3.

Table 4.17. Fuzzy decision matrix

Criteria	**TEC1**	**TEC2**	**TEC3**	**TEC4**	**ECO1**	**ECO2**	**ECO3**	**ECO4**
Reinforced Concrete	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
Structural Steel	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
Timber	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
Reinforced Masonry	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**	**ENV1**	**ENV2**	**ENV3**	**ENV4**
	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: Combined Decision Matrix (Table 4.18) is the combination of three stakeholders' fuzzy input values of the same team Table. The combination is done such that the first value of each cell is the minimum of the set, 4th one is the maximum of the set and intermediates values are the average of the same order values of the set.

Table 4.18: Combined Decision Matrix

Criteria	**TEC1**	**TEC2**	**TEC3**	**TEC4**	**ECO1**	**ECO2**	**ECO3**	**ECO4**
Reinforced Concrete	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
Structural Steel	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
Timber	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
Reinforced Masonry	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

	SOC1	SOC2	SOC3	SOC4	ENV1	ENV2	ENV3	ENV4
	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
	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
	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
	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: Normalized Fuzzy Decision Matrix is calculated based on the criteria category, whether it is a beneficial or a cost criterion. For beneficial criteria, the membership function is divided by the maximum value of the sets; for cost criteria, it is reciprocal of the values divided by the minimum values of the set.

Table 4.19. Normalized Fuzzy Decision Matrix

Criteria	TEC1	TEC2	TEC3	TEC4	ECO1	ECO2	ECO3	ECO4
Reinforced Concrete	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
Structural Steel	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
Timber	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
Reinforced Masonry	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
	SOC1	SOC2	SOC3	SOC4	ENV1	ENV2	ENV3	ENV4
	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
	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
	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
	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 (Table 4.20) based on owner's input and criteria weight derived from Fuzzy AHP.

Table 4.20. Weighted Normalized Fuzzy Decision Matrix

Criteria	TEC1	TEC2	TEC3	TEC4	ECO1	ECO2	ECO3	ECO4
Reinforced Concrete	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
Structural Steel	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
Timber	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
Reinforced Masonry	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
	SOC1	SOC2	SOC3	SOC4	ENV1	ENV2	ENV3	ENV4
	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
	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
	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
	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: Deriving fuzzy ideal solution; Fuzzy positive ideal solution (FPIS) and Fuzzy negative ideal solution (FNIS) are derived from weighted normalized Fuzzy Decision Matrix and tabulated in Table 4.21.

Table 4.21. Fuzzy Ideal Solution

	TEC1	TEC2	TEC3	TEC4	ECO1	ECO2	ECO3	ECO4
A* FPIS	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- FNIS	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

	SOC1	SOC2	SOC3	SOC4	ENV1	ENV2	ENV3	ENV4
	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
	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: Euclidian distance of each criterion of any alternative has been measured in this step. Distance from the FPIS is shown in Table 4.22, and distance from FNIS is shown in Table 4.23.

Table 4.22. Distance from the FPIS

Alternative / Criteria	TEC1	TEC2	TEC3	TEC4	ECO1	ECO2	ECO3	ECO4	SOC1	SOC2	SOC3	SOC4	ENV1	ENV2	ENV3	ENV4	SUM (di*)
Reinforced Concrete	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**
Structural Steel	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**
Timber	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**
Reinforced Masonry	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 4.23. Distance from FNIS

Alternative / Criteria	TEC1	TEC2	TEC3	TEC4	ECO1	ECO2	ECO3	ECO4	SOC1	SOC2	SOC3	SOC4	ENV1	ENV2	ENV3	ENV4	SUM (di−)
Reinforced Concrete	0.23	0.02	0.22	0.04	0.14	0.09	0.00	0.00	0.02	0.19	0.00	0.00	0.02	0.05	0.10	0.00	**1.11**
Structural Steel	0.08	0.15	0.00	0.00	0.13	0.07	0.03	0.19	0.00	0.00	0.03	0.01	0.02	0.10	0.08	0.24	**1.12**
Timber	0.00	0.32	0.11	0.01	0.00	0.00	0.03	0.10	0.13	0.01	0.10	0.11	0.06	0.00	0.00	0.41	**1.39**
Reinforced Masonry	0.16	0.00	0.08	0.02	0.11	0.09	0.00	0.04	0.05	0.19	0.00	0.15	0.00	0.06	0.06	0.12	**1.12**

Step 8: The closeness coefficient is measured using the formula $CC_i = \frac{d_i^-}{d_i^- + d_i^*}$; where d_i^* is the sum of all distance from FPIS and d_i^- is the sum of all distance from FNIS of an alternative.

CC_{rc}= $\frac{1.11}{1.76+1.11}$ = 0.38629, CC_t= $\frac{1.39}{0.94+1.39}$ = 0.59663,

CC_{ss}= $\frac{1.12}{1.52+1.12}$ = 0.425182, CC_{rm}= $\frac{1.12}{1.62+1.12}$ = 0.408299.

The value of the CC_i is the measure of performance of the alternative. The alternative is ranked based on the value of CC_i in descending order as shown in Table 4.24.

Table 4.24. Ranking of one stakeholder (Owner of Team 3)

Alternatives	di*	di⁻	CC	Rank
Reinforced Concrete	1.76	1.11	0.38629	4
Structural Steel	1.52	1.12	0.425182	2
Timber	0.94	1.39	0.59663	1
Reinforced Masonry	1.62	1.12	0.408299	3

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 a greater priority in this case, with a weighting of 40%, while the opinions of the other two team members received a weighting of 30%.

Table 4.25. 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					
Reinforced Concrete	0.3863	0.3888	0.3139	0.3653	4
Structural Steel	0.4252	0.4873	0.4756	0.4590	2
Timber	0.5966	0.6365	0.7026	0.6404	1
Reinforced Masonry	0.4083	0.3966	0.3209	0.3786	3

Step 9: The ranking of alternatives is determined similarly for teams 1 and 2. The overall results of all groups involving Fuzzy TOPSIS are displayed in Table 4.26.

Table 4.26. The overall result of all teams (Using Fuzzy TOPSIS)

	Team 1		**Team 2**		**Team 3**	
Alternatives	Weighted CC	Rank	Weighted CC	Rank	Weighted CC	Rank
Reinforced Concrete	0.5753	1	0.7572	1	0.3653	4
Structural Steel	0.5502	2	0.5441	2	0.4590	2
Timber	0.3915	4	0.1892	4	0.6404	1
Reinforced Masonry	0.4327	3	0.3884	3	0.3786	3

4.6 Ranking of Alternatives with Fuzzy VIKOR (Using Fuzzy AHP Weightage)

Step 1: Here, the input parameters of stakeholders are similar to those used in Fuzzy TOPSIS. The values of the owner of Team 3 (as described in Table 4.15 and Table 4.16) are utilized to develop a sample calculation.

Step 2: Transforming subjective values of the matrix into the fuzzy membership function is performed in this step and shown in Table 4.27.

Table 4.27. Fuzzified user input matrix

Alternatives \ Criteria	TEC1	TEC2	TEC3	TEC4	ECO1	ECO2	ECO3	ECO4
Reinforced Concrete	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
Structural Steel	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
Timber	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
Reinforced Masonry	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
Criteria	SOC1	SOC2	SOC3	SOC4	ENV1	ENV2	ENV3	ENV4
Reinforced Concrete	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
Structural Steel	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
Timber	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
Reinforced Masonry	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 importance and weightage of the stakeholders' criterion (Taken from FAHP) are listed here. The owner's opinion was given a higher weightage of 40%, while the rest of the team received 30%.

Table 4.28. Importance and Criteria weightage of the members of the team

Decision Makers	Importance	TEC1	TEC2	TEC3	TEC4	ECO1	ECO2	ECO3	ECO4
Owners	0.4	0.070	0.054	0.063	0.029	0.105	0.064	0.041	0.028
Constructor	0.3	0.052	0.057	0.051	0.030	0.058	0.049	0.044	0.026
Designer	0.3	0.070	0.054	0.063	0.029	0.105	0.064	0.041	0.028
		SOC1	SOC2	SOC3	SOC4	ENV1	ENV2	ENV3	ENV4
		0.039	0.038	0.036	0.026	0.168	0.100	0.081	0.059
		0.037	0.033	0.031	0.018	0.125	0.122	0.137	0.130
		0.039	0.038	0.036	0.026	0.168	0.100	0.081	0.059

Step 4: The method outlined in chapter 3 is used to create a combined fuzzy decision matrix (Table 4.29). Here, the decision maker's importance factor, fuzzified user input, and the relative weights assigned to the criterion are used to generate the matrix.

Table 4.29. Combined Decision Matrix

Alternative	TEC1	TEC2	TEC3	TEC4	ECO1	ECO2	ECO3	ECO4
Reinforced Concrete	0.11,0.17,0.19,0.28	0.02,0.07,0.09,0.13	0.04,0.12,0.13,0.25	0.06,0.07,0.09,0.11	0.12,0.21,0.24,0.42	0.04,0.09,0.11,0.15	0.01,0.04,0.05,0.11	0.01,0.02,0.03,0.04
Structural Steel	0.08,0.14,0.16,0.22	0.08,0.12,0.14,0.17	0.05,0.08,0.10,0.15	0.03,0.05,0.06,0.09	0.09,0.18,0.21,0.34	0.01,0.04,0.06,0.10	0.05,0.07,0.09,0.11	0.05,0.08,0.09,0.11
Timber	0.08,0.14,0.16,0.22	0.08,0.12,0.14,0.17	0.05,0.10,0.11,0.20	0.03,0.05,0.06,0.08	0.02,0.06,0.08,0.17	0.01,0.13,0.15,0.24	0.04,0.06,0.08,0.11	0.04,0.06,0.07,0.09
Reinforced Masonry	0.05,0.13,0.15,0.28	0.02,0.05,0.06,0.13	0.04,0.10,0.12,0.20	0.05,0.07,0.08,0.11	0.05,0.11,0.14,0.25	0.07,0.15,0.17,0.26	0.01,0.04,0.05,0.11	0.03,0.04,0.05,0.07
	SOC1	**SOC2**	**SOC3**	**SOC4**	**ENV1**	**ENV2**	**ENV3**	**ENV4**
Reinforced Concrete	0.03,0.07,0.08,0.13	0.04,0.08,0.09,0.15	0.03,0.04,0.05,0.09	0.01,0.02,0.02,0.04	0.26,0.42,0.47,0.67	0.10,0.22,0.25,0.37	0.15,0.23,0.26,0.41	0.02,0.04,0.05,0.16
Structural Steel	0.01,0.06,0.07,0.13	0.01,0.03,0.04,0.09	0.04,0.05,0.06,0.09	0.01,0.02,0.03,0.04	0.11,0.25,0.30,0.43	0.10,0.17,0.20,0.32	0.04,0.11,0.14,0.19	0.06,0.15,0.18,0.31
Timber	0.07,0.10,0.11,0.16	0.01,0.04,0.05,0.09	0.04,0.06,0.07,0.11	0.04,0.05,0.06,0.08	0.05,0.14,0.15,0.37	0.02,0.04,0.05,0.08	0.02,0.05,0.07,0.13	0.14,0.20,0.22,0.31
Reinforced Masonry	0.05,0.07,0.09,0.13	0.04,0.08,0.09,0.15	0.03,0.04,0.05,0.09	0.03,0.05,0.06,0.10	0.16,0.28,0.33,0.54	0.10,0.17,0.20,0.29	0.06,0.18,0.21,0.33	0.02,0.10,0.12,0.23

Step 5: Normalized Fuzzy Decision Matrix is generated using the formula given in chapter 3.

Table 4.30. Normalized Fuzzy Decision Matrix

Alternative	TEC1	TEC2	TEC3	TEC4	ECO1	ECO2	ECO3	ECO4
Reinforced Concrete	0.39,0.60,0.69,1.00	0.12,0.38,0.49,0.75	0.15,0.46,0.53,1.00	0.54,0.69,0.79,1.00	0.14,0.08,0.07,0.04	0.33,0.17,0.14,0.10	1.00,0.35,0.27,0.12	0.07,0.18,0.26,0.40
Structural Steel	0.28,0.50,0.58,0.80	0.49,0.68,0.80,1.00	0.18,0.32,0.39,0.60	0.25,0.49,0.60,0.86	0.20,0.09,0.08,0.05	1.00,0.34,0.23,0.14	0.27,0.18,0.15,0.12	0.48,0.70,0.79,1.00
Timber	0.28,0.50,0.58,0.80	0.49,0.68,0.80,1.00	0.18,0.38,0.45,0.80	0.25,0.42,0.53,0.75	1.00,0.31,0.21,0.10	1.00,0.12,0.10,0.06	0.33,0.21,0.17,0.12	0.34,0.53,0.61,0.80
Reinforced Masonry	0.17,0.47,0.55,1.00	0.10,0.27,0.35,0.75	0.15,0.39,0.46,0.80	0.42,0.63,0.74,1.00	0.33,0.16,0.12,0.07	0.20,0.10,0.09,0.06	1.00,0.35,0.27,0.12	0.28,0.40,0.48,0.60
	SOC1	**SOC2**	**SOC3**	**SOC4**	**ENV1**	**ENV2**	**ENV3**	**ENV4**
Reinforced Concrete	0.21,0.42,0.50,0.80	0.28,0.51,0.59,1.00	0.22,0.37,0.47,0.75	0.05,0.15,0.22,0.40	0.20,0.13,0.11,0.08	0.20,0.10,0.08,0.06	0.14,0.09,0.08,0.05	0.07,0.13,0.17,0.50
Structural Steel	0.07,0.37,0.45,0.80	0.06,0.21,0.29,0.60	0.37,0.48,0.57,0.75	0.07,0.18,0.26,0.40	0.48,0.22,0.18,0.13	0.20,0.12,0.10,0.07	0.52,0.19,0.15,0.11	0.20,0.49,0.58,1.00
Timber	0.43,0.62,0.70,1.00	0.07,0.25,0.33,0.60	0.37,0.56,0.65,1.00	0.38,0.53,0.60,0.80	1.00,0.38,0.35,0.14	1.00,0.53,0.45,0.25	1.00,0.43,0.32,0.17	0.46,0.63,0.72,1.00
Reinforced Masonry	0.31,0.47,0.54,0.80	0.28,0.51,0.59,1.00	0.22,0.37,0.47,0.75	0.27,0.51,0.59,1.00	0.33,0.19,0.16,0.10	0.20,0.12,0.10,0.07	0.33,0.12,0.10,0.07	0.07,0.31,0.40,0.75

Step 6: Table 4.31 is the De-fuzzified matrix of the Table 4.30. A single number output is obtained from the aggregated fuzzy set. For beneficial criteria, the values of Table 4.30 are normalized by dividing the maximum value of the set, and for cost criteria, inverse values of Table 4.30 are normalized by dividing by the minimum value of the set.

Table 4.31. De-fuzzified Matrix

Alternative	TEC1	TEC2	TEC3	TEC4	ECO1	ECO2	ECO3	ECO4
Reinforced Concrete	0.67	0.43	0.53	0.75	0.09	0.18	0.44	0.23
Structural Steel	0.54	0.74	0.37	0.55	0.11	0.43	0.18	0.74
Timber	0.54	0.74	0.45	0.49	0.40	0.32	0.21	0.57
Reinforced Masonry	0.55	0.37	0.45	0.70	0.17	0.11	0.44	0.44

	SOC1	SOC2	SOC3	SOC4	ENV1	ENV2	ENV3	ENV4
Reinforced Concrete	0.48	0.60	0.45	0.21	0.13	0.11	0.09	0.22
Structural Steel	0.42	0.29	0.54	0.23	0.25	0.12	0.24	0.57
Timber	0.69	0.31	0.65	0.58	0.47	0.56	0.48	0.70
Reinforced Masonry	0.53	0.60	0.45	0.59	0.20	0.12	0.16	0.38

Step 7: Best Element of Criteria (X_i^*) and Worst Element of Criteria (X_i^-) is calculated from Table 4.31. X_i^* is the highest value among all alternatives for a criterion and, X_i^- is the lowest value among all alternatives for the same criterion. The calculated result is shown in Table 4.32.

Table 4.32. Best element and worst element criteria value

Criteria	TEC1	TEC2	TEC3	TEC4	ECO1	ECO2	ECO3	ECO4	SOC1	SOC2	SOC3	SOC4	ENV1	ENV2	ENV3	ENV4
X_i^*	0.67	0.74	0.53	0.75	0.09	0.11	0.18	0.74	0.69	0.60	0.65	0.59	0.13	0.11	0.09	0.70
X_i^-	0.54	0.37	0.37	0.49	0.40	0.43	0.44	0.23	0.42	0.29	0.45	0.21	0.47	0.56	0.48	0.22

Step 8: Finally, using the formula Utility Measure (S_i), Regret Measure (R_i) and VIKOR Index (Q_i) value are obtained as shown in Table 4.33. The alternatives are ranked based on the value of the VIKOR Index (Q_i). Lower the value of Q_i, the solution is close to the ideal solution, and the ranking of the alternative is higher. Here the Q_i The value for timber is 0.000 means that there is no distance from the ideal solution, and the value for RC is 1.000 means that the distance is maximum. Therefore, the ranking of timber is one, and RC is four as the alternatives.

Table 4.33. Utility Measure (S_i), Regret Measure (R_i) and VIKOR Index (Q_i) value

Criteria	**TEC1**	**TEC2**	**TEC3**	**TEC4**	**ECO1**	**ECO2**	**ECO3**	**ECO4**	**SOC1**	**SOC2**	**SOC3**	**SOC4**	**ENV1**	**ENV2**	**ENV3**	**ENV4**	**Si**	**Ri**	**Qi**	**Rank**
Reinforced Concrete	0.0000	0.0363	0.0000	0.0000	0.1054	0.0642	0.0000	0.0278	0.0196	0.0000	0.0356	0.0256	0.1681	0.1000	0.0806	0.0589	0.7222	0.1681	1.0000	4
Structural Steel	0.0696	0.0000	0.0631	0.0000	0.0703	0.0214	0.0203	0.0000	0.0392	0.0000	0.0356	0.0256	0.1681	0.1000	0.0403	0.0147	0.6681	0.1681	0.9485	3
Timber	0.0696	0.0000	0.0315	0.0000	0.0000	0.0000	0.0405	0.0093	0.0000	0.0382	0.0000	0.0085	0.0000	0.0000	0.0000	0.0000	0.1976	0.0696	0.0000	1
Reinforced Masonry	0.0000	0.0545	0.0315	0.0000	0.0351	0.0642	0.0000	0.0185	0.0196	0.0000	0.0356	0.0000	0.1261	0.0667	0.0806	0.0295	0.5619	0.1261	0.6340	2

Step 9: Similarly, Step 1 to 8 was repeated for the constructor and designer of the team. The combined result of the stakeholders of Team 3 is thus obtained and shown in Table 4.34.

Table 4.34. Ranking of Alternatives for Team 3

	Qi (Owner)	Qi (Constructor)	Qi (Designer)	Weighted Qi	Rank
Importance of Opinion	0.4	0.3	0.3		
Alternatives					
Reinforced Concrete	1.000	1.000	1.000	1.000	4
Structural Steel	0.948	0.699	0.854	0.845	3
Timber	0.000	0.000	0.000	0.000	1
Reinforced Masonry	0.634	0.663	0.796	0.692	2

Step 10: Similar analysis was done on the user inputs from teams 1 and 2 to rank the alternatives. All the results are compiled in Table 4.35.

Table 4.35. The overall result of Fuzzy VIKOR for different teams

	Team 1		**Team 2**		**Team 3**	
Alternatives	Weighted Q_i	Rank	Weighted Q_i	Rank	Weighted Q_i	Rank
Reinforced Concrete	0.027	1	0.306	2	1.000	4
Structural Steel	0.342	2	0.199	1	0.845	3
Timber	0.997	4	0.850	4	0.000	1
Reinforced Masonry	0.946	3	0.580	3	0.692	2

4.7 Calculation of Criteria Weightage Using Decision Matrix

In this stage, criteria weightage was calculated with the decision matrix using equation 3.34 mentioned in chapter 3. A summary of the result is shown in Table 4.36.

Table 4.36. Criteria weightage of all teams with a decision matrix

Stakeholders	Team 1			**Team 2**			Team 3		
Criteria	Owner 1	Constructor 1	Designer 1	**Owner 2**	**Constructor 2**	**Designer 2**	Owner 3	Constructor 3	Designer 3
Durability (life expectancy)	0.057	0.092	0.067	**0.062**	**0.121**	**0.054**	0.070	0.052	0.087
Constructability (Ease of construction)	0.040	0.107	0.084	**0.067**	**0.016**	**0.113**	0.054	0.057	0.069
Maintainability	0.050	0.068	0.053	**0.061**	**0.103**	**0.046**	0.063	0.051	0.042
Resistance to Water and Weather	0.063	0.061	0.071	**0.087**	**0.033**	**0.061**	0.029	0.030	0.045
Material Cost	0.126	0.119	0.112	**0.044**	**0.012**	**0.137**	0.105	0.058	0.081
Construction Cost	0.178	0.141	0.117	**0.065**	**0.012**	**0.137**	0.064	0.049	0.081
Maintenance Cost	0.064	0.058	0.065	**0.088**	**0.102**	**0.069**	0.041	0.044	0.059
End of Life Cost	0.050	0.027	0.036	**0.045**	**0.106**	**0.021**	0.028	0.026	0.035
Job Opportunity Creation	0.038	0.024	0.044	**0.058**	**0.039**	**0.023**	0.039	0.037	0.032
Fire Resistance and Safety	0.097	0.063	0.081	**0.094**	**0.068**	**0.094**	0.038	0.033	0.029
Skilled Labor Availability	0.037	0.086	0.043	**0.077**	**0.012**	**0.098**	0.036	0.031	0.028
Compatibility with Heritage	0.031	0.019	0.033	**0.070**	**0.087**	**0.044**	0.026	0.018	0.024
Green House Gas Emission	0.052	0.027	0.066	**0.047**	**0.086**	**0.026**	0.168	0.125	0.178
Impact During Manufacturing	0.037	0.033	0.051	**0.044**	**0.077**	**0.026**	0.100	0.122	0.070
Impact During Construction	0.037	0.040	0.051	**0.046**	**0.044**	**0.028**	0.081	0.137	0.071
Recycle and Reuse Potential	0.044	0.036	0.028	**0.046**	**0.081**	**0.023**	0.059	0.130	0.069

4.8 Ranking of Alternatives with Fuzzy TOPSIS (Using Decision Matrix Weightage)

Previously Fuzzy TOPSIS ranking in Section 4.5 was done using the criteria weightage of Fuzzy AHP. Here the same process has been repeated using the weightage obtained through the decision matrix to compare outcomes in the subsequent phase. Table 4.37 shows the result of this combination.

Table 4.37. 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
Reinforced Concrete	0.5674	1	0.6897	1	0.3899	3
Structural Steel	0.5546	2	0.5510	2	0.4289	2
Timber	0.4592	3	0.2967	4	0.6695	1
Reinforced Masonry	0.4282	4	0.3736	3	0.3529	4

4.9 Results and Discussions

Initially, fuzzified normalized weightage of criteria was calculated using AHP for nine responses. From Figure 4.7, it is understood that construction cost, material cost and GHG emissions were essential criteria decided by the stakeholders and thus got higher weightage. A graphical representation of the weightage summary of teams is given in Figure 4.8. Team 1 assigned higher weightage for technical and lower for the environmental criteria. Criteria weightage of technical, economic and social of Team 2 are in a close range; however, they assigned relatively minor importance to the environmental criteria. Team 3, on the other hand, closely distributed the weightage for all, giving the highest emphasis on environmental criteria. The weightage obtained through these calculations is used in subsequent phases for ranking the alternatives. The result's acceptance in this method was determined by checking the consistency ratio, which was less than 10% in all cases.

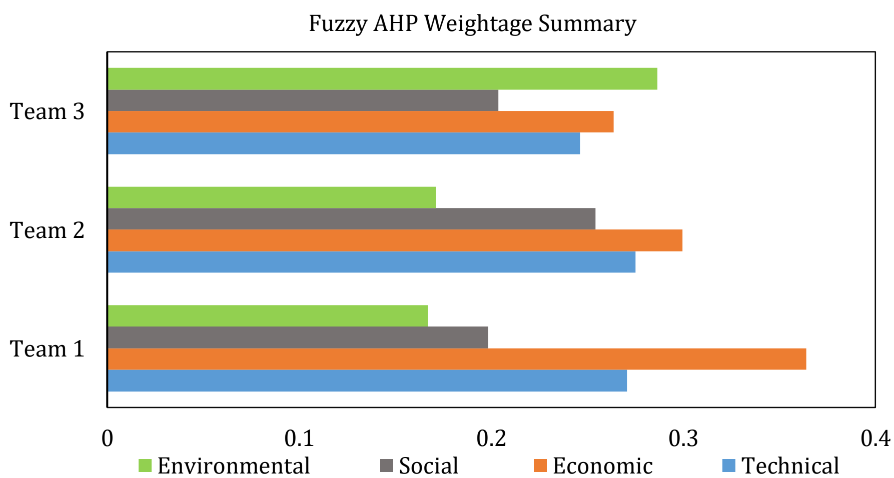


Figure 4.8. Summary of the fuzzified normalized weightage of all teams

The next step of the calculation was ranking alternatives with Fuzzy TOPSIS using criteria weightage calculated by Fuzzy AHP. The result of this method is interpreted from the CC (closeness coefficient); the greater the CC, the higher the ranking. Any team's weighted CC was calculated considering the importance of the opinion of the owner, constructor and designer as 40%, 30%, and 30%, respectively, in the group decision-making process. For Team 1, the final weighted CC for RC, SS, Timber and RM were

0.5753, 0.5502, 0.3915, and 0.44327, respectively. The ranking of alternatives for that group was the first priority: RC, second priority: SS, third priority: RM and last priority: Timber. The weighted CC of Team 2 for RC, SS, Timber and RM were 0.7572, 0.5441, 0.1892, and 0.3884, respectively. RC also became the first choice according to their preferences, followed by SS, RM and Timber. In the case of Team 3, the weighted CC were 0.3653, 0.4590, 0.6404, and 0.3786 for RC, SS, Timber and RM, respectively. Timber became the first preference for this group, and then the SS, RM and RC sequentially. As a whole, RC was the first and timber was the last preference of Teams 1 and 2. On the contrary, timber was the first and RC was the last choice in the case of Team 3.

The same sets of data were then calculated using the Fuzzy VIKOR method. Criteria weightage obtained through Fuzzy AHP was applied here while ranking the alternatives. As discussed, its ranking is based on closeness to the ideal solution and is expressed with the term VIKOR Index (Qi). In the case of Team 1, the Qi values for RC, SS, Timber and RM were 0.027, 0.342, 0.997, and 0.946; therefore, RC was this group's most preferred option. The Qi values for Team 2 were 0.306, 0.199, 0.850, and 0.580 for RC, SS, Timber and RM respectively. Priority of options of this group was SS, RC, RM and Timber, respectively. Finally, Qi for Team 3 was 1.000, 0.845, 0.000, and 0.692 for RC, SS, Timber and RM, and timber was the most preferred alternative among all options. In brief, Team 1 preferred RC, Team 2 preferred SS and Team 3 preferred timber as the best option. On the contrary, timber was the least preferred option for Team 1 and 2; RC was the same choice for Team 3.

In addition to Fuzzy AHP, we employed a decision matrix to calculate criteria weightage in this research. The summary of the weight for all respondents are given in Table 4.38. Fuzzy AHP is a widely used method to calculate the criteria weightage. However, once the number of criteria is large, it becomes difficult for the users to make the pairwise comparison of all, and thus inconsistency of the result increases. We had to review the responses of individuals a couple of times in many cases to bring consistency to pairwise comparisons in this study. In this method, users can not assign weightage to any criteria; instead, the computation technique does that depending on the pairwise comparisons the users give. Users cannot also make an irrational comparison of criteria as that would cause inconsistency.

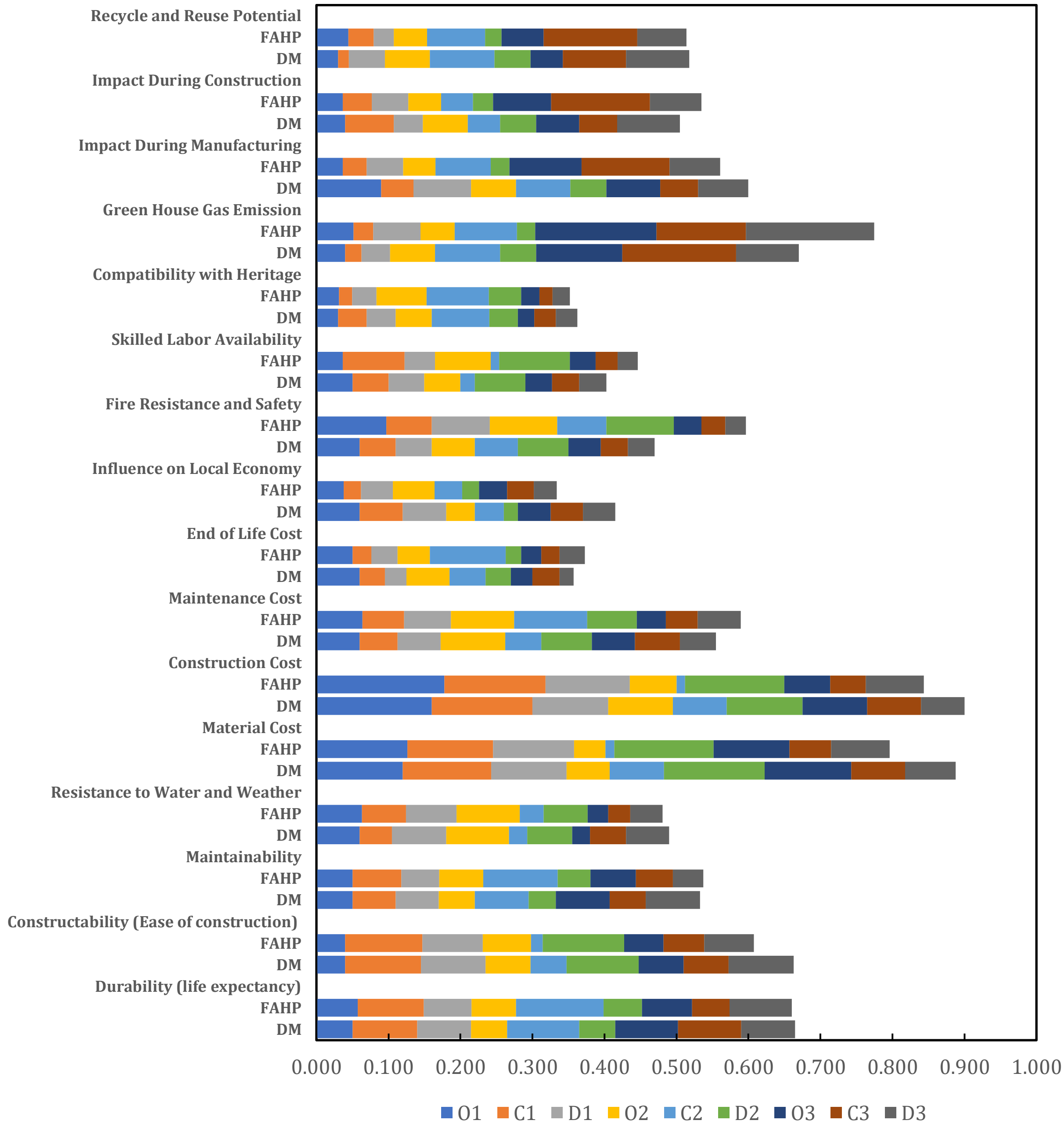


Figure 4.9. Comparison of criteria weightage- FAHP vs Decision Matrix

Compared to Fuzzy AHP, the decision matrix employed a straightforward way to assign preference and weightage to the users. The respondents could perceive the relative importance of criteria and assign weightage to those. It takes significantly less time, and there is no chance of inconsistency. A comparative study of the criteria weights obtained through these two techniques is given in Figure 4.9. The result shows differences in the computed weightage of criteria due to variations in input techniques and calculation methodologies. However, the notable finding is that the result reflects that an individual who gave relatively more importance to any criterion in Fuzzy AHP did the same for the decision matrix. For example, the criterion 'compatibility with local heritage' was less important to Owner 1 of Team 1, and the criterion 'construction cost' was too essential, and these are prominent in both techniques.

Both Fuzzy TOPSIS and Fuzzy VIKOR are based on the principle of an aggregating function representing closeness to the ideal solution. However, these methods use different types of normalization, where TOPSIS uses vector normalization and VIKOR uses linear normalization. The aggregate function used in VIKOR represents a distance (Q_i) from the ideal solution, whereas TOPSIS uses a ranking index (CC) that calculates the distance from positive and negative ideal solutions. Therefore, the highest-ranked alternative by TOPSIS is the highest-ranked index and always not necessarily the closest to the ideal solution, which is in the case of VIKOR (Opricovic and Tzeng, 2004). In this study, rankings of alternatives were done employing both these methods using the criteria weightage from Fuzzy AHP. A comparison of the results obtained is shown in Figure 4.10. We obtained twenty-four ranking results in this study, involving twelve from Fuzzy TOPSIS and Fuzzy VIKOR. Except for four cases, all other results were similar in both techniques. For Team 2, exceptions were in the case of RC, where it was ranked 1 with Fuzzy TOPSIS and 2 with Fuzzy VIKOR and SS in the opposite order. For Team 3, exceptions were in the case of SS, which was ranked 2 with Fuzzy TOPSIS and 3 with Fuzzy VIKOR, and RM was ranked 3 with Fuzzy TOPSIS and 2 with Fuzzy VIKOR. These happened once there were conflicting situations between the distance measured from the ideal solution by these techniques.

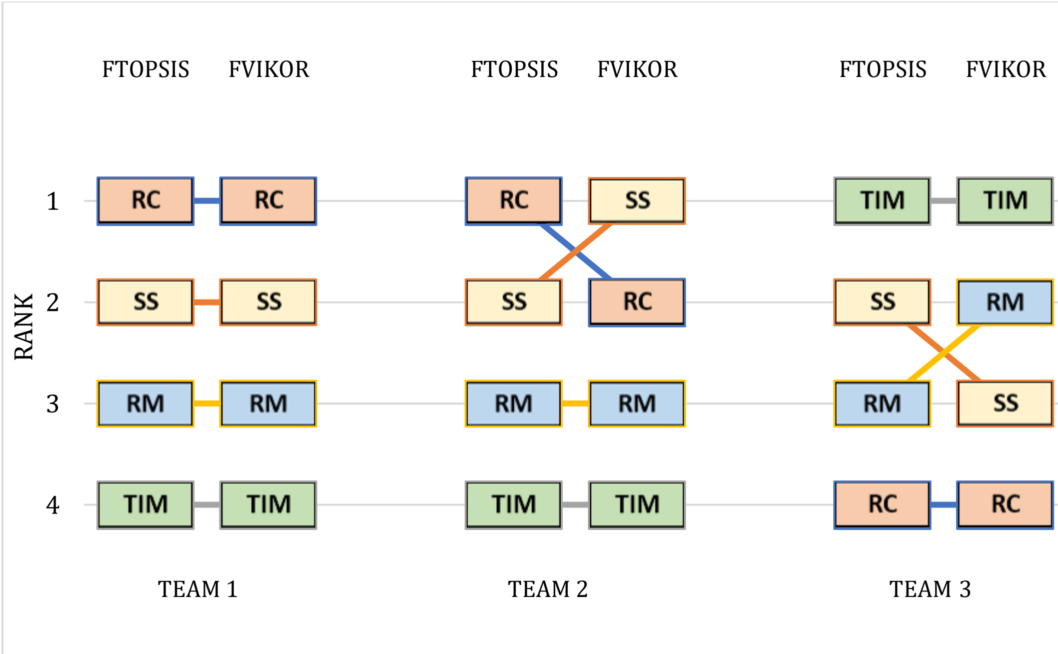


Figure 4.10. Comparison of final ranking results by Fuzzy TOPSIS and Fuzzy VIKOR

Data analysis and results deduced that a decision from this model is entirely dependent on the user inputs. There is no ideal solution for these problems; instead, an optimum solution is desired considering all sustainability factors. This system calculates based on the users' information: weightage of the criteria and preferences for different alternatives. Therefore, it can be concluded that a sustainable selection is only possible if the stakeholders change their traditional thinking process based on short-term economic gain and seek a sustainable solution. In this study, out of three teams, two were from traditional construction industries, and the third team comprised members who were either researching or implementing sustainable construction. The results reflected their organizational behaviour and showed that the selection of Teams 1 and 2 was more inclined towards technical and economic aspects. Their priority for social and environmental aspects was relatively lower; therefore, reinforced concrete or structural steel was the top-ranked alternative resulting from inputs on criteria weightage and preferences. On the contrary, the preferences of Team 3 were more balanced, giving due importance to social and environmental aspects; therefore, timber was the most preferred selection as the structural material for this eight-story residential building.

One of the expected industrial contributions of this research was to develop a DSS that should assist the decision-makers in choosing evaluation criteria and assign relative importance to those in the combination of qualitative and quantitative methods in an IPD framework for selecting the most sustainable structural material. In doing so, the user input pane was kept as simple as possible, and the decision matrix technique was used to calculate criteria weightage. Fuzzy TOPSIS with a trapezoidal membership function was used for ranking the alternatives. Details of the multi-criteria DSS are explained in the next section of this chapter.

4.10 Details of DSS Software

4.10.1 Brief Description

'Microsoft dot-net framework' was used to develop this software, which can run on the Windows platform. The coding was done using C sharp. The algorithm for criteria weightage is based on the decision matrix, and the ranking of alternatives is based on Fuzzy TOPSIS logic following trapezoidal membership distribution functions. 'MySQL' and the 'windows database server' were used for database management. A few notable features of this multi-criteria DSS desktop application are given below:

- It is a joint application where all stakeholders (owner, constructor, design team) can give their inputs in the IPD framework for a decision.
- Users can edit/ modify the alternatives and evaluation criteria. The numbers of qualitative and quantitative inputs can also be adjusted.
- Users have the option to set the importance of criteria.
- This application can handle both qualitative and quantitative data. It shall take the qualitative inputs as the users' preferences (i.e., 'very high,' 'high,' etc.) and quantitative inputs as computed numerical values.
- Stakeholders can also set the importance of their opinions in group decision-making (for example, the matter of the owner's opinion may have 40% weightage, and that of the constructor and design team maybe 30% each).

- It can develop, store and compare multiple scenarios of a project.
- Most importantly, it is a generic model that can be used for multiple sustainable group decision-making purposes.

4.10.2 User Input to the System

4.10.2.1 Basic Information

Initially, users need to create a project ID and password to use this application and retrieve and secure data for future use. After logging in, they will be asked to insert a few basic information about the project, like, the name and location of the project, building height, gross floor area, etc.

Figure 4.11. User login page of the software

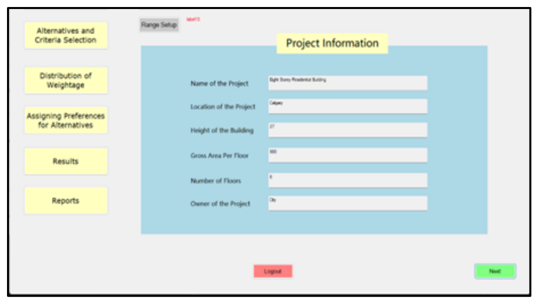


Figure 4.12. Basic information about the project

4.10.2.2 Alternatives and Criteria Selection

The following input of the application regards the selection of the alternatives (e.g., Reinforced Concrete, Structural Steel, Timber, and Reinforced Masonry in this study). They can include new alternatives here or retrieve information from the created database. Next is the selection of evaluation criteria for all pillars of sustainable construction, and users have the flexibility here to select criteria pertinent to any project.

Figure 4.13. Alternative and evaluation criteria selection

4.10.2.3 Weightage Distribution

In this input stage, all stakeholders of the decision-making team need to assign weightage for four main criteria and a group of sub-criteria under each criterion. It takes place in two steps. In step one, the owner, design team, and constructor need to assign weightage for technical, economic, social, and environmental criteria out of 100. This distribution of weightage is the setting of overall importance for pillars of sustainable construction. In step two, stakeholders need to assign a percentage of importance to each sub-criterion under technical, economic, social, and environmental criteria.

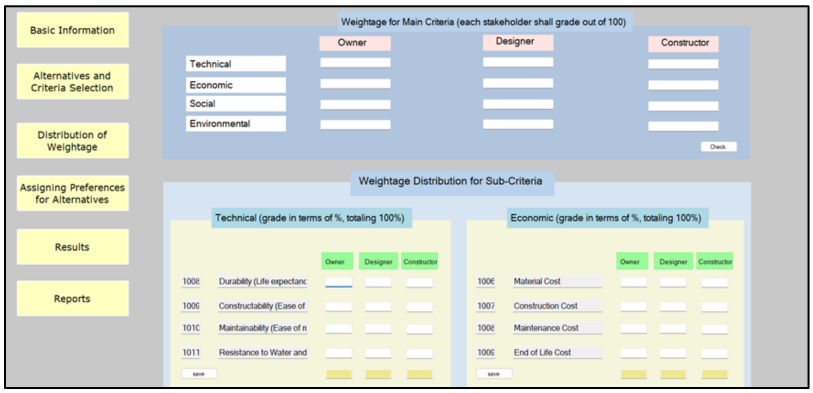


Figure 4.14. Distribution of weightage

4.10.2.4 Assigning Preferences for Different Alternatives

The final user's input is regarding assigning preference for different alternatives. Here all stakeholders need to assign their importance to different alternatives chosen at the initial stage. The inputs are in terms of 'very high,' 'high,' etc. for all the evaluation criteria that need to be assigned, comparing all alternatives considered for the decision-making problem. The Fuzzy TOPSIS algorithm then analyzes these inputs to rank the alternatives.

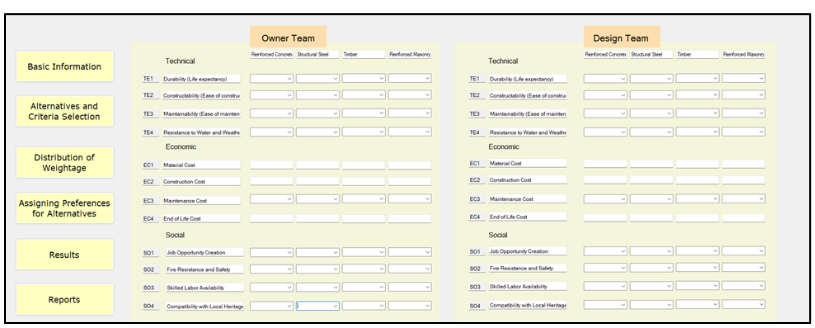


Figure 4.15. Assigning preferences for different alternatives

4.10.3 C Sharp Coding and Computation Algorithm

The computation algorithm and coding were used to control the user's inputs, develop logic for calculations, and generate outputs in this application. A few screenshots of software codes are given in Figures 4.16 to Figure 4.18 and more details are given in Appendix C.

```
if (wRSTO1 != 0 && wRSTO1 != 0 && wRSTO1 != 0 && wRSTO1 != 0)
{
    string query1, query2, query3, query4, query5, query6, query7, query8, query9, query10, query11, query12, query13, qu
    query1 = "insert into [MCDM].[dbo].[Owner_Weightage_value](item,weightage_value,rank) values('" + txtTe1.Text + "','"
    query2 = "insert into [MCDM].[dbo].[Owner_Weightage_value](item,weightage_value,rank) values('" + txtTe2.Text + "','"
    query3 = "insert into [MCDM].[dbo].[Owner_Weightage_value](item,weightage_value,rank) values('" + txtTe3.Text + "','"
    query4 = "insert into [MCDM].[dbo].[Owner_Weightage_value](item,weightage_value,rank) values('" + txtTe4.Text + "','"
    query5 = "insert into [MCDM].[dbo].[Owner_Weightage_value](item,weightage_value,rank) values('" + txtEc1.Text + "','"
    query6 = "insert into [MCDM].[dbo].[Owner_Weightage_value](item,weightage_value,rank) values('" + txtEc2.Text + "','"
    query7 = "insert into [MCDM].[dbo].[Owner_Weightage_value](item,weightage_value,rank) values('" + txtEc3.Text + "','"
    query8 = "insert into [MCDM].[dbo].[Owner_Weightage_value](item,weightage_value,rank) values('" + txtEc4.Text + "','"
    query9 = "insert into [MCDM].[dbo].[Owner_Weightage_value](item,weightage_value,rank) values('" + txtSo1.Text + "','"
    query10 = "insert into [MCDM].[dbo].[Owner_Weightage_value](item,weightage_value,rank) values('" + txtSo2.Text + "','
    query11 = "insert into [MCDM].[dbo].[Owner_Weightage_value](item,weightage_value,rank) values('" + txtSo3.Text + "','
    query12 = "insert into [MCDM].[dbo].[Owner_Weightage_value](item,weightage_value,rank) values('" + txtSo4.Text + "','
    query13 = "insert into [MCDM].[dbo].[Owner_Weightage_value](item,weightage_value,rank) values('" + txtEn4.Text + "','
    query14 = "insert into [MCDM].[dbo].[Owner_Weightage_value](item,weightage_value,rank) values('" + txtEn2.Text + "','
    query15 = "insert into [MCDM].[dbo].[Owner_Weightage_value](item,weightage_value,rank) values('" + txtEn3.Text + "','
    query16 = "insert into [MCDM].[dbo].[Owner_Weightage_value](item,weightage_value,rank) values('" + txtEn4.Text + "','
```

Figure 4.16. C sharp codes for computing weightage value given by users

```
//calculation for owner
//owner technical
//first row
//ot11

if (ot11.Text == "Very High")
{
    os5rct1[0] = s4rct1[0]*7;
    os5rct1[1] = s4rct1[1]*8;
    os5rct1[2] = s4rct1[2]*9;
    os5rct1[3] = s4rct1[3]*10;

}
else if (ot11.Text == "High")
{
    os5rct1[0] = s4rct1[0]*5;
```

Figure 4.17. C sharp codes for fuzzification (trapezoidal distribution) from user input

```
//step 8 calculation owner
//Math.Pow(b, 2);
//Math.Sqrt(x)
//rc pos
os8rct1[0] = Math.Sqrt(0.25 * (Math.Pow((opt1[0] - os6rct1[0]), 2) + Math.Pow((opt1[1] - os6rct1[1]), 2) + Math.Pow((opt1[2] - os6rct1[2]), 2) + Math.Pow((opt1
os8rct2[0] = Math.Sqrt(0.25 * (Math.Pow((opt2[0] - os6rct2[0]), 2) + Math.Pow((opt2[1] - os6rct2[1]), 2) + Math.Pow((opt2[2] - os6rct2[2]), 2) + Math.Pow((opt2
os8rct3[0] = Math.Sqrt(0.25 * (Math.Pow((opt3[0] - os6rct3[0]), 2) + Math.Pow((opt3[1] - os6rct3[1]), 2) + Math.Pow((opt3[2] - os6rct3[2]), 2) + Math.Pow((opt3
os8rct4[0] = Math.Sqrt(0.25 * (Math.Pow((opt4[0] - os6rct4[0]), 2) + Math.Pow((opt4[1] - os6rct4[1]), 2) + Math.Pow((opt4[2] - os6rct4[2]), 2) + Math.Pow((opt4
os8rce1[0] = Math.Sqrt(0.25 * (Math.Pow((ope1[0] - os6rce1[0]), 2) + Math.Pow((ope1[1] - os6rce1[1]), 2) + Math.Pow((ope1[2] - os6rce1[2]), 2) + Math.Pow((ope1
os8rce2[0] = Math.Sqrt(0.25 * (Math.Pow((ope2[0] - os6rce2[0]), 2) + Math.Pow((ope2[1] - os6rce2[1]), 2) + Math.Pow((ope2[2] - os6rce2[2]), 2) + Math.Pow((ope2
os8rce3[0] = Math.Sqrt(0.25 * (Math.Pow((ope3[0] - os6rce3[0]), 2) + Math.Pow((ope3[1] - os6rce3[1]), 2) + Math.Pow((ope3[2] - os6rce3[2]), 2) + Math.Pow((ope3
os8rce4[0] = Math.Sqrt(0.25 * (Math.Pow((ope4[0] - os6rce4[0]), 2) + Math.Pow((ope4[1] - os6rce4[1]), 2) + Math.Pow((ope4[2] - os6rce4[2]), 2) + Math.Pow((ope4
os8rcs1[0] = Math.Sqrt(0.25 * (Math.Pow((ops1[0] - os6rcs1[0]), 2) + Math.Pow((ops1[1] - os6rcs1[1]), 2) + Math.Pow((ops1[2] - os6rcs1[2]), 2) + Math.Pow((ops1
os8rcs2[0] = Math.Sqrt(0.25 * (Math.Pow((ops2[0] - os6rcs2[0]), 2) + Math.Pow((ops2[1] - os6rcs2[1]), 2) + Math.Pow((ops2[2] - os6rcs2[2]), 2) + Math.Pow((ops2
os8rcs3[0] = Math.Sqrt(0.25 * (Math.Pow((ops3[0] - os6rcs3[0]), 2) + Math.Pow((ops3[1] - os6rcs3[1]), 2) + Math.Pow((ops3[2] - os6rcs3[2]), 2) + Math.Pow((ops3
os8rcs4[0] = Math.Sqrt(0.25 * (Math.Pow((ops4[0] - os6rcs4[0]), 2) + Math.Pow((ops4[1] - os6rcs4[1]), 2) + Math.Pow((ops4[2] - os6rcs4[2]), 2) + Math.Pow((ops4
os8rcen1[0] = Math.Sqrt(0.25 * (Math.Pow((open1[0] - os6rcen1[0]), 2) + Math.Pow((open1[1] - os6rcen1[1]), 2) + Math.Pow((open1[2] - os6rcen1[2]), 2) + Math.Pc
os8rcen2[0] = Math.Sqrt(0.25 * (Math.Pow((open2[0] - os6rcen2[0]), 2) + Math.Pow((open2[1] - os6rcen2[1]), 2) + Math.Pow((open2[2] - os6rcen2[2]), 2) + Math.Pc
os8rcen3[0] = Math.Sqrt(0.25 * (Math.Pow((open3[0] - os6rcen3[0]), 2) + Math.Pow((open3[1] - os6rcen3[1]), 2) + Math.Pow((open3[2] - os6rcen3[2]), 2) + Math.Pc
os8rcen4[0] = Math.Sqrt(0.25 * (Math.Pow((open4[0] - os6rcen4[0]), 2) + Math.Pow((open4[1] - os6rcen4[1]), 2) + Math.Pow((open4[2] - os6rcen4[2]), 2) + Math.Pc

//rc neg
os8rct1[1]= Math.Sqrt(0.25 * (Math.Pow((ont1[0] - os6rct1[0]), 2) + Math.Pow((ont1[1] - os6rct1[1]), 2) + Math.Pow((ont1[2] - os6rct1[2]), 2) + Math.Pow((ont1[
os8rct2[1]= Math.Sqrt(0.25 * (Math.Pow((ont2[0] - os6rct2[0]), 2) + Math.Pow((ont2[1] - os6rct2[1]), 2) + Math.Pow((ont2[2] - os6rct2[2]), 2) + Math.Pow((ont2[
```

Figure 4.18. C sharp codes to calculate the distance of each alternative from FPIS and FNIS

4.10.4 System Output

In the end, this application shall generate several outputs for the users. The outputs include a graph with criteria weightage, rankings for individual stakeholders, and an overall ranking of alternatives. A screenshot of the output is shown in Figure 4.19. The weightage distribution graph shall display a summary of the weightage assigned by different stakeholders. It shall represent the different importance stakeholders gave to technical, economic, social and environmental aspects. The results for the priority of alternatives for different stakeholders will also be displayed in three tables. Finally, the stakeholders will have the opportunity to assign importance to their opinion to get the overall ranking of the alternatives.

Figure 4.19. Graphical output for weightage distribution and ranking of alternatives

CHAPTER 5: VERIFICATION AND VALIDATION

5.1 Introduction

This chapter discussed the methods for verifying and validating calculations and developing DSS. Input and output validation of the DSS was done through experts' feedback and comments, whereas verification of calculations and DSS was done through sensitivity analysis.

5.2 Sensitivity Analysis

Sensitivity analysis studies how changes to input factors or variables affect the output of a system. It is a verification process to check that the system fulfils the intended purpose by analyzing the output results with the variations of input parameters. In this research, sensitivity analysis was carried out by running the developed model under various scenarios to ensure that it is responsive to changes in its input and that the output makes meaningful results. The decision made by the multi-criteria DSS in this study is based on two types of user inputs: inputs to calculate the criteria's weight and preferences to rank alternatives according to the criteria's attributes (i.e., 'very high,' 'high,' etc). The procedure is discussed in subsequent sections.

5.2.1 Criteria Weightage Sensitivity

The sensitivity of user input and criteria weight was analyzed, creating four different scenarios. Four sets of weights for criteria were used to represent four instances, as shown in table 5.1. Those scenarios were then tested to observe their influences on CC_i values of the developed DSS expressing the ranking of alternatives. Here, one pillar's criterion weights were assigned larger weights than the others' for each scenario, as shown in Table 5.1. In Table 5.2, input value findings and in Figure. 5.1 results demonstrate that altering the weights of the criterion significantly affects the CC_i values of the alternatives. If the criteria weightage for any sustainability pillar is increased, giving more priority to that, the CC_i value also increased significantly and had a substantial impact on ranking.

Table 5.1. Scenarios based on the sustainability pillar's focus

Sustainability Pillars	Criteria	Code	Criteria Weight			
			Scenario 1	Scenario 2	Scenario 3	Scenario 4
Technical	Durability (life expectancy)	TEC1	**0.10**	0.05	0.05	0.05
	Constructability (Ease of construction)	TEC2	**0.10**	0.05	0.05	0.05
	Maintainability	TEC3	**0.10**	0.05	0.05	0.05
	Resistance to Water and Weather	TEC4	**0.10**	0.05	0.05	0.05
Economical	Material Cost	ECO1	0.05	**0.10**	0.05	0.05
	Construction Cost	ECO2	0.05	**0.10**	0.05	0.05
	Maintenance Cost	ECO3	0.05	**0.10**	0.05	0.05
	End of Life Cost	ECO4	0.05	**0.10**	0.05	0.05
Social	Job Opportunity Creation	SOC1	0.05	0.05	**0.10**	0.05
	Fire Resistance and Safety	SOC2	0.05	0.05	**0.10**	0.05
	Skilled Labor Availability	SOC3	0.05	0.05	**0.10**	0.05
	Compatibility with Heritage	SOC4	0.05	0.05	**0.10**	0.05
Environmental	Green House Gas Emission	ENV1	0.05	0.05	0.05	**0.10**
	Impact During Manufacturing	ENV2	0.05	0.05	0.05	**0.10**
	Impact During Construction	ENV3	0.05	0.05	0.05	**0.10**
	Recycle and Reuse Potential	ENV4	0.05	0.05	0.05	**0.10**

In Table 5.1, for each scenario, four criteria of one sustainability pillar were weighted higher value of 0.10 each, and the other 12 criteria were weighted by 0.05. Users' input for preferences for different alternatives was kept constant to observe the impact on the decision-making process. The option with a greater input in favorable of positive criteria would be ranked higher; conversely, negative or cost factors would have the opposite effect. For validation, criteria weightage from this table was then used in the same sample Fuzzy TOPSIS calculation that was explained in chapter 4 to rank the alternatives. Each scenario derived one set of ranking results for the alternatives while criteria weightage was only altered, and user preferences were kept constant. The output results for different scenarios are shown 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
CC_{rc}	0.367	0.493	0.358	0.402	2	0.287	0.393	0.337	0.334	4
CC_{ss}	0.352	0.394	0.438	0.390	3	0.451	0.471	0.478	0.465	2
CC_t	0.621	0.533	0.685	0.614	1	0.625	0.534	0.616	0.595	1
CC_{rm}	0.395	0.394	0.333	0.376	4	0.409	0.441	0.394	0.414	3

Criteria	Scenario 3					Scenario 4				
	Owner	Constructor	Designer	Overall	Rank	Owner	Constructor	Designer	Overall	Rank
CC_{rc}	0.308	0.398	0.339	0.345	4	0.269	0.432	0.318	0.332	4
CC_{ss}	0.308	0.357	0.390	0.347	3	0.404	0.418	0.425	0.415	2
CC_t	0.638	0.610	0.678	0.642	1	0.676	0.553	0.655	0.633	1
CC_{rm}	0.479	0.477	0.434	0.465	2	0.390	0.416	0.333	0.381	3

In scenario 1, it is observed that providing the technical pillars with a greater criteria weightage affected the ranking of RC for Team 3, which is ranked here as the second priority. Figure 5.1 displays all other impacts graphically once technical, economic, social and environmental factors are prioritized more. When the overall impact of Team 3 is considered, giving more technical priorities resulted in reinforced concrete having a higher CC_i value, whereas higher social and environmental priorities resulted in better CC_i for timber. SS was given higher consideration when ranking according to economic priorities. Similar explanations are applicable for other scenarios too.

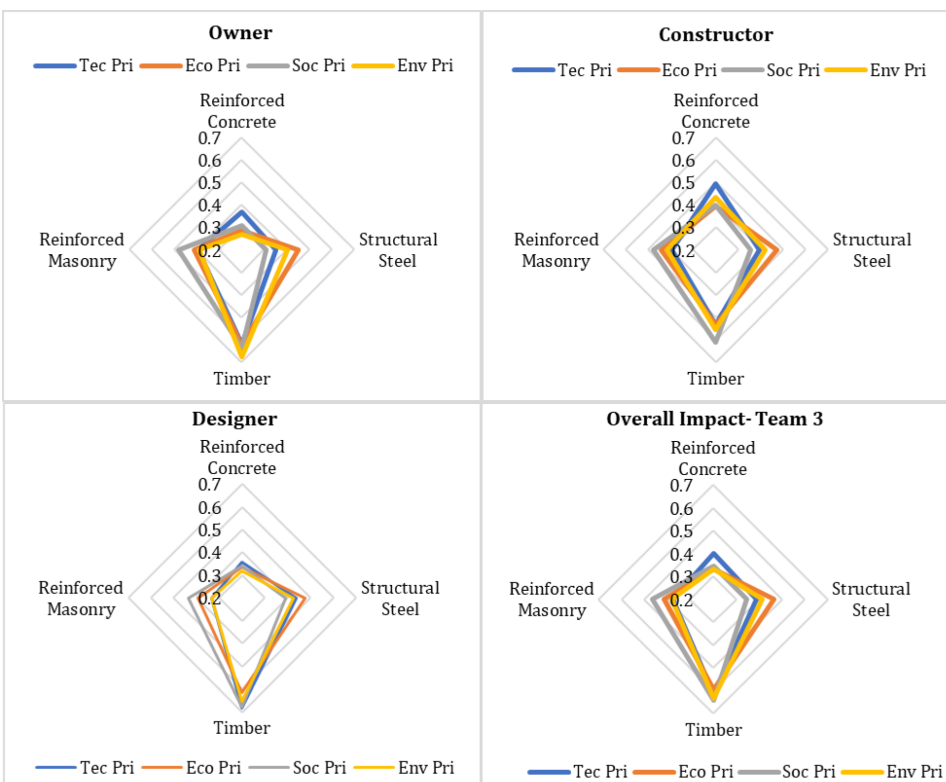


Figure 5.1. Radar chart showing the sensitivity of the model for criteria weightage

5.2.2 Sensitivity Analysis of User Preferences for Alternatives

The user's input determines how the alternatives are ranked. Four scenarios are depicted here to investigate the variability of the CC_i value caused by various user inputs regarding preferences for alternatives. Here, all the criteria were given equal weight to verify the model's sensitivity to visualize the user preference input vividly.

5.2.2.1 Scenario 1

For scenario 1, the cost criteria (i.e., lower is better) were given lower preference values, and the benefit criteria (i.e., higher is better) were given higher preference values for Alternative 1. The preferences were then gradually altered by one step for the subsequent alternatives (i.e., from very high to high, high to medium subsequently). Each criterion weight = 1/16 = 0.0625 was the same; all the decision-makers of the team (owner, constructor, and designer) were given equal importance, and then alternatives were evaluated with the inputs, as shown in table 5.3.

Table 5.3. Hypothetical user input for Scenario 1

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

The output result of this hypothetical user input is shown in Table 5.4 and Figure 5.2. From the ranking result, it is derived that higher input value of beneficial criteria and lower input values in cost criteria increased the CC_i value.

Table 5.4. CC_i values for scenario 1

Alternatives	CC_i	Rank
Alternative 1	1	1
Alternative 2	0.542	2
Alternative 3	0.268	3
Alternative 4	0	4

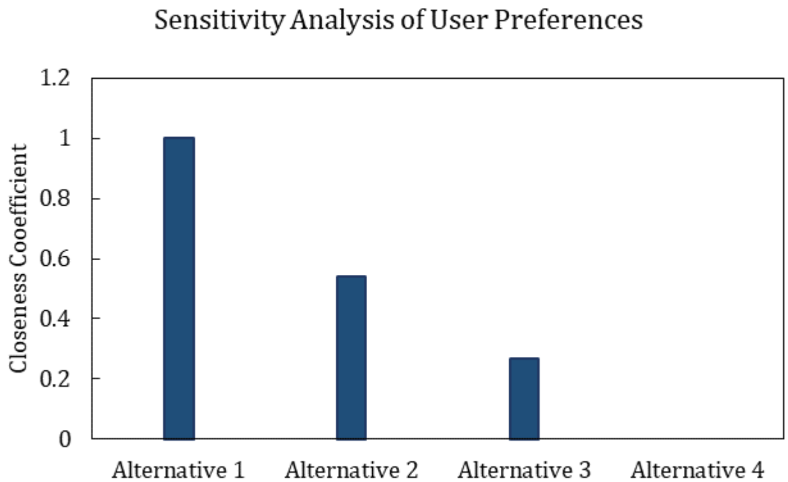


Figure 5.2. CC_i values for scenario 1

In this case (Scenario 1), the best possible condition was created for Alternative 1. It was given the highest preferences (very high) for beneficial criteria and lower preferences (low) for cost criteria. At the same time, weightage for all criteria and stakeholders' importance was kept constant and equal. As a result, Alternative 1 obtained the highest CC_i value, which was expected to determine the model's sensitivity. Similarly, priorities for Alternatives 2, 3 and 4 were gradually altered in the case of user input, and the expected reflection of that was observed in the system's output (Table 5.4 and Figure 5.2).

5.2.2.2 Scenario 2

For scenario 2, each alternative was evaluated with similar preferences for all beneficial and cost criteria (e.g., for Alternative 1, 'very high' preference for all beneficial and cost criteria), as shown in Table 5. 5, to see the influence on the output. The resultant output is tabulated in Table 5.6 and Figure 5.3.

Table 5.5. Hypothetical user input for Scenario 2

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

Alternatives	CC_i	Rank
Alternative 1	0.095	4
Alternative 2	0.261	3
Alternative 3	0.541	2
Alternative 4	0.905	1

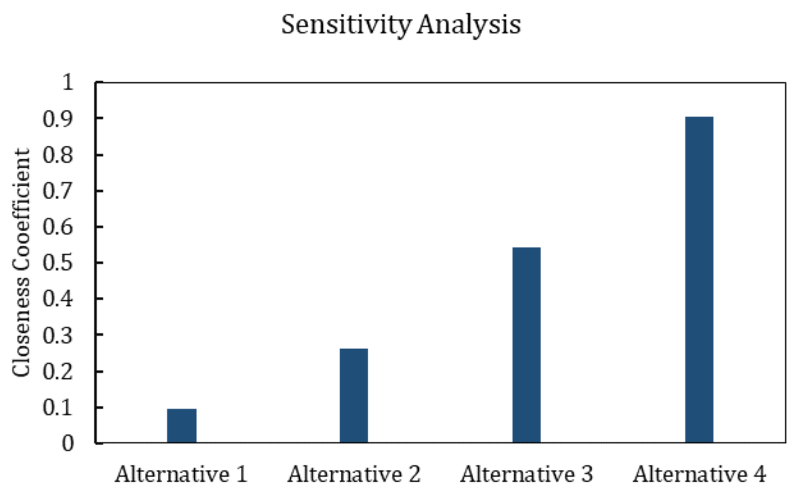


Figure 5.3. CC_i values for scenario 2

In the case of scenario 2, for both beneficial and cost criteria highest preferences (Very High) were given. However, higher preferences would increase ranking when it comes to beneficial criteria, but they have the opposite effect when it comes to cost criteria. From the ranking result of scenario 2, it was derived that a higher input value of cost criteria resultant a lower CC_i value from scenario 1. And for Alternative 4, it added some value CC_i due to its lower preference input in cost criteria. Similarly, priorities for Alternatives 2, 3 and 4 were gradually altered in the case of user input, and the expected reflection of that was observed in the system's output (Table 5.6 and Figure 5.3).

5.2.2.3 Scenario 3

Here, the alternatives are evaluated as shown in Table 5.7, where each alternative is given an identical set of user input. The output is tabulated in Table 5.8 and Figure 5.4.

Table 5.7. Hypothetical 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_ivalues for Scenario 3

Alternatives	CC_i	Rank
Alternative 1	0.5378	1
Alternative 2	0.3692	3
Alternative 3	0.5378	1
Alternative 4	0.3692	3

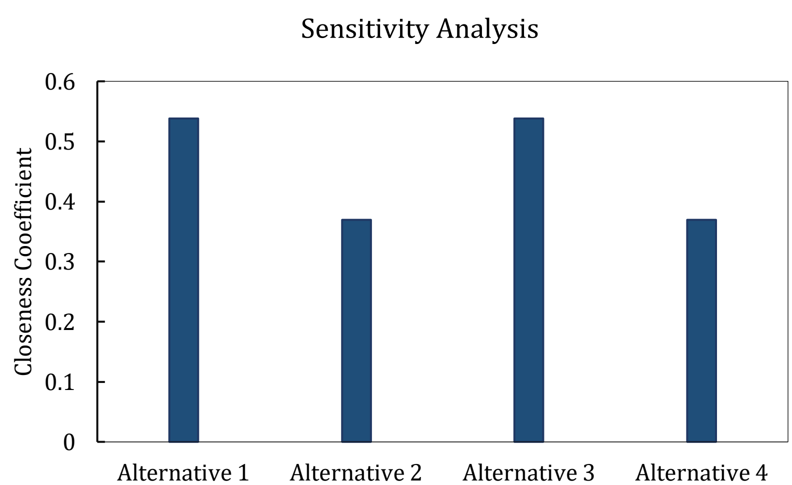


Figure 5.4. CC_i values for scenario 3

In this case (scenario 3), it is noticeable that even though each alternative had the identical nature of user preferences ("Very High" for 4 criteria, "High" for 4 criteria, "Medium" for 4 criteria, and "Low" for 4 criteria) assigned to it, the outcome varied. This is due to the existence of beneficial and cost criteria. The CC_i values for Alternatives 2 and 4 were negatively impacted by higher cost criterion values. This demonstrates that the developed model is sensitive to the input given on its core cost-benefit criteria.

5.2.2.4 Scenario 4

Here, the alternatives are evaluated with randomly assigned user input for various criteria groups (pillars), as shown in Table 5.9, and the output is tabulated in Table 5.10 and Figure 5.5.

Table 5.9. Hypothetical user input for Scenario 4

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

Table 5.10. CC_ivalues 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

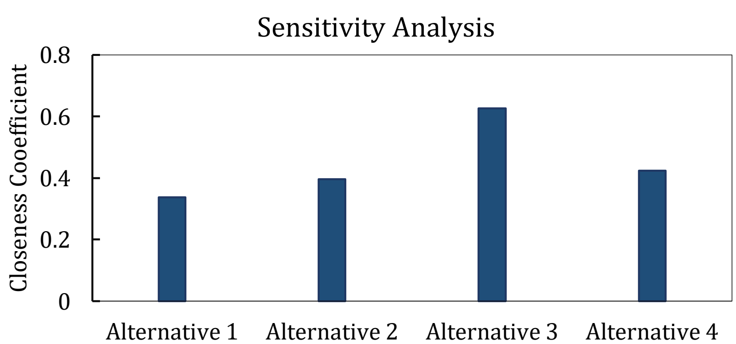


Figure 5.5. CC_i values for scenario 4

In the case of scenario 4, the output result demonstrates that alternative 3 achieved a better rank with a higher CC_i value since it was randomly allocated with a greater number of higher value inputs. Regarding Alternative 3, it received very high preferences across more number (five beneficial) beneficial criteria, which raised its CC_i value and drove it to the top of the ranking. An overall graphical result of the preceding scenarios is presented in Figure 5.6.

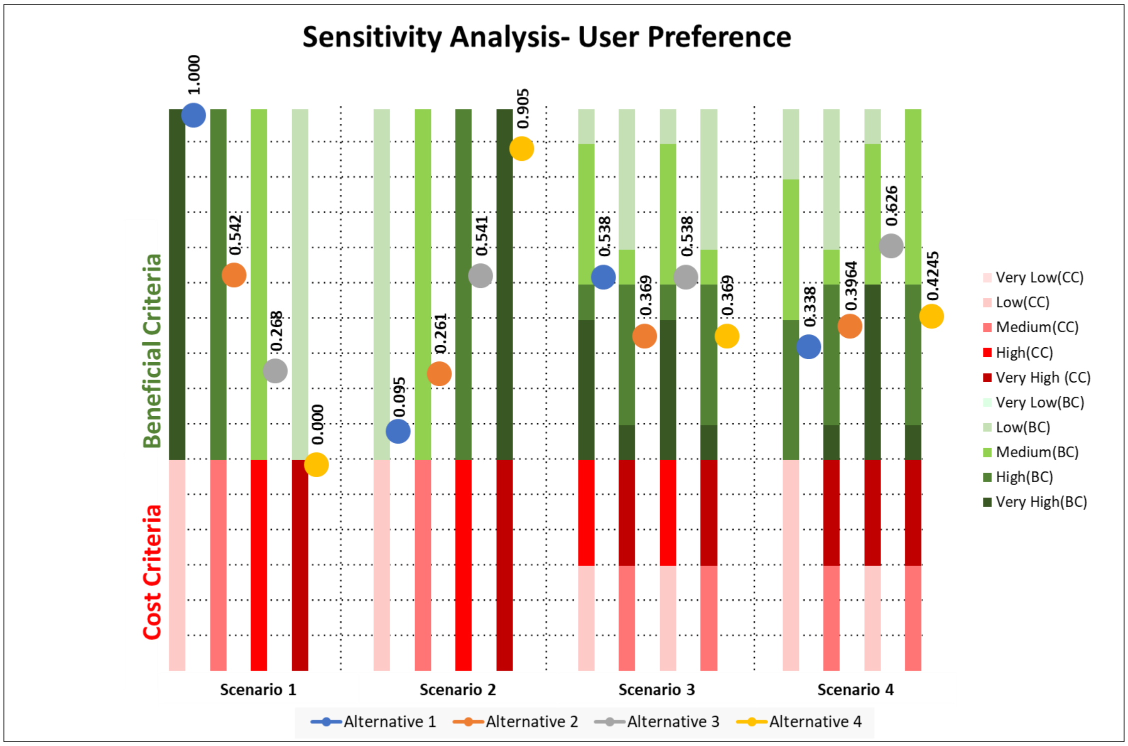


Figure 5.6. User preference sensitivity for all scenarios

5.3 Input Validation of the Developed Decision Support System

5.3.1 Experts' Feedback and Comments During Input Validation Phase

We conducted a series of discussion sessions and meetings with industry and academic experts at the initial stage of the research to know the existing practices and identify the research gap. Based on their comments, expectations and recommendations, we designed the DSS to select the most sustainable alternative from several options. We selected sixteen evaluation criteria most pertinent to this study by combining the literature review and their opinion. After that, a list of criteria and Microsoft Excel templates were emailed to them to check and comment on the criteria' appropriateness, compare those pairwise, and assign preferences for alternatives. They were also requested to comment on the framework of the model, i.e., if the input, output and evaluation system makes sense. All nine participants responded within two weeks and conveyed their feedback. A few salient aspects of their responses and feedback are as follows:

- All respondents agreed on the appropriateness of chosen evaluation criteria for selecting sustainable structural materials for multistoried building construction. Besides, a few commented to add an explanation with some criteria for better understanding.
- Several experts mentioned including both quantitative and qualitative evaluation criteria.
- A few experts commented that assigning weightage was more convenient and time-saving than a pairwise comparison of criteria.
- Different stakeholders might have a distinct role in the decision-making process. For example, if the project owner is the lead role player in the team and might opt to have more importance in their opinion. As such, several experts commented on including the weightage of the opinion of stakeholders in the decision-making.
- All participants filled up their responses for distributing weightage for criteria, pairwise comparison, assigning preferences for alternatives and sending those by email. Some of the responses had consistency issues, which were solved after several revisions.

5.3.2 Steps Taken to Address Experts' Feedback and Comments

We took the necessary steps to address the feedback and comments made by respondents. For example, initially, there was confusion regarding the meaning of the criterion 'maintainability' and whether 'High' means high maintenance or high preference due to low maintenance. Therefore, an explanation for that term was added, 'ease of maintenance.' Quantitative inputs for appropriate criteria were also included in the model, such as the material cost, construction cost, etc. Initially, there were two options to weigh the criteria, i.e., using Fuzzy AHP and a decision matrix. Weightage derived from the decision matrix was used in subsequent phases of the DSS to rank alternatives. Options for the importance of the opinion of stakeholders in terms of percentage have also been included in the model.

5.4 Output Validation of the Developed Decision Support System

5.4.1 Experts Feedback and Comments for Output Validation

At this stage, a series of presentations and demonstrations were conducted to academic and industry experts. Each time an overview of the DSS was given through a 10/ 15 minutes presentation, and then the desktop application of the DSS was demonstrated. Similar DSS in Excel template with user interface and sample calculations was emailed several days before the meetings. The demonstration began with the team's login, and they went through several steps to give input to the system. The developed DSS is generic, and users have the flexibility to choose and modify the number of alternatives and evaluation criteria. However, four alternatives and sixteen evaluation criteria were constant in this study. Users' comments on those were validated in the input validation phase. In the first step of users' input, the selection of alternatives and evaluation criteria were reconfirmed with the stakeholders. Next, each team distributed weightage for all the evaluation criteria. In the third step, different teams assigned preferences for all qualitative evaluation criteria. Values for all quantitative evaluation criteria were determined through LCA, LCCA and cost estimation with Athena Impact Estimator for Building software. In the next step, the application displayed a summary of the weightage distributed for different sustainability pillars by stakeholders. It also displayed the ranking results for different teams. Finally, they were asked to make input on the importance of opinion in the group decision-making process, and then the system displayed the final ranking for all the alternatives. At this point, the stakeholders were requested to comment on the DSS and share their feedback. A few notable comments and feedback are given below:

- As a whole, industry experts expressed their satisfaction with developing a DSS which can assist in selecting the most sustainable alternative. They suggested conducting a similar study on other building components and preparing a DSS that could work for the entire structure.
- Academic experts validated the outcome of the system and reiterated the necessity of connecting the DSS with the database to manage various project information.

5.4.2 Modifications Performed to Include Experts Feedback and Comments

Windows database server was used in the DSS for database management. Project data on cost, use of material, etc., would likely vary depending on the location, and users might therefore store required data for comparison and future use. The scope of this research was limited to the selection of structural components of the building, however, developed DSS might be applicable for other selections too. Required options have been kept for the users to select alternatives and evaluation criteria to deal with other building components.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Overview of the Study

Sustainable construction aims at minimizing harm and maximizing value by balancing social, economic, technical, and environmental pillars of sustainability. Traditionally, construction projects are selected based on return on investment, prioritizing technical and economic aspects, whereas social and environmental considerations receive relatively little attention. When all pillars of sustainability are considered, decision-making becomes more complicated as it combines multiple factors in the selection process. Consequently, in most cases, the project stakeholders opt not to employ a formal decision-making process in determining the most sustainable alternatives. The construction industry plays a vital role in the development and economic production and creates many employment opportunities. However, this sector has also been critiqued for intensive consumption of world resources, high rates of energy use and greenhouse gas emissions. Therefore, it desperately needs better resource efficiency, improved productivity, less waste, and increased value.

The core concept of sustainable construction includes prudent use of natural resources, ensuring increasing economic growth levels, reducing unemployment rates, providing adequate protection of the environment, and assuring increased social progress that recognizes the needs of everyone. Previously numerous works have been done on the selection of building materials; however, none of the works integrated the inputs of all stakeholders, i.e., owner, design team and constructors in the IPD framework from the project's inception to decide on the most preferred sustainable option. Besides, although several researchers argued that the technical pillar is an essential analytic element of sustainability assessment for civil infrastructure, there is hardly any work that systematically integrates the technical pillar with economic, social, and environmental pillars to analyze the overall sustainability aspects. The interview with several industry experts also identified that selecting structural material is commonly taken considering technical and economic factors. There is no structured tool to integrate all stakeholders' opinions or assess the overall aspects of sustainable construction in the selection process. MCDM techniques aid stakeholders in more precise decision-making by effectively using timely and appropriate data, information, and knowledge management. This research developed a multi-criteria DSS involving hybrid MCDM techniques that integrated all stakeholders' preferences into an IPD framework for selecting the most sustainable structural material from the technical, economic, social, and environmental sustainability points of view.

Beams, columns, tension members and their connections are generally considered the structural components of the building, and their selection plays a vital role since they act as the backbone of the structure and demand vast resources. This study compared and analyzed the performances of commonly used structural materials for a multistory building from the sustainability point of view, considering the project's complete life cycle compared to several others focused on technical or economic goals.

6.2 Conclusions

In order to solve the aforementioned problem, this study followed a hybrid approach to develop the decision support system using Fuzzy AHP, decision matrix, Fuzzy TOPSIS and Fuzzy VIKOR multi-criteria decision-making techniques. The foundation of the study was created by an exhaustive literature review and discussion sessions with industry and academic experts. Thereby it reviewed the existing selection process of the structural materials from the point of sustainable construction practices, identification of structural materials in use for multistory building construction, sustainability analysis of structural materials in use, etc. The finding showed that construction industries select the structural materials considering technical and economic aspects, and there was a lack of any sustainable decision-making system. Most of the previous research in this area either focused on technical or economic aspects only or considered three pillars of sustainable construction. However, several researchers and industry experts argued that technical performance should be explicitly included as a pillar of infrastructure sustainability theory. Therefore, this research integrated four pillars in DSS to obtain a sustainable solution.

The evaluation criteria for assessing the technical, economic, social, and environmental pillars of sustainable construction vary based on the type and nature of the construction projects and stakeholders' preferences. The opinions of several industry experts and academic researchers were obtained to finalize the list of sub-criteria appropriate for this research. However, this list was used as the basis for the calculation and development of the algorithms of the DSS. Users would always have the opportunity to change the evaluation criteria depending on the type of the project, its location and stakeholders' preferences. Still, the methodology would work in a similar way for sustainable decision-making.

Steel, concrete, masonry, and timber are the commonly used structural materials in building construction practices. Reinforced concrete is the most often used for its strength, durability, reflectivity, and adaptability. However, ironically, concrete is one of the leading sources of environmental degradation and is harmful to the ecosystem and environment. This phenomenon has led to concerns about seeking alternatives in building construction materials to achieve sustainability.

MCDM has been extensively used in construction industry to select the best possible option from several alternatives. The MCDM techniques generate alternative scenarios, establish criteria, assess alternatives, weigh the criteria, and rank the alternatives. Fuzzy AHP is one of the most powerful and extensively used tools to assign weightage to criteria in MCDM and was used in this research to give weightage to the sixteen chosen evaluation criteria. The trapezoidal membership function was used as it is known to be better at handling uncertainties, imprecision, or a lack of information. In addition, a simple decision matrix was used to assign the weightage of the criteria as inconsistency of data enhances in FAHP with an increasing number of criteria. Fuzzy TOPSIS was chosen to rank the alternatives as it is a widely used, familiar and easy tool for decision-making that has acceptance by industry and academia. Furthermore, a relatively new and less familiar tool, Fuzzy VIKOR, was used in parallel to rank the alternatives, compare the results with Fuzzy TOPSIS and validate its reliability in construction industry. The DSS was designed considering the IPD project delivery method since it contributes more towards sustainability by integrating all stakeholders from the initial stage of the project. It also seeks to improve the triple constraint (cost, time, and quality) outcomes by aligning the project team goals and applying a shared risk and reward system.

For calculations, development and verifications of the DSS, a hypothetical 8-story building was considered in this study. *Athena Impact Estimator for Buildings* has an inbuilt database for Calgary;

therefore, it was chosen as the structure's location for the convenience of LCA and LCCA calculations. Nine industrial and academic experts from Clark Builders, Stantec, GEC Architecture, RJC Engineers, Alberta Masonry Council, Chandos Construction, Wood Works, and the University of Alberta took part in the case study. They were grouped into three teams in the IPD framework, each representing owner, designer, and constructor. Two of the teams included decision-makers from the traditional construction industry, whereas the third team comprised members either researching or implementing sustainable construction.

The collected data were analyzed and calculated in several steps. Though Fuzzy AHP is a widely used method to calculate the criteria weightage, we identified from the responses that once the number of criteria is large, it becomes difficult for the users to make the pairwise comparison of all; thus, inconsistency of the result increases. Therefore, in addition to Fuzzy AHP, we employed a decision matrix to calculate criteria weightage. The results show that differences exist in the computed weightage of criteria due to variations in input techniques and calculation methodologies. However, a notable finding was that an individual who gave relatively more importance to any criterion in Fuzzy AHP did the same for the decision matrix. The criteria weightage obtained through Fuzzy AHP was then used in Fuzzy TOPSIS and Fuzzy VIKOR for ranking the alternatives. There are some similarities and differences in the computation techniques followed by these two methods. Both approaches are based on the principle of an aggregating function representing closeness to the ideal solution. However, these methods use different types of normalization, where TOPSIS uses vector normalization and VIKOR uses linear normalization. The aggregate function used in VIKOR represents a distance from the ideal solution, whereas TOPSIS uses a ranking index that calculates the distance from positive and negative ideal solutions. Therefore, the highest-ranked alternative by TOPSIS is the highest-ranked index and always not necessarily the closest to the ideal solution, which is in the case of VIKOR. In this study, we obtained similar rankings of alternatives applying these methods with similar types of inputs. With the exception of four cases out of twenty-four ranking outcomes, the results were similar in both techniques. These four exceptions happened due to conflicting situations between the distance measured from the ideal solution by these methods.

There were notable differences in the final ranking of the alternatives of different teams. Moreover, it was deduced that there were no ideal solutions to these kinds of problems; instead, optimum solutions can be obtained considering all factors of sustainable construction practices. In some cases, reinforced concrete got the top priority and timber in others. Out of three teams in this study, two were from traditional construction industries and the third one comprised of members who are either researching or implementing sustainable construction. The results reflected their organizational behaviour and showed that the preferences of Teams 1 and 2 were more toward technical and economic aspects. Their priority for social and environmental factors was relatively lower; therefore, reinforced concrete or structural steel was the highest-ranked alternative resulting from their selection. On the contrary, the preferences of Team 3 were more balanced, giving due importance to social and environmental aspects; therefore, timber was the most preferred selection as the structural material for this eight-story residential building. This determined that a decision from this DSS entirely depends on the user inputs. This system calculates based on the users' response to the weightage of the criteria and preferences for different alternatives. If users give more importance to economic gain and ignore the environmental aspects, the output result would reflect that. On the contrary, if the stakeholders make a balanced choice combining all factors of sustainable construction and considering the entire life cycle of the project, their preferred option will comply with sustainable construction, as displayed by the selection of Team 3 in this study.

The DSS has been developed to assist the decision-makers in making a sustainable selection in an IPD framework. A few notable advantages of the developed DSS software include: it is a joint application where all stakeholders can give their inputs in the IPD framework for a decision, users can edit/ modify the alternatives and evaluation criteria according to their needs, and users have the option to set the importance of criteria; this application can handle both qualitative and quantitative data; It shall take the qualitative inputs as the users' preferences (i.e., 'very high,' 'high,' etc.) and quantitative inputs as computed numerical values; the stakeholder can also set the importance of their opinions in group decision-making, and most importantly, it is a generic model that can be used for multiple sustainable group decision-making purposes. This convenient, adaptable, and simple DSS is expected to increase objectivity, improve transparency and consistency in sustainable construction and systemize the process.

The remarkable contributions of this research comprise: a review of literature, expert opinions and industry practices to identify the factors impacting the sustainable selection of structural materials; integration of technical aspects with the commonly used three pillars (economic, social and environmental) of sustainability for assessment including a case study; application of two different MCDM methods (Fuzzy TOPSIS and Fuzzy VIKOR) to rank alternatives with Shannon's entropy to handle qualitative and quantitative data, and trapezoidal membership functions to get more realistic results; development of a DSS that shall assist the decision-makers in choosing evaluation criteria and assign relative importance to those in the combination of qualitative and quantitative methods in an IPD framework for selecting not only the most sustainable structural material but also to solve a wide range of construction related problems.

The construction industry's overall performance warns it of extreme concern about reducing negative impacts and improving global sustainability. The appropriate selection of materials can achieve sustainability in building construction. Each material has its sustainability characteristics; therefore, one may be cost-effective but more environmentally harmful or aesthetically incompatible with the environment. Multi-criteria decision-making is essential for selecting the most sustainable material from several alternatives. The developed DSS is expected to enhance objectivity and consistency in selection and to assist in making better decisions in terms of sustainability for construction projects. This research argued that a sustainable section is only possible once the stakeholders come out from the traditional short-term cost-benefit analysis and choose to balance all factors of sustainable construction to maximize the value and minimize harm. Therefore, the onus is on the users to make conscious decisions to improve the balance between development and sustainability to pave the way to a harmonious society for future generations.

6.3 Limitations of this Research

The research did not focus on the structural analysis of materials from the designer's point of view; instead, it identified the most sustainable option from the feasible alternatives of choosing the structural material for multistory building construction in the IPD framework. Therefore, detailed structural analysis was out of the scope of this study. Reinforced Concrete, Structural Steel, Timber and Reinforced Masonry were kept as alternatives to the structural elements discarding any other composites. The height of the building was decided so that all options of structural materials could remain acceptable alternatives. The developed DSS was tested with a hypothetical case study on an eight-story building in Calgary, Alberta, considering the opinions of nine academic and industry experts.

6.4 Recommendations for Future Works

In addition to TOPSIS and VIKOR, further researchers can use other techniques like PROMETHEE, DEMATEL, CBA and ANP to verify the applications developed in this research. This study was conducted on selecting structural elements only, and there is further scope to evaluate the entire building for sustainability using the developed DSS. Researchers can also take a large number of samples for AHP and decision matrix to compare the results of criteria weightage. We identified some variations in ranking results obtained through TOPSIS and VIKOR, and there can be a more detailed study to investigate and comment on those variations. The desktop application has a database to store information related to life cycle analysis, cost, location, etc., which users can enrich and update according to their needs.

Bibliography:

Abidin, N.Z., Pasquire, C.L., 2007. Revolutionize Value Management: A Mode Towards Sustainability. *International Journal of Project Management* **25**, 275–282. https://doi.org/10.1016/j.ijproman.2006.10.005

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

Ahmadi-Nedushan, B., St-Hilaire, A., Bérubé, M., Ouarda, T.B.M.J., Robichaud, É., 2008. Instream Flow Determination Using a Multiple Input Fuzzy-Based Rule System: A Case Study. *River Research and Applications* **24**, 279–292. https://doi.org/10.1002/rra.1059

AIA, 2007. Integrated Project Delivery: A Guide. [*WWW Document*]. URL https://www.bdcnetwork.com/aia-and-aia-california-council-partner-introduce-integrated-project-delivery-guide (accessed 2.14.22).

Akadiri, P.O., Olomolaiye, P.O., 2012. Development of Sustainable Assessment Criteria for Building Materials Selection. *Engineering, Construction and Architectural Management* **19**, 666–687. https://doi.org/10.1108/09699981211277568

Akadiri, P.O., Olomolaiye, P.O., Chinyio, E.A., 2013. Multi-criteria Evaluation Model for the Selection of Sustainable Materials for Building Projects. *Automation in Construction* **30**, 113–125. https://doi.org/10.1016/j.autcon.2012.10.004

Akbas, T., Sause, R., Ricles, J.M., Ganey, R., Berman, J., Loftus, S., Dolan, J.D., Pei, S., Van De Lindt, J.W., Blomgren, H.-E., 2017. Analytical and Experimental Lateral-Load Response of Self-Centering Posttensioned CLT Walls. *Journal of Structural Engineering* **143**, 04017019. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001733

Albadvi, A., Chaharsooghi, S.K., Esfahanipour, A., 2007. Decision Making in Stock Trading: An Application of PROMETHEE. *European Journal of Operational Research* **177**, 673–683. https://doi.org/10.1016/j.ejor.2005.11.022

Albayrak, E., Erensal, Y.C., 2004. Using Analytic Hierarchy Process (AHP) to Improve Human Performance: An Application of Multiple Criteria Decision-Making Problem. *Journal of Intelligent Manufacturing* **15**, 491–503. https://doi.org/10.1023/b:jims.0000034112.00652.4c

Allwood, J.M., Cullen, J.M., Milford, R.L., 2010. Options for Achieving a 50% Cut in Industrial Carbon Emissions by 2050. *Environmental Science & Technology* **44**, 1888–1894. https://doi.org/10.1021/es902909k

Almahmoud, E., Doloi, H.K., 2015. Assessment of Social Sustainability in Construction Projects Using Social Network Analysis. *Facilities* **33**, 152–176. https://doi.org/10.1108/f-05-2013-0042

Alyami, S.H., Rezgui, Y., 2012. Sustainable Building Assessment Tool Development Approach. *Sustainable Cities and Society* **5**, 52–62. https://doi.org/10.1016/j.scs.2012.05.004

Amiri Fard, F., Jafarpour, A., Nasiri, F., 2021. Comparative Assessment of Insulated Concrete Wall Technologies and Wood-Frame Walls in Residential Buildings: A Multi-Criteria Analysis of Hygrothermal Performance, Cost, and Environmental Footprints. *Advances in Building Energy Research* **15**, 466–498. https://doi.org/10.1080/17512549.2019.1600583

Arroyo, P., Tommelein, I.D., Ballard, G., 2012. Deciding a Sustainable Alternative by Choosing by Advantages' in the AEC industry. *Presented at the 20th Annual Conference of the International Group for Lean Construction*.

Arushanyan, Y., Ekener, E., Moberg, Å., 2017. Sustainability Assessment Framework for Scenarios – SAFS. *Environmental Impact Assessment Review* **63**, 23–34. https://doi.org/10.1016/j.eiar.2016.11.001

ATHENA, 2022. Impact Estimator for Buildings. *Athena Institute*.

Bakhoum, E.S., Brown, D.C., 2015. An Automated Decision Support System for Sustainable Selection of Structural Materials. *International Journal of Sustainable Engineering* **8**, 80–92. https://doi.org/10.1080/19397038.2014.906513

Bauer, M., Mösle, P., Schwarz, M., 2009. Green Building: Guidebook for Sustainable Architecture. *Springer Science & Business Media.*

Belton, V., Stewart, T.J., 2002. Multiple Criteria Decision Analysis: An Integrated Approach. *Springer US*.

Bennett, M., James, P., 2017. Key Themes in Environmental, Social and Sustainability Performance Evaluation and Reporting. *Sustainable Measures* 29–74. https://doi.org/10.4324/9781351283007-2

Bernardi, E., Carlucci, S., Cornaro, C., Bohne, R., 2017. An Analysis of the Most Adopted Rating Systems for Assessing the Environmental Impact of Buildings. *Sustainability* **9,** 1226. https://doi.org/10.3390/su9071226

Borah, B., Singhal, V., Kaushik, H.B., 2019. Sustainable Housing Using Confined Masonry Buildings. *SN Appl. Sci.* **1,** 983. https://doi.org/10.1007/s42452-019-1020-4

Börjesson, P., Gustavsson, L., 2000. Greenhouse Gas Balances in Building Construction: Wood Versus Concrete from Life-Cycle and Forest Land-Use Perspectives. *Energy Policy* **28,** 575–588. https://doi.org/10.1016/s0301-4215(00)00049-5

Bouyssou, D., 1994. Multicriteria Decision-Aid, Vincke, Ph., Chichester: Wiley, 1992. *Journal of Multi-Criteria Decision Analysis* **3,** 131–131. https://doi.org/10.1002/mcda.4020030208

Brans, J.-P., Mareschal, B., 1995. The Promethee Vi Procedure: How to Differentiate Hard from Soft Multicriteria Problems. *Journal of Decision Systems* **4,** 213–223. https://doi.org/10.1080/12460125.1995.10511652

Brans, J.P., Mareschal, B., 1992. Promethee V: MCDM Problems with Segmentation Constraints. *Infor: Information Systems and Operational Research* **30,** 85–96. https://doi.org/10.1080/03155986.1992.11732186

Brans, J.P., Vincke, Ph., 1985. Note—A Preference Ranking Organization Method. *Management Science* **31,** 647–656. https://doi.org/10.1287/mnsc.31.6.647

Brans, J.P., Vincke, Ph., Mareschal, B., 1986. How to Select and How to Rank Projects: The PROMETHEE Method. *European Journal of Operational Research* **24,** 228–238. https://doi.org/10.1016/0377-2217(86)90044-5

BSI, 2008. Standardized Method of Life Cycle Costing for Construction Procurement. A Supplement to BS ISO 15686-5. Buildings and Constructed Assets. Service Life Planning. Life Cycle Costing. *BSI British Standards.* https://doi.org/10.3403/30184346

Buchanan, A.H., 2016. Fire Resistance of Multistory Timber Buildings. *Fire Science and Technology* **2015,** 9–16. https://doi.org/10.1007/978-981-10-0376-9_2

Buchanan, A.H., Levine, S.B., 1999. Wood-Based Building Materials and Atmospheric Carbon Emissions. *Environmental Science & Policy* **2,** 427–437. https://doi.org/10.1016/s1462-9011(99)00038-6

Buck, D., Wang, X.A., Hagman, O., Gustafsson, A., 2015. Comparison of Different Assembling Techniques Regarding Cost, Durability and Ecology - A Survey of Multi-Layer Wooden Panel Assembly Load-Bearing Construction Elements. *Bio Resources* **10,** 8378–8396. https://doi.org/10.15376/biores.10.4.8378-8396

Büyüközkan, G., Çifçi, G., 2012. A Novel Hybrid MCDM Approach Based on Fuzzy DEMATEL, Fuzzy ANP and Fuzzy TOPSIS to Evaluate Green Suppliers. *Expert Systems with Applications* **39,** 3000–3011. https://doi.org/10.1016/j.eswa.2011.08.162

Cabeza, L.F., Barreneche, C., Miró, L., Morera, J.M., Bartolí, E., Inés Fernández, A., 2013. Low Carbon and Low Embodied Energy Materials in Buildings: A Review. *Renewable and Sustainable Energy Reviews* **23,** 536–542. https://doi.org/10.1016/j.rser.2013.03.017

Canada, S., 2022. 2030 Emissions Reduction Plan: Clean Air, Strong Economy [WWW Document]. *URL https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/climate-plan-overview/emissions-reduction-2030.html* (accessed 9.12.22).

Cato, M.S., 2009. Green Economics: An Introduction to Theory, Policy and Practice. *Earthscan, London; Sterling, VA.*

Chai, J., Liu, J.N.K., Ngai, E.W.T., 2013. Application of Decision-Making Techniques in Supplier Selection: A Systematic Review of Literature. *Expert Systems with Applications* **40,** 3872–3885. https://doi.org/10.1016/j.eswa.2012.12.040

Chan, F.T.S., Kumar, N., 2007. Global Supplier Development Considering Risk Factors Using Fuzzy Extended AHP-Based Approach. *Omega* **35,** 417–431. https://doi.org/10.1016/j.omega.2005.08.004

Chang, B., Chang, C.-W., Wu, C.-H., 2011. Fuzzy DEMATEL Method for Developing Supplier Selection Criteria. *Expert Systems with Applications* **38,** 1850–1858. https://doi.org/10.1016/j.eswa.2010.07.114

Chen, C.C., Tseng, M.L., Lin, Y.H., 2008. Using Fuzzy DEMATEL to Develop a Causal and Effect Model of Hot Spring Service Quality Expectation. *Presented at the 2008 IEEE International Conference on Industrial Engineering and Engineering Management, IEEE*. https://doi.org/10.1109/ieem.2008.4738021

Chen, C.-T., Lin, C.-T., Huang, S.-F., 2006. A Fuzzy Approach for Supplier Evaluation and Selection in Supply Chain Management. *International Journal of Production Economics* **102,** 289–301. https://doi.org/10.1016/j.ijpe.2005.03.009

Chen, T.-Y., Tsao, C.-Y., 2008. The Interval-Valued Fuzzy TOPSIS Method and Experimental Analysis. *Fuzzy Sets and Systems* **159,** 1410–1428. https://doi.org/10.1016/j.fss.2007.11.004

Chen, X., Yang, H., Lu, L., 2015. A Comprehensive Review on Passive Design Approaches in Green Building Rating Tools. *Renewable and Sustainable Energy Reviews* **50,** 1425–1436. https://doi.org/10.1016/j.rser.2015.06.003

Chodnekar, H., Yadav, P., Chaturvedi, H., 2021. Review and Assessment of Factors Associated with Green Building Rating Systems. *IOP Conf. Ser.: Earth Environ. Sci.* **795,** 012033. https://doi.org/10.1088/1755-1315/795/1/012033

Cole, R.J., 1999. Building Environmental Assessment Methods: Clarifying Intentions. *Building Research & Information* **27,** 230–246. https://doi.org/10.1080/096132199369354

Collins, D., Junghans, A., Haugen, T., 2018. Green Leasing in Commercial Real Estate. *Journal of Corporate Real Estate* **20,** 244–259. https://doi.org/10.1108/jcre-01-2017-0003

COP26, 2021. The Glasgow Climate Pact – Key Outcomes from COP26 | UNFCCC [WWW Document]. *URL https://unfccc.int/process-and-meetings/the-paris-agreement/the-glasgow-climate-pact-key-outcomes-from-cop26* (accessed 9.12.22).

Cowan, H.J., 1977. A History of Masonry and Concrete Domes in Building Construction. *Building and Environment* **12,** 1–24. https://doi.org/10.1016/0360-1323(77)90002-6

Crawley, D., Aho, I., 1999. Building Environmental Assessment Methods: Applications and Development Trends. *Building Research & Information* **27,** 300–308. https://doi.org/10.1080/096132199369417

Cumming, G.S., 2010. Spatial Resilience and Fragmentation in Social Systems. *Spatial Resilience in Social-Ecological Systems* 185–204. https://doi.org/10.1007/978-94-007-0307-0_9

CURT, 2022. CURT. Managing Construction Productivity. URL https://www.curt.org/committees/managing-construction-productivity/. (accessed 6.9.22).

Da Porto, F., Mosele, F., Modena, C., 2010. Experimental Testing of Tall Reinforced Masonry Walls Under Out-of-Plane actions. *Construction and Building Materials* **24,** 2559–2571. https://doi.org/10.1016/j.conbuildmat.2010.05.020

Dağdeviren, M., Yavuz, S., Kılınç, N., 2009. Weapon Selection Using the AHP and TOPSIS Methods Under Fuzzy Environment. *Expert Systems with Applications* **36,** 8143–8151. https://doi.org/10.1016/j.eswa.2008.10.016

Dahmen, J., Kim, J., Ouellet-Plamondon, C.M., 2018. Life Cycle Assessment of Emergent Masonry Blocks. *Journal of Cleaner Production* **171,** 1622–1637. https://doi.org/10.1016/j.jclepro.2017.10.044

Danso, H., 2018. Dimensions and Indicators for Sustainable Construction Materials: A Review. *RDMS* **3.** https://doi.org/10.31031/RDMS.2018.03.000568

Dara, C., Hachem-Vermette, C., Assefa, G., 2019. Life Cycle Assessment and Life Cycle Costing of Container-Based Single-Family Housing in Canada: A Case Study. *Building and Environment* **163**, 106332. https://doi.org/10.1016/j.buildenv.2019.106332

Debnath, A., Singh, S.V., Singh, Y.P., 1995. Comparative Assessment of Energy Requirements for Different Types of Residential Buildings in India. *Energy and Buildings* **23,** 141–146. https://doi.org/10.1016/0378-7788(95)00939-6

Degani, C.M., Cardoso, F.F., 2002. Environmental Performance and Lean Construction Concepts: Can We Talk About a "Clean Construction"? **13.**

Deng, H., Yeh, C.-H., Willis, R.J., 2000. Inter-Company Comparison Using Modified Topsis with Objective Weights. *Computers & Operations Research* **27,** 963–973. https://doi.org/10.1016/s0305-0548(99)00069-6

Dhanasekar, M., 2011. Shear in Reinforced and Unreinforced Masonry: Response, Design and Construction. *Procedia Engineering* **14,** 2069–2076. https://doi.org/10.1016/j.proeng.2011.07.260

Ding, G.K.C., 2008. Sustainable Construction—The Role of Environmental Assessment Tools. *Journal of Environmental Management* **86,** 451–464. https://doi.org/10.1016/j.jenvman.2006.12.025

Doan, D.T., Ghaffarianhoseini, Ali, Naismith, N., Zhang, T., Ghaffarianhoseini, Amirhosein, Tookey, J., 2017. A Critical Comparison of Green Building Rating Systems. *Building and Environment* **123,** 243–260. https://doi.org/10.1016/j.buildenv.2017.07.007

Du Pisani, J.A., 2006. Sustainable Development – Historical Roots of the Concept. *Environmental Sciences (15693430)* **3,** 83–96. https://doi.org/10.1080/15693430600688831

Dwi Putra, M.S., Andryana, S., Fauziah, Gunaryati, A., 2018. Fuzzy Analytical Hierarchy Process Method to Determine the Quality of Gemstones. *Advances in Fuzzy Systems* **2018,** 1–6. https://doi.org/10.1155/2018/9094380

Ek, K., Mathern, A., Rempling, R., Rosén, L., Claeson-Jonsson, C., Brinkhoff, P., Norin, M., 2019. Multi-Criteria Decision Analysis Methods to Support Sustainable Infrastructure Construction. *Presented at the IABSE Symposium, Guimarães 2019: Towards a Resilient Built Environment Risk and Asset Management, Guimarães, Portugal, pp.* 1084–1091. https://doi.org/10.2749/guimaraes.2019.1084

El khouli, S., John, V., Zeumer, M., 2015. Sustainable Construction Techniques: From Structural Design to Material Selection: Assessing and Improving the Environmental Impact of Buildings. *Institut für Internationale Architektur-Dokumentation GmbH & Co. KG*. https://doi.org/10.11129/9783955532390

El Wardani, M.A., Messner, J.I., Horman, M.J., 2006. Comparing Procurement Methods for Design-Build Projects. *Journal of Construction Engineering and Management* **132,** 230–238. https://doi.org/10.1061/(asce)0733-9364(2006)132:3(230)

El-Dakhakhni, W., Ashour, A., 2017. Seismic Response of Reinforced-Concrete Masonry Shear-Wall Components and Systems: State of the Art. *Journal of Structural Engineering* **143,** 03117001. https://doi.org/10.1061/(asce)st.1943-541x.0001840

Elghaish, F., Hosseini, M.R., Talebi, S., Abrishami, S., Martek, I., Kagioglou, M., 2020. Factors Driving Success of Cost Management Practices in Integrated Project Delivery (IPD). *Sustainability* **12,** 9539. https://doi.org/10.3390/su12229539

Elkington, J., 1998. Cannibals with Forks: The Triple Bottom Line of 21st Century Business, Conscientious Commerce. *New Society Publishers*.

Energy Policies, 2017. Energy Policies of IEA Countries: Norway 2017. *Energy Policies of IEA Countries.* https://doi.org/10.1787/9789264269002-en

Eom, S.B., 1999. Decision Support Systems Research: Current State and Trends. *Industrial Management & Data Systems* **99,** 213–221. https://doi.org/10.1108/02635579910253751

Ertuğrul, İ., Karakaşoğlu, N., 2008. Comparison of Fuzzy AHP and Fuzzy Topsis Methods for Facility Location Selection. *Int J Adv Manuf Technol* **39,** 783–795. https://doi.org/10.1007/s00170-007-1249-8

Espinoza, L.R., Brioso, X., Herrera, R.F., 2021. Applying CBA to Decide the Best Excavation Method: Scenario During the Covid-19 Pandemic 10.

Fallahpour, A., Wong, K.Y., Rajoo, S., Olugu, E.U., Nilashi, M., Turskis, Z., 2020. A Fuzzy Decision Support System for Sustainable Construction Project Selection: An Integrated FPP-FIS Model. *Journal of Civil Engineering And Management* **26,** 247–258. https://doi.org/10.3846/jcem.2020.12183

Farzanehrafat, M., Akbarnezhad, A., Ghoddousi, P., 2015. Analysis of Different Views Towards Social Sustainability in Construction. *Presented at the 32nd International Symposium on Automation and Robotics in Construction, Oulu, Finland.* https://doi.org/10.22260/ISARC2015/0113

Fazeli, A., Jalaei, F., Khanzadi, M., Banihashemi, S., 2019. BIM-Integrated Topsis-Fuzzy Framework to Optimize Selection of Sustainable Building Components. *International Journal of Construction Management* 1–20. https://doi.org/10.1080/15623599.2019.1686836

Figueira, J., Roy, B., 2002. Determining the Weights of Criteria in the Electre Type Methods with a Revised Simos' Procedure. *European Journal of Operational Research* **139,** 317–326. https://doi.org/10.1016/S0377-2217(01)00370-8

Figueiredo, K., Pierott, R., Hammad, A.W.A., Haddad, A., 2021. Sustainable Material Choice for Construction Projects: A Life Cycle Sustainability Assessment Framework Based on BIM and Fuzzy-AHP. *Building and Environment* **196,** 107805. https://doi.org/10.1016/j.buildenv.2021.107805

Filho, M.V.A.P.M., da Costa, B.B.F., Najjar, M., Figueiredo, K.V., de Mendonça, M.B., Haddad, A.N., 2022. Sustainability Assessment of a Low-Income Building: *A BIM-LCSA-FAHP-Based Analysis. Buildings* **12,** 181. https://doi.org/10.3390/buildings12020181

Finkbeiner, M., Schau, E.M., Lehmann, A., Traverso, M., 2010. *Towards Life Cycle Sustainability Assessment. Sustainability* **2,** 3309–3322. https://doi.org/10.3390/su2103309

Forman, E.H., Gass, S.I., 2001. The Analytic Hierarchy Process—An Exposition. *Operations Research* **49,** 469–486. https://doi.org/10.1287/opre.49.4.469.11231

Gale, F.P., 1998. The Tropical Timber Trade. *The Tropical Timber Trade Regime* 61–78. https://doi.org/10.1057/9780230371521_5

Ganey, R., Berman, J., Akbas, T., Loftus, S., Daniel Dolan, J., Sause, R., Ricles, J., Pei, S., Lindt, J. Van De, Blomgren, H.-E., 2017. *Experimental Investigation of Self-Centering Cross-Laminated Timber Walls. J. Struct. Eng.* **143,** 04017135. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001877

Gartner, E., 2004. Industrially Interesting Approaches to "Low-CO2" Cements. *Cement and Concrete Research* **34,** 1489–1498. https://doi.org/10.1016/j.cemconres.2004.01.021

Gavali, H.R., Ralegaonkar, R.V., 2019. Design Feasibility of Load-Bearing Masonry Building for Energy-Efficient Construction. *Proceedings of the Institution of Civil Engineers - Energy* **172,** 19–25. https://doi.org/10.1680/jener.18.00013

GBI, 2022. Green Building Initiative: About GBI [*WWW Document*]. URL https://thegbi.org/about-gbi/. (accessed 2.28.22).

Gharehbaghi, K., 2015. Advancements in Concrete Technology in Australia: Geo-Polymer Concrete. *The International Journal of the Constructed Environment* **7,** 19–29. https://doi.org/10.18848/2154-8587/cgp/v07i01/37460

Gharehbaghi, K., Georgy, M., 2019. Sustainable Construction by Means of Improved Material Selection Process. *Archive* **3,** 85. https://doi.org/10.21625/archive.v3i1.433

Gligoric, Z., Beljic, C., Simeunovic, V., 2010. Shaft Location Selection at Deep Multiple Orebody Deposit by Using Fuzzy Topsis Method and Network Optimization. *Expert Systems with Applications* **37,** 1408–1418. https://doi.org/10.1016/j.eswa.2009.06.108

Gloet, M., 2006. Knowledge Management and the Links to HRM. *Management Research News* **29,** 402–413. https://doi.org/10.1108/01409170610690862

Goggins, J., Keane, T., Kelly, A., 2010. The Assessment of Embodied Energy in Typical Reinforced Concrete Building Structures in Ireland. *Energy and Buildings* **42,** 735–744. https://doi.org/10.1016/j.enbuild.2009.11.013

Gong, X., Nie, Z., Wang, Z., Cui, S., Gao, F., Zuo, T., 2012. Life Cycle Energy Consumption and Carbon Dioxide Emission of Residential Building Designs in Beijing. *Journal of Industrial Ecology* **16,** 576–587. https://doi.org/10.1111/j.1530-9290.2011.00415.x

Goodhew, S., 2016. *Sustainable Construction Processes*. https://doi.org/10.1002/9781119247937

Government of Canada, S.C., 2022. Canada Mortgage and Housing Corporation, Housing Starts, Under Construction and Completions in Centres 10,000 and over, Canada, Provinces, Selected Census Metropolitan Areas [*WWW Document*]. URL https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3410014301 (accessed 6.16.22).

Government of Canada, S.C., 2018. Average Expected Useful Life of New Municipally Owned Social and Affordable Housing Assets, by Urban and Rural, and Population Size, Infrastructure Canada [*WWW Document*]. URL https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=4610000801 (accessed 6.16.22).

Guinée, J., 2016. Life Cycle Sustainability Assessment: What Is It and What are Its Challenges? *Taking Stock of Industrial Ecology* 45–68. https://doi.org/10.1007/978-3-319-20571-7_3

Guo, H., Liu, Y., Meng, Y., Huang, H., Sun, C., Shao, Y., 2017. A Comparison of the Energy Saving and Carbon Reduction Performance Between Reinforced Concrete and Cross-Laminated Timber Structures in Residential Buildings in the Severe Cold Region of China. *Sustainability* **9,** 1426. https://doi.org/10.3390/su9081426

Gustafsson, S.I., 1997. Optimising Ash Wood Chairs. *Wood Science and Technology* **31,** 291–301. https://doi.org/10.1007/bf00702616

Hajare, A., Elwakil, E., 2020. Integration of Life Cycle Cost Analysis and Energy Simulation for Building Energy-Efficient Strategies Assessment. *Sustainable Cities and Society* **61,** 102293. https://doi.org/10.1016/j.scs.2020.102293

Hall, D.M., Scott, W.R., 2019. Early Stages in the Institutionalization of Integrated Project Delivery. *Project Management Journal* **50,** 128–143. https://doi.org/10.1177/8756972818819915

Halloran, D., 2019. Life-Cycle Costing Within the Construction Sector. *Cost and EU Public Procurement Law* 158–180. https://doi.org/10.4324/9780429060045-8

Hannouf, M., Assefa, G., 2018. A Life Cycle Sustainability Assessment-Based Decision-Analysis Framework. *Sustainability* **10,** 3863. https://doi.org/10.3390/su10113863

Heinzle, E., Biwer, A.P., Cooney, C.L., 2006. Development of Sustainable Bioprocesses. *John Wiley & Sons, Ltd.* https://doi.org/10.1002/9780470058916

Heitz, J., 2016. American Heavy Timber Construction. *Fire Resistance in American Heavy Timber Construction* 1–14. https://doi.org/10.1007/978-3-319-32128-8_1

Hendry, E.A.W., 2001. Masonry Walls: Materials and Construction. *Construction and Building Materials* **15,** 323–330. https://doi.org/10.1016/s0950-0618(01)00019-8

Hill, R.C., Bowen, P.A., 1997. Sustainable Construction: Principles and a Framework for Attainment. *Construction Management and Economics* **15,** 223–239. https://doi.org/10.1080/014461997372971

Holling, C.S., 2001. Understanding the Complexity of Economic, Ecological, and Social Systems. *Ecosystems* **4,** 390–405. https://doi.org/10.1007/s10021-001-0101-5

Hunkeler, D., 2006. Societal LCA Methodology and Case Study (12 pp). *The International Journal of Life Cycle Assessment* **11,** 371–382. https://doi.org/10.1065/lca2006.08.261

Hwang, C.-L., Yoon, K., 1981. Methods for Multiple Attribute Decision Making. *Multiple Attribute Decision Making* 58–191. https://doi.org/10.1007/978-3-642-48318-9_3

Ibbs, C.W., Kwak, Y.H., Ng, T., Odabasi, A.M., 2003. Project Delivery Systems and Project Change: Quantitative Analysis. *Journal of Construction Engineering and Management* **129,** 382–387. https://doi.org/10.1061/(asce)0733-9364(2003)129:4(382)

II.5 2005 World Summit Outcome United Nations World Summit, 16 September 2005, 2006. *Reforming the United Nations* 442–484. https://doi.org/10.1163/ej.9789004151314.i-531.72

Ijadi Maghsoodi, Abteen, Ijadi Maghsoodi, Arta, Poursoltan, P., Antucheviciene, J., Turskis, Z., 2019. Dam Construction Material Selection by Implementing the Integrated SWARA–CODAS Approach with Target-Based Attributes. *Archives of Civil and Mechanical Engineering* **19,** 1194–1210. https://doi.org/10.1016/j.acme.2019.06.010

Illankoon, I.M.C.S., Lu, W., 2019. Optimizing Choices of 'Building Services' for Green Building: Interdependence and Life Cycle Costing. *Building and Environment* **161,** 106247. https://doi.org/10.1016/j.buildenv.2019.106247

IPCC, 2013. Technical Summary. *Climate Change 2013 - The Physical Science Basis* 31–116. https://doi.org/10.1017/cbo9781107415324.005

Ishizaka, A., Labib, A., 2009. Analytic Hierarchy Process and Expert Choice: Benefits and limitations. *OR Insight* **22,** 201–220. https://doi.org/10.1057/ori.2009.10

Islam, H., Jollands, M., Setunge, S., Bhuiyan, M.A., 2015a. Optimization Approach of Balancing Life Cycle Cost and Environmental Impacts on Residential Building Design. *Energy and Buildings* **87,** 282–292. https://doi.org/10.1016/j.enbuild.2014.11.048

Islam, H., Jollands, M., Setunge, S., Haque, N., Bhuiyan, M.A., 2015b. Life Cycle Assessment and Life Cycle Cost Implications for Roofing and Floor Designs in Residential Buildings. *Energy and Buildings* **104,** 250–263. https://doi.org/10.1016/j.enbuild.2015.07.017

ISO 14040, 2006. ISO 14040:2006. Environmental Management - Life Cycle Assessment - Principles and Framework [WWW Document]. ISO. URL https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/03/74/37456.html (accessed 2.16.22).

ISO, 14044, 2006. Environmental Management: Life Cycle Assessment. Critical Review Processes and Reviewer Competencies: Additional Requirements and Guidelines to ISO 14044:2006. *BSI British Standards*. https://doi.org/10.3403/30290345

ISO 14044, 2006. ISO 14044:2006 [WWW Document]. ISO. URL https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/03/84/38498.html. (accessed 2.16.22).

ISO 15686, 2017. ISO 15686-5:2017 [WWW Document]. ISO. URL https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/06/11/61148.html. (accessed 2.16.22).

Iyer-Raniga, U., Erasmus, P., Huovila, P., Maity, S., 2019. Circularity in the Built Environment: A Focus on India. *World Sustainability Series* 739–755. https://doi.org/10.1007/978-3-030-26759-9_43

Jang, W., You, H.-W., Han, S., 2015. Quantitative Decision-Making Model for Carbon Reduction in Road Construction Projects Using Green Technologies. *Sustainability* **7,** 11240–11259. https://doi.org/10.3390/su70811240

Jato-Espino, D., Castillo-Lopez, E., Rodriguez-Hernandez, J., Canteras-Jordana, J.C., 2014. A Review of Application of Multi-Criteria Decision-Making Methods in Construction. *Automation in Construction* **45,** 151–162. https://doi.org/10.1016/j.autcon.2014.05.013

Jayasinghe, C., Fonseka, W.M.C.D.J., Abeygunawardhene, Y.M., 2016. Load Bearing Properties of Composite Masonry Constructed with Recycled Building Demolition Waste and Cement Stabilized Rammed Earth. *Construction and Building Materials* **102,** 471–477. https://doi.org/10.1016/j.conbuildmat.2015.10.136

Jones, B., 2014. Integrated Project Delivery (IPD) for Maximizing Design and Construction Considerations Regarding Sustainability. *Procedia Engineering* **95,** 528–538. https://doi.org/10.1016/j.proeng.2014.12.214

Jørgensen, A., Le Bocq, A., Nazarkina, L., Hauschild, M., 2008. Methodologies for Social Life Cycle Assessment. *Int J Life Cycle Assess* **13,** 96–103. https://doi.org/10.1065/lca2007.11.367

Josiah Marut, J., Alaezi, J.O., Obeka, I.C., 2020. A Review of Alternative Building Materials for Sustainable Construction Towards Sustainable Development. *J. Mod. Mater.* **7,** 68–78. https://doi.org/10.21467/jmm.7.1.68-78

Jost, L., 2006. Entropy and Diversity. *Oikos* **113**, 363–375. https://doi.org/10.1111/j.2006.0030-1299.14714.x

Kahraman, C., Yasin Ateş, N., Çevik, S., Gülbay, M., Ayça Erdoğan, S., 2007. Hierarchical Fuzzy TOPSIS Model for Selection Among Logistics Information Technologies. *Journal of Enterprise Information Management* **20,** 143–168. https://doi.org/10.1108/17410390710725742

Kamali, M., Hewage, K.N., 2015. Performance Indicators for Sustainability Assessment of Buildings 11.

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

Kannan, D., Khodaverdi, R., Olfat, L., Jafarian, A., Diabat, A., 2013. Integrated Fuzzy Multi Criteria Decision Making Method and Multi-Objective Programming Approach for Supplier Selection and Order Allocation in a Green Supply Chain. *Journal of Cleaner Production* **47,** 355–367. https://doi.org/10.1016/j.jclepro.2013.02.010

Kappenthuler, S., Seeger, S., 2020. From Resources to Research—A framework for Identification and Prioritization of Materials Research for Sustainable Construction. *Materials Today Sustainability* 7–8, 100009. https://doi.org/10.1016/j.mtsust.2019.100009

Kaya, T., Kahraman, C., 2011. Multicriteria Decision Making in Energy Planning Using a Modified Fuzzy TOPSIS Methodology. *Expert Systems with Applications* **38,** 6577–6585. https://doi.org/10.1016/j.eswa.2010.11.081

Kaziolas, D.N., Zygomalas, I., Stavroulakis, G.E., Baniotopoulos, C.C., 2017. LCA of Timber and Steel Buildings with Fuzzy Variables Uncertainty Quantification. *European Journal of Environmental and Civil Engineering* **21,** 1128–1150. https://doi.org/10.1080/19648189.2016.1150899

Keeble, B.R., 1988. The Brundtland Report: 'Our Common Future.' *Medicine and War* **4,** 17–25. https://doi.org/10.1080/07488008808408783

Khasreen, M., Banfill, P.F., Menzies, G., 2009. Life-Cycle Assessment and the Environmental Impact of Buildings: A Review. *Sustainability* **1,** 674–701. https://doi.org/10.3390/su1030674

Khodadadzadeh, T., 2016. Green Building Project Management: Obstacles and Solutions for Sustainable Development. *Journal of Project Management* 21–26. https://doi.org/10.5267/j.jpm.2017.1.003

Kiani Mavi, R., Gengatharen, D., Kiani Mavi, N., Hughes, R., Campbell, A., Yates, R., 2021. Sustainability in Construction Projects: A Systematic Literature Review. *Sustainability* **13,** 1932. https://doi.org/10.3390/su13041932

Kishk, M., Al-Hajj, A., 1999. An Integrated Framework for Life Cycle Costing in Buildings. *RISC Research Foundation 11.*

Kloepffer, W., 2008. Life Cycle Sustainability Assessment of Products: (With Comments by Helias A. Udo de Haes, p. 95). *International Journal of Life Cycle Assessment* **13,** 89–95. https://doi.org/10.1065/lca2008.02.376

Klüppel, H.-J., 2005. The Revision of ISO Standards 14040-3 - ISO 14044: Environmental Management. *The International Journal of Life Cycle Assessment* **10,** 165–165. https://doi.org/10.1065/lca2005.03.001

Kolb, J., 2008. Systems in Timber Engineering. https://doi.org/10.1007/978-3-7643-8690-0

Krause, P.J., 1995. Foundations of Fuzzy Systems by Rudolf Kruse, Jörg Gebhardt and Frank Klawonn, John Wiley & Sons, Chichester, 1994, pp 265, £29.95, ISBN 0-471-94243-X. *The Knowledge Engineering Review* **10,** 101–102. https://doi.org/10.1017/s0269888900007359

Kulak, O., Durmuşoğlu, M.B., Kahraman, C., 2005. Fuzzy Multi-Attribute Equipment Selection Based on Information Axiom. *Journal of Materials Processing Technology* **169,** 337–345. https://doi.org/10.1016/j.jmatprotec.2005.03.030

Laguarda Mallo, M.F., Espinoza, O., 2015. Awareness, Perceptions and Willingness to Adopt Cross-Laminated Timber by the Architecture Community in the United States. *Journal of Cleaner Production* **94,** 198–210. https://doi.org/10.1016/j.jclepro.2015.01.090

Lee, W.L., 2013. A Comprehensive Review of Metrics of Building Environmental Assessment Schemes. *Energy and Buildings* **62,** 403–413. https://doi.org/10.1016/j.enbuild.2013.03.014

Levitt, R.E., 2007. CEM Research for the Next 50 Years: Maximizing Economic, Environmental, and Societal Value of the Built Environment. *Journal of Construction Engineering and Management* **133,** 619–628. https://doi.org/10.1061/(asce)0733-9364(2007)133:9(619)

Li, P., Froese, T.M., 2017. A Green Home Decision-Making Tool: Sustainability Assessment for Homeowners. *Energy and Buildings* **150,** 421–431. https://doi.org/10.1016/j.enbuild.2017.06.017

Li, W., Dong, L., Ren, J., Lin, R., 2021. Coupling LCSA and Multi-Criteria Decision Analysis for Energy System Prioritization, in: Ren, J. (Ed.), Energy Systems Evaluation (Volume 2), Green Energy and Technology. *Springer International Publishing, Cham, pp.* 129–160. https://doi.org/10.1007/978-3-030-67376-5_6

Li, X., Zhu, Y., Zhang, Z., 2010. An LCA-Based Environmental Impact Assessment Model for Construction Processes. *Building and Environment* **45,** 766–775. https://doi.org/10.1016/j.buildenv.2009.08.010

Lippke, B., Bowyer, J.L., 2007. Environmental Life-Cycle Analysis of Alternative Building Materials. *Environmentally Conscious Materials and Chemicals Processing* 179–206. https://doi.org/10.1002/9780470168219.ch7

Llatas, C., Soust-Verdaguer, B., Passer, A., 2020. Implementing Life Cycle Sustainability Assessment During Design Stages in Building Information Modelling: From Systematic Literature Review to a Methodological Approach. *Building and Environment* **182,** 107164. https://doi.org/10.1016/j.buildenv.2020.107164

Lozano, R., 2008. Envisioning Sustainability Three-Dimensionally. *Journal of Cleaner Production* **16,** 1838–1846. https://doi.org/10.1016/j.jclepro.2008.02.008

Lu, J., Zhang, G., Ruan, D., Wu, F., 2007. Multi-Objective Group Decision Making, Series in Electrical and Computer Engineering. *Imperial College Press*. https://doi.org/10.1142/p505

Lukacs, I., Björnfot, A., Tomasi, R., 2019. Strength and Stiffness of Cross-Laminated Timber (CLT) Shear Walls: State-of-the-Art of Analytical Approaches. *Engineering Structures* **178,** 136–147. https://doi.org/10.1016/j.engstruct.2018.05.126

Macombe, C., Feschet, P., Garrabé, M., Loeillet, D., 2011. 2nd International Seminar in Social Life Cycle Assessment—Recent Developments in Assessing the Social Impacts of Product Life Cycles. *The International Journal of Life Cycle Assessment* **16,** 940–943. https://doi.org/10.1007/s11367-011-0331-5

Manning, S., Boons, F., Von Hagen, O., Reinecke, J., 2012. National Contexts Matter: The Co-Evolution of Sustainability Standards in Global Value Chains. *Ecological Economics* **83,** 197–209. https://doi.org/10.1016/j.ecolecon.2011.08.029

Mardani, A., Hooker, R.E., Ozkul, S., Yifan, S., Nilashi, M., Sabzi, H.Z., Fei, G.C., 2019. Application of Decision Making and Fuzzy Sets Theory to Evaluate the Healthcare and Medical Problems: A Review of Three Decades of Research with Recent Developments. *Expert Systems with Applications* **137,** 202–231. https://doi.org/10.1016/j.eswa.2019.07.002

Marjaba, G.E., Chidiac, S.E., 2016. Sustainability and Resiliency Metrics for Buildings – Critical Review. *Building and Environment* **101,** 116–125. https://doi.org/10.1016/j.buildenv.2016.03.002

Marszal, A.J., Heiselberg, P., 2011. Life Cycle Cost Analysis of a Multi-Storey Residential Net Zero Energy Building in Denmark. *Energy* **36,** 5600–5609. https://doi.org/10.1016/j.energy.2011.07.010

Martens, M.L., Carvalho, M.M., 2017. Key Factors of Sustainability in Project Management Context: A Survey Exploring the Project Managers' Perspective. *International Journal of Project Management* **35,** 1084–1102. https://doi.org/10.1016/j.ijproman.2016.04.004

Mattoni, B., Guattari, C., Evangelisti, L., Bisegna, F., Gori, P., Asdrubali, F., 2018. Critical Review and Methodological Approach to Evaluate the Differences Among International Green Building Rating Tools. *Renewable and Sustainable Energy Reviews* **82,** 950–960. https://doi.org/10.1016/j.rser.2017.09.105

Mei-Fang Chen, Gwo-Hshiung Tzeng, Ding, C.G., 2003. Fuzzy MCDM Approach to Select Service Provider. Presented at the 12th IEEE International Conference on Fuzzy Systems, 2003. *Fuzz* **'03.,** IEEE. https://doi.org/10.1109/fuzz.2003.1209427

Mergias, I., Moustakas, K., Papadopoulos, A., Loizidou, M., 2007. Multi-Criteria Decision Aid Approach for the Selection of the Best Compromise Management Scheme for ELVs: The Case of Cyprus. *Journal of Hazardous Materials* **147,** 706–717. https://doi.org/10.1016/j.jhazmat.2007.01.071

Miller, A., Ip, K., 2013. Sustainable Construction Materials, in: Yao, R. (Ed.), Design and Management of Sustainable Built Environments. *Springer London, London, pp.* 341–358. https://doi.org/10.1007/978-1-4471-4781-7_17

Minhas, M.R., Potdar, V., 2020. Development of an Effective System for Selecting Construction Materials for Sustainable Residential Housing in Western Australia. *AM* **11,** 825–844. https://doi.org/10.4236/am.2020.118054

Mocq, J., St-Hilaire, A., Cunjak, R.A., 2013. Assessment of Atlantic Salmon (Salmo salar) Habitat Quality and its Uncertainty Using a Multiple-Expert Fuzzy Model Applied to the Romaine River (Canada). *Ecological Modelling* **265,** 14–25. https://doi.org/10.1016/j.ecolmodel.2013.05.020

Mohammad, M., Masad, E., Al-Ghamdi, S.G., 2020. 3D Concrete Printing Sustainability: A Comparative Life Cycle Assessment of Four Construction Method Scenarios. *Buildings* **10,** 245. https://doi.org/10.3390/buildings10120245

Moir, S., Carter, K., 2012. Diagrammatic Representations of Sustainability - A Review and Synthesis, in: Proceedings of the 28th Annual Conference. Presented at the Association of Researchers in Construction Management, ARCOM 2012, Association of Researchers in Construction Management, pp. 1479–1489.

Moynihan, M.C., Allwood, J.M., 2014. Utilization of Structural Steel in Buildings. *Proc. R. Soc. A.* **470,** 20140170. https://doi.org/10.1098/rspa.2014.0170

Nassar, R.-U.-D., Soroushian, P., Ghebrab, T., 2013. Field Investigation of High-Volume Fly Ash Pavement Concrete. *Resources, Conservation and Recycling* **73,** 78–85. https://doi.org/10.1016/j.resconrec.2013.01.006

Nijkamp, P., Rietveld, P., Voogd, H., 1990. Preface. Contributions to Economic Analysis Vii–Viii. https://doi.org/10.1016/b978-0-444-88124-3.50005-9

Nwodo, M.N., Anumba, C.J., 2019. A Review of Life Cycle Assessment of Buildings Using a Systematic Approach. *Building and Environment* **162,** 106290. https://doi.org/10.1016/j.buildenv.2019.106290

Ochshorn, J., 2020. Structural Elements for Architects and Builders, Third Edition. ed. *Proudly and Independently Published*.

Oldfield, P., 2019. The Sustainable Tall Building. https://doi.org/10.4324/9781315695686

Olson, D.L., 2004. Comparison of Weights in TOPSIS Models. *Mathematical and Computer Modelling* **40,** 721–727. https://doi.org/10.1016/j.mcm.2004.10.003

Omer, M.A.B., Noguchi, T., 2020. A Conceptual Framework for Understanding the Contribution of Building Materials in the Achievement of Sustainable Development Goals (SDGs). *Sustainable Cities and Society* **52,** 101869. https://doi.org/10.1016/j.scs.2019.101869

Onat, N., Kucukvar, M., Halog, A., Cloutier, S., 2017. Systems Thinking for Life Cycle Sustainability Assessment: A Review of Recent Developments, Applications, and Future Perspectives. *Sustainability* **9,** 706. https://doi.org/10.3390/su9050706

Opon, J., Henry, M., 2019. An Indicator Framework for Quantifying the Sustainability of Concrete Materials from the Perspectives of Global Sustainable Development. *Journal of Cleaner Production* **218,** 718–737. https://doi.org/10.1016/j.jclepro.2019.01.220

Opricovic, S., 2011. Fuzzy VIKOR with an Application to Water Resources Planning. *Expert Systems with Applications* **38,** 12983–12990. https://doi.org/10.1016/j.eswa.2011.04.097

Opricovic, S., Tzeng, G.-H., 2004. Compromise Solution by MCDM Methods: A Comparative Analysis of VIKOR and TOPSIS. *European Journal of Operational Research* **156,** 445–455. https://doi.org/10.1016/s0377-2217(03)00020-1

Opricovic, S., Tzeng, G.-H., 2002. Multicriteria Planning of Post-Earthquake Sustainable Reconstruction. *Computer-Aided Civil and Infrastructure Engineering* **17,** 211–220. https://doi.org/10.1111/1467-8667.00269

Oss, H.G., Padovani, A.C., 2003. Cement Manufacture and the Environment Part II: Environmental Challenges and Opportunities. *Journal of Industrial Ecology* **7,** 93–126. https://doi.org/10.1162/108819803766729212

Parent, J., Cucuzzella, C., Revéret, J.-P., 2010. Impact Assessment in SLCA: Sorting the SLCIA Methods According to Their Outcomes. *Int J Life Cycle Assess* **15,** 164–171. https://doi.org/10.1007/s11367-009-0146-9

Parrish, K., Tommelein, I.D., 2009. Making Design Decisions Using Choosing by Advantages. Presented at the 17th Annual Conference of the International Group for Lean Construction, pp. 501–510.

Pearce, A.R., Hastak, M., Vanegas, J.A., 1995. A Decision Support System for Construction Materials Selection using Sustainability as a Criterion 13.

Petti, L., Serreli, M., Di Cesare, S., 2018. Systematic Literature Review in Social Life Cycle Assessment. *Int J Life Cycle Assess* **23,** 422–431. https://doi.org/10.1007/s11367-016-1135-4

Petzek, E., Toduţi, L., Băncilă, R., 2016. Deconstruction of Bridges an Environmental Sustainable Concept. *Procedia Engineering* **156,** 348–355. https://doi.org/10.1016/j.proeng.2016.08.307

Purvis, B., Mao, Y., Robinson, D., 2019. Three Pillars of Sustainability: In Search of Conceptual Origins. *Sustainability Science* **14,** 681–695. https://doi.org/10.1007/s11625-018-0627-5

Rahim, F.A., Muzaffar, S.A., Yusoff, N.S.M., Zainon, N., Wang, C., 2014. *Sustainable Construction Through Life Cycle Costing* **5,** 12.

Ramesh, T., Prakash, R., Shukla, K.K., 2010. Life Cycle Energy Analysis of Buildings: An Overview. Energy and Buildings **42,** 1592–1600. https://doi.org/10.1016/j.enbuild.2010.05.007

Ramos Huarachi, D.A., Piekarski, C.M., Puglieri, F.N., De Francisco, A.C., 2020. Past and Future of Social Life Cycle Assessment: Historical Evolution and Research Trends. *Journal of Cleaner Production* **264,** 121506. https://doi.org/10.1016/j.jclepro.2020.121506

Reeder, L., 2010. Guide to Green Building Rating Systems, in: Guide to Green Building Rating Systems. *John Wiley & Sons, Ltd, pp.* 143–161. https://doi.org/10.1002/9781118259894.ch9

Reinecke, J., Manning, S., Von Hagen, O., 2012. The Emergence of a Standards Market: Multiplicity of Sustainability Standards in the Global Coffee Industry. *Organization Studies* **33,** 791–814. https://doi.org/10.1177/0170840612443629

Ren, J., Manzardo, A., Mazzi, A., Zuliani, F., Scipioni, A., 2015. Prioritization of Bioethanol Production Pathways in China Based on Life Cycle Sustainability Assessment and Multicriteria Decision-Making. *The International Journal of Life Cycle Assessment* **20,** 842–853. https://doi.org/10.1007/s11367-015-0877-8

Reza, B., Sadiq, R., Hewage, K., 2014. Emergy-Based Life Cycle Assessment (Em-LCA) of Multi-Unit and Single-Family Residential Buildings in Canada. *International Journal of Sustainable Built Environment* **3**, 207–224. https://doi.org/10.1016/j.ijsbe.2014.09.001

Rezaei, J., 2015. Best-Worst Multi-Criteria Decision-Making Method. *Omega* **53,** 49–57. https://doi.org/10.1016/j.omega.2014.11.009

Roufechaei, K.M., Hassan Abu Bakar, A., Tabassi, A.A., 2014. Energy-Efficient Design for Sustainable Housing Development. *Journal of Cleaner Production* **65,** 380–388. https://doi.org/10.1016/j.jclepro.2013.09.015

Roy, B., 1991. The Outranking Approach and the Foundations of Electre Methods. *Theory and Decision* **31,** 49–73. https://doi.org/10.1007/bf00134132

Russell-Smith, S.V., Lepech, M.D., 2015. Cradle-to-Gate Sustainable Target Value Design: Integrating Life Cycle Assessment and Construction Management for Buildings. *Journal of Cleaner Production* **100,** 107–115. https://doi.org/10.1016/j.jclepro.2015.03.044

Saaty, T.L., 1977. A Scaling Method for Priorities in Hierarchical Structures. *Journal of Mathematical Psychology* **15**, 234–281. https://doi.org/10.1016/0022-2496(77)90033-5

Saaty, T.L., 2006. The Analytic Network Process – Dependence and Feedback in Decision-Making. *Business Applications and Computational Intelligence* 360–387. https://doi.org/10.4018/978-1-59140-702-7.ch018

Saaty, T.L., 1988. How to Make A Decision: The Analytic Hierarchy Process. Presented at the Proceedings of the International Symposium on the Analytic Hierarchy Process, Creative Decisions Foundation. https://doi.org/10.13033/isahp.y1988.042

Saaty, T.L., Vargas, L.G., 2013. The Analytic Network Process. *Decision Making with the Analytic Network Process* 1–40. https://doi.org/10.1007/978-1-4614-7279-7_1

Safa, M., Sabet, A., MacGillivray, S., Davidson, M., Kaczmarczyk, K., Gibson, G.E., Rayside, D., Haas, C., 2015. Classification of Construction Projects.

Sahlol, D.G., Elbeltagi, E., Elzoughiby, M., Abd Elrahman, M., 2021. Sustainable Building Materials Assessment and Selection Using System Dynamics. *Journal of Building Engineering* **35,** 101978. https://doi.org/10.1016/j.jobe.2020.101978

Sakalasooriya, N., 2021. Conceptual Analysis of Sustainability and Sustainable Development. *JSS* **09,** 396–414. https://doi.org/10.4236/jss.2021.93026

Sala, S., Farioli, F., Zamagni, A., 2012a. Life Cycle Sustainability Assessment in the Context of Sustainability Science Progress (Part 2). *The International Journal of Life Cycle Assessment* **18,** 1686–1697. https://doi.org/10.1007/s11367-012-0509-5

Sala, S., Farioli, F., Zamagni, A., 2012b. Progress in Sustainability Science: Lessons Learnt from Current Methodologies for Sustainability Assessment: Part 1. *The International Journal of Life Cycle Assessment* **18,** 1653–1672. https://doi.org/10.1007/s11367-012-0508-6

Saltelli, A., Tarantola, S., Campolongo, F., Ratto, M., 2002. Sensitivity Analysis in Practice. *John Wiley & Sons, Ltd*. https://doi.org/10.1002/0470870958

Sánchez Cordero, A., Gómez Melgar, S., Andújar Márquez, J.M., 2019. Green Building Rating Systems and the New Framework Level(s): A Critical Review of Sustainability Certification within Europe. *Energies* **13,** 66. https://doi.org/10.3390/en13010066

Sarkis, J., Sundarraj, R.P., 2006. Evaluation of Enterprise Information Technologies: A Decision Model for High-Level Consideration of Strategic and Operational Issues. *IEEE Transactions on Systems, Man and Cybernetics, Part C (Applications and Reviews)* **36,** 260–273. https://doi.org/10.1109/tsmcc.2004.843245

Sartori, I., Hestnes, A.G., 2007. Energy Use in the Life Cycle of Conventional and Low-Energy Buildings: A Review Article. *Energy and Buildings* **39,** 249–257. https://doi.org/10.1016/j.enbuild.2006.07.001

Sartori, T., Drogemuller, R., Omrani, S., Lamari, F., 2021. A Schematic Framework for Life Cycle Assessment (LCA) and Green Building Rating System (GBRS). *Journal of Building Engineering* **38,** 102180. https://doi.org/10.1016/j.jobe.2021.102180

Sasirekha, V., Ilanzkumaran, M., 2013. Heterogeneous Wireless Network Selection Using FAHP Integrated with TOPSIS and VIKOR. *Presented at the 2013 International Conference on Pattern Recognition, Informatics and Mobile Engineering* (PRIME), IEEE, Salem, pp. 399–407.

Schade, J., 2006. Life Cycle Cost Calculation Models for Buildings **10**.

Schoolman, E., Guest, J., Bush, K., Bell, A., 2012. How Interdisciplinary is Sustainability Research? Analyzing the Structure of an Emerging Scientific Field. *Sustainability Science* **7,** 67–80. https://doi.org/10.1007/s11625-011-0139-z

Schröpfer, V.L.M., Tah, J., Kurul, E., 2017. Mapping the Knowledge Flow in Sustainable Construction Project Teams Using Social Network Analysis. *Engineering, Construction and Architectural Management* **24,** 229–259. https://doi.org/10.1108/ECAM-08-2015-0124

Sev, A., 2009. How Can the Construction Industry Contribute to Sustainable Development? A Conceptual Framework. *Sustainable Development* **17,** 161–173. https://doi.org/10.1002/sd.373

Shanian, A., Savadogo, O., 2006. A Material Selection Model Based on the Concept of Multiple Attribute Decision Making. *Materials & Design* **27,** 329–337. https://doi.org/10.1016/j.matdes.2004.10.027

Sharma, A., Saxena, A., Sethi, M., Shree, V., Varun, 2011. Life Cycle Assessment of Buildings: *A Review. Renewable and Sustainable Energy Reviews* **15,** 871–875. https://doi.org/10.1016/j.rser.2010.09.008

Shemshadi, A., Shirazi, H., Toreihi, M., Tarokh, M.J., 2011. A Fuzzy VIKOR Method for Supplier Selection Based on Entropy Measure for Objective Weighting. *Expert Systems with Applications* **38,** 12160–12167. https://doi.org/10.1016/j.eswa.2011.03.027

Shen, L., Tam, V.W.Y., Tam, L., Ji, Y., 2010. Project Feasibility Study: The Key to Successful Implementation of Sustainable and Socially Responsible Construction Management Practice. *Journal of Cleaner Production* **18,** 254–259. https://doi.org/10.1016/j.jclepro.2009.10.014

Sherif, G., Carmela, C., 2019. Integrating the Sustainable Development Goals in Building Projects. *Journal of Sustainability Research.* https://doi.org/10.20900/jsr20190010

Sinha, A., Gupta, R., Kutnar, A., 2013. Sustainable Development and Green Buildings. *Drvna industrija* **64,** 45–53. https://doi.org/10.5552/drind.2013.1205

Sirisawat, P., Kiatcharoenpol, T., 2018. Fuzzy AHP-TOPSIS Approaches to Prioritizing Solutions for Reverse Logistics Barriers. *Computers & Industrial Engineering* **117**, 303–318. https://doi.org/10.1016/j.cie.2018.01.015

Solangi, Y.A., Tan, Q., Mirjat, N.H., Valasai, G.D., Khan, M.W.A., Ikram, M., 2019. An Integrated Delphi-AHP and Fuzzy Topsis Approach Toward Ranking and Selection of Renewable Energy Resources in Pakistan. *Processes* **7,** 118. https://doi.org/10.3390/pr7020118

Sonnemann, G., Valdivia, S., 2014. The UNEP/SETAC Life Cycle Initiative. *LCA Compendium – The Complete World of Life Cycle Assessment* 107–144. https://doi.org/10.1007/978-94-017-8697-3_4

Stazi, F., Mastrucci, A., Munafò, P., 2012. Life Cycle Assessment Approach for the Optimization of Sustainable Building Envelopes: An Application on Solar Wall Systems. *Building and Environment* **58,** 278–288. https://doi.org/10.1016/j.buildenv.2012.08.003

Stephan, A., Stephan, L., 2016. Life Cycle Energy and Cost Analysis of Embodied, Operational and User-Transport Energy Reduction Measures for Residential Buildings. *Applied Energy* **161,** 445–464. https://doi.org/10.1016/j.apenergy.2015.10.023

Stirling, A., 1999. The Appraisal of Sustainability: Some Problems and Possible Responses. *Local Environment* **4,** 111–135. https://doi.org/10.1080/13549839908725588

Suhr, J., 1999. The Choosing by Advantages Decision-making System. Quorum, Westport, CT.

Švajlenka, J., Kozlovská, M., 2018. Houses Based on Wood as an Ecological and Sustainable Housing Alternative—Case Study. *Sustainability* **10,** 1502–1502. https://doi.org/10.3390/su10051502

Švajlenka, J., Kozlovská, M., 2017. Modern Method of Construction Based on Wood in the Context of Sustainability. *Civil Engineering and Environmental Systems* **34,** 127–143. https://doi.org/10.1080/10286608.2017.1340458

Tanguay, G.A., Rajaonson, J., Lefebvre, J.-F., Lanoie, P., 2010. Measuring the Sustainability of Cities: An Analysis of the Use of Local Indicators. *Ecological Indicators* **10,** 407–418. https://doi.org/10.1016/j.ecolind.2009.07.013

Tazikova, A., 2017. Environmental Life-Cycle Costs of Building Materials. ZNPRzBiS. https://doi.org/10.7862/rb.2017.201

Thamboo, J.A., n.d. Reinforced Masonry, An Alternative to Reinforced Concrete 6.

Thirunavukkarasu, K., Kanthasamy, E., Gatheeshgar, P., Poologanathan, K., Rajanayagam, H., Suntharalingam, T., Dissanayake, M., 2021. Sustainable Performance of a Modular Building System Made of Built-Up Cold-Formed Steel Beams. *Buildings* **11,** 460. https://doi.org/10.3390/buildings11100460

Thormark, C., 2002. A Low Energy Building in a Life Cycle—its Embodied Energy, Energy Need for Operation and Recycling Potential. *Building and Environment* **37,** 429–435. https://doi.org/10.1016/s0360-1323(01)00033-6

Todd, J.A., Crawley, D., Geissler, S., Lindsey, G., 2001. Comparative Assessment of Environmental Performance Tools and the Role of the Green Building Challenge. *Building Research & Information* **29,** 324–335. https://doi.org/10.1080/09613210110064268

Touran, A., Gransberg, D.D., Molenaar, K.R., Ghavamifar, K., Mason, D.J., Fithian, L.A., 2009. A Guidebook for the Evaluation of Project Delivery Methods. https://doi.org/10.17226/14238

UNEP, 2021. 2021 Global Status Report for Buildings and Construction | Global abc [www Document]. URL https://globalabc.org/resources/publications/2021-global-status-report-buildings-and-construction. (accessed 6.9.22).

UNEP, 2009. Publications & Data [www Document]. UNEP - UN Environment Programme. URL http://www.unep.org/publications-data. (accessed 3.2.22).

UNEP, 2021. 2021 Global Status Report for Buildings and Construction | Global abc [www Document]. URL https://globalabc.org/resources/publications/2021-global-status-report-buildings-and-construction. (accessed 6.9.22).

USGBC, 2022. Why LEED Certification, U.S. *Green Building Council* [*www Document*]. URL https://www.usgbc.org/leed/why-leed. (accessed 2.13.22).

Uygunoğlu, T., Keçebaş, A., 2011. Lcc Analysis for Energy-Saving in Residential Buildings with Different Types of Construction Masonry Blocks. *Energy and Buildings* **43,** 2077–2085. https://doi.org/10.1016/j.enbuild.2011.04.011

Valdes-Vasquez, R., Klotz, L.E., 2013. Social Sustainability Considerations During Planning and Design: Framework of Processes for Construction Projects. *Journal of Construction Engineering and Management* **139,** 80–89. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000566

Van Ooteghem, K., Xu, L., 2012. The Life-Cycle Assessment of a Single-Storey Retail Building in Canada. *Building and Environment* **49**, 212–226. https://doi.org/10.1016/j.buildenv.2011.09.028

Vos, R.O., 2007. Defining Sustainability: A Conceptual Orientation. *Journal of Chemical Technology and Biotechnology* **82,** 334–339. https://doi.org/10.1002/jctb.1675

Wang, T.-C., Lee, H.-D., 2009. Developing a Fuzzy TOPSIS Approach Based on Subjective Weights and Objective Weights. *Expert Systems with Applications* **36,** 8980–8985. https://doi.org/10.1016/j.eswa.2008.11.035

WCED (World Commission on Environment and Development), 1987. Our Common Future. Oxford: Oxford University Press.

Wen, B., Musa, S.N., Onn, C.C., Ramesh, S., Liang, L., Wang, W., Ma, K., 2020. The Role and Contribution of Green Buildings on Sustainable Development Goals. *Building and Environment* **185,** 107091. https://doi.org/10.1016/j.buildenv.2020.107091

Werner, F., Richter, K., 2007. Wooden Building Products in Comparative LCA. *The International Journal of Life Cycle Assessment* **12,** 470–479. https://doi.org/10.1065/lca2007.04.317

Wieser, A.A., Scherz, M., Maier, S., Passer, A., Kreiner, H., 2019. Implementation of Sustainable Development Goals in Construction Industry - A Systemic Consideration of Synergies and Trade-Offs. *IOP Conference Series: Earth and Environmental Science* **323,** 12177–12177. https://doi.org/10.1088/1755-1315/323/1/012177

Wiss, R.A., Roberts, R.T., David Phraner, S., 2000. Beyond Design-Build-Operate-Maintain: New Partnership Approach Toward Fixed Guideway Transit Projects. Transportation Research Record: *Journal of the Transportation Research Board* **1704,** 13–18. https://doi.org/10.3141/1704-03

Wong, J.K.W., Zhou, J., 2015. Enhancing Environmental Sustainability Over Building Life Cycles Through Green Bim: A Review. *Automation in Construction* **57,** 156–165. https://doi.org/10.1016/j.autcon.2015.06.003

Worrell, E., Price, L., Martin, N., 2001. Energy Efficiency and Carbon Dioxide Emissions Reduction Opportunities in the US Iron and Steel Sector. *Energy* **26,** 513–536. https://doi.org/10.1016/s0360-5442(01)00017-2

Wu, Z., Shen, L., Yu, A.T.W., Zhang, X., 2016. A Comparative Analysis of Waste Management Requirements Between Five Green Building Rating Systems for New Residential Buildings. *Journal of Cleaner Production* **112,** 895–902. https://doi.org/10.1016/j.jclepro.2015.05.073

Xing, S., Xu, Z., Jun, G., 2008. Inventory Analysis of LCA on Steel-and Concrete-Construction Office Buildings. *Energy and Buildings* **40,** 1188–1193. https://doi.org/10.1016/j.enbuild.2007.10.016

Yadegaridehkordi, E., Hourmand, M., Nilashi, M., Alsolami, E., Samad, S., Mahmoud, M., Alarood, A.A., Zainol, A., Majeed, H.D., Shuib, L., 2020. Assessment of Sustainability Indicators for Green Building Manufacturing Using Fuzzy Multi-Criteria Decision-Making Approach. *Journal of Cleaner Production* **277,** 122905. https://doi.org/10.1016/j.jclepro.2020.122905

Yadegaridehkordi, E., Hourmand, M., Nilashi, M., Shuib, L., Ahani, A., Ibrahim, O., 2018. Influence of Big Data Adoption on Manufacturing Companies' Performance: An Integrated Dematel-Anfis Approach. *Technological Forecasting and Social Change* **137,** 199–210. https://doi.org/10.1016/j.techfore.2018.07.043

Yang, J., Ogunkah, I.C.B., 2013. A Multi-Criteria Decision Support System for the Selection of Low-Cost Green Building Materials and Components. *JBCPR* **01,** 89–130. https://doi.org/10.4236/jbcpr.2013.14013

Yeo, D., Gabbai, R.D., 2011. Sustainable Design of Reinforced Concrete Structures Through Embodied Energy Optimization. *Energy and Buildings* **43,** 2028–2033. https://doi.org/10.1016/j.enbuild.2011.04.014

Yılmaz, M., Bakış, A., 2015. Sustainability in Construction Sector. *Procedia - Social and Behavioral Sciences* **195,** 2253–2262. https://doi.org/10.1016/j.sbspro.2015.06.312

Young, J.W.S., 1997. A Framework for the Ultimate Environmental Index – Putting Atmospheric Change into Context with Sustainability. *Environ Monit Assess* **46,** 135–149. https://doi.org/10.1023/A:1005700321608

Yu, W., Cheng, S., Ho, W., Chang, Y., 2018. Measuring the Sustainability of Construction Projects throughout Their Lifecycle: A Taiwan Lesson. *Sustainability* **10,** 1523. https://doi.org/10.3390/su10051523

Zabihi, H., Habib, F., Mirsaeedie, L., 2012. Sustainability in Building and Construction: Revising Definitions and Concepts. *International Journal for Emerging Science* **2,** 570–578.

Zadeh, L.A., 1965. Fuzzy Sets. *Information and Control* **8,** 338–353. https://doi.org/10.1016/s0019-9958(65)90241-x

Zaim, S., Sevkli, M., Camgöz-Akdağ, H., Demirel, O.F., Yesim Yayla, A., Delen, D., 2014. Use of ANP Weighted Crisp and Fuzzy QFD for Product Development. *Expert Systems with Applications* **41,** 4464–4474. https://doi.org/10.1016/j.eswa.2014.01.008

Zanchi, L., Delogu, M., Dattilo, C.A., Zamagni, A., Del Pero, F., 2021. Integrating Life Cycle Sustainability Assessment Results Using Fuzzy-TOPSIS in Automotive Light Weighting. *SAE International Journal of Materials and Manufacturing* **14.** https://doi.org/10.4271/05-14-03-0022

Zavadskas, E.K., Antucheviciene, J., 2007. Multiple Criteria Evaluation of Rural Building's Regeneration Alternatives. *Building and Environment* **42,** 436–451. https://doi.org/10.1016/j.buildenv.2005.08.001

Zhang, H., Haapala, K.R., 2015. Integrating Sustainable Manufacturing Assessment into Decision Making for A Production Work Cell. *Journal of Cleaner Production* **105,** 52–63. https://doi.org/10.1016/j.jclepro.2014.01.038

Zhang, L., Sun, X., Xue, H., 2019. Identifying Critical Risks in Sponge City PPP Projects Using DEMATEL Method: A Case Study of China. *Journal of Cleaner Production* **226,** 949–958. https://doi.org/10.1016/j.jclepro.2019.04.067

Zhong, Y., Wu, P., 2015. Economic Sustainability, Environmental Sustainability and Constructability Indicators Related to Concrete and Steel-Projects. *Journal of Cleaner Production* **108,** 748–756. https://doi.org/10.1016/j.jclepro.2015.05.095

Zhou, Z., Jiang, H., Qin, L., 2007. Life Cycle Sustainability Assessment of Fuels. *Fuel* **86,** 256–263. https://doi.org/10.1016/j.fuel.2006.06.004

Zhu, X., Meng, X., Zhang, M., 2021. Application of Multiple Criteria Decision-Making Methods in Construction: A Systematic Literature Review. *Journal of Civil Engineering and Management* **27,** 372–403. https://doi.org/10.3846/jcem.2021.15260

Zijp, M.C., Van De Meent, D., Hollander, A., Posthuma, L., Heijungs, R., Van Der Voet, E., Huijbregts, M.A.J., 2015. An Identification Key for Selecting Methods for Sustainability Assessments. *Sustainability (Switzerland)* **7,** 2490–2512. https://doi.org/10.3390/su7032490

Zuo, J., Jin, X.-H., Flynn, L., 2012. Social Sustainability in Construction – An Explorative Study. *International Journal of Construction Management* **12,** 51–63. https://doi.org/10.1080/15623599.2012.10773190

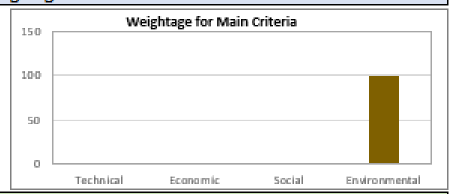
Appendix A: MCDM and DSS Templates Used for Data Collection

Table 1: Excel Template for Distribution of Weightage

Table 1: Distribution of Weightage

Weightage for Main Criteria (Total= 100)

Criteria	Weightage
Technical	0
Economic	0
Social	0
Environmental	100



Percentage of Weightage for Each Sub-Criteria

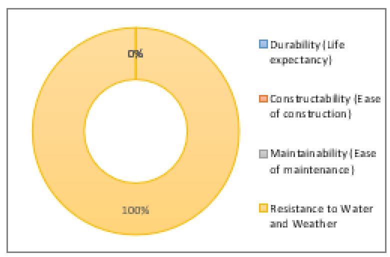
Technical Sub-Criteria	ercentage (totaling 100%)
Durability (Life expectancy)	0%
Constructability (Ease of construction)	0%
Maintainability (Ease of maintenance)	0%
Resistance to Water and Weather	100%

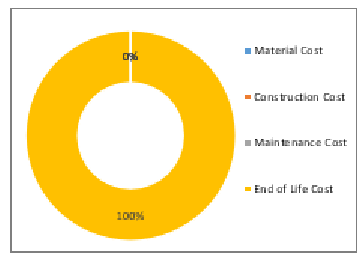
Economic Sub-Criteria	ercentage (totaling 100%)
Material Cost	0%
Construction Cost	0%
Maintenance Cost	0%
End of Life Cost	100%

Social Sub-Criteria	ercentage (totaling 100%)
Job Opportunity Creation	0%
Fire Resistance and Safety	0%
Skilled Labor Availability	0%
Compatibility with Local Heritage	100%

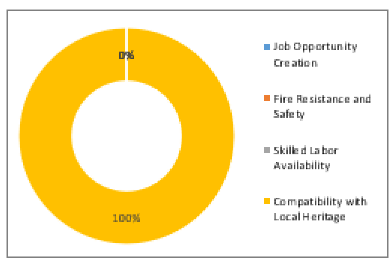
Environmental Sub-Criteria	ercentage (totaling 100%)
Greenhouse Gas Emission	0%
Impact During Manufacturing	0%
Impact During Construction	0%
Recycle and Reuse Potential	100%

Instructions:
1. Please insert values in the **yellow shaded cells only**.
2. Table 3.a: Weightage for all main criteria (total sum = 100) as per their importance.
3. Table 3.b: Please distribute 100% weightage among 4 sub-criteria considering their





Criteria	Weightage	Rank
Durability (Life expectancy)	0.0000	2
Constructability (Ease of construction)	0.0000	2
Maintainability (Ease of maintenance)	0.0000	2
Resistance to Water and Weather	0.0000	2
Material Cost	0.0000	2
Construction Cost	0.0000	2
Maintenance Cost	0.0000	2
End of Life Cost	0.0000	2
Job Opportunity Creation	0.0000	2
Fire Resistance and Safety	0.0000	2
Skilled Labor Availability	0.0000	2
Compatibility with Local Heritage	0.0000	2
Greenhouse Gas Emission	0.0000	2
Impact During Manufacturing	0.0000	2
Impact During Construction	0.0000	2
Recycle and Reuse Potential	1.0000	1
	1.0000	



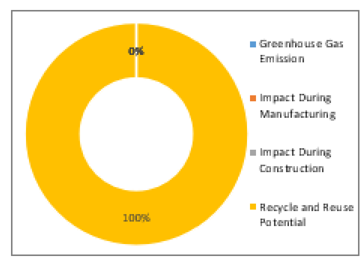


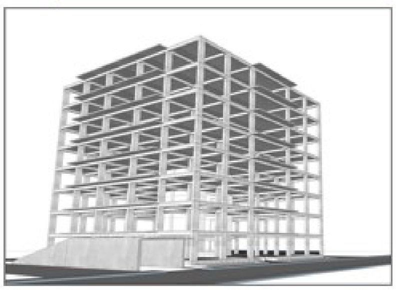
Table 2: Excel Template for Assigning Preferences for Alternatives

Table 2: Assigning Preferences for Alternatives

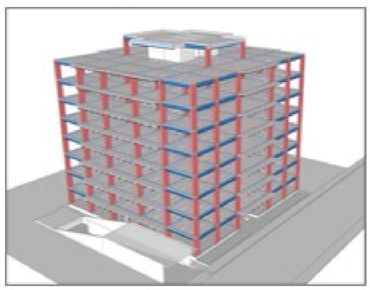
Criteria	Reinforced Concrete	Structural Steel	Timber	Reinforced Masonry
Technical				
Durability (Life expectancy)				
Constructability (Ease of construction)				
Maintainability (Ease of maintenance)				
Resistance to Water and Weather				
Economic				
Material Cost	0	0	0	0
Construction Cost	0	0	0	0
Maintenance Cost				
End of Life Cost	0	0	0	0
Social				
Job Opportunity Creation				
Fire Resistance and Safety				
Skilled Labor Availability				
Compatibility with Local Heritage				
Environmental				
Greenhouse Gas Emission	0	0	0	0
Impact During Manufacturing				
Impact During Construction				
Recycle and Reuse Potential				

Instructions:
Please insert your choice (criteria for each alternative) from the drop-down options (**Very high, High, Medium, Low, Very low**) in the **yellow shaded** cells only.

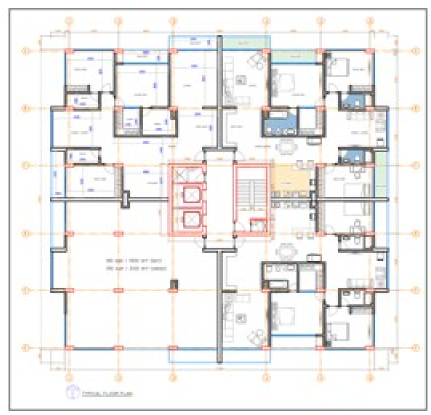
Architectural View



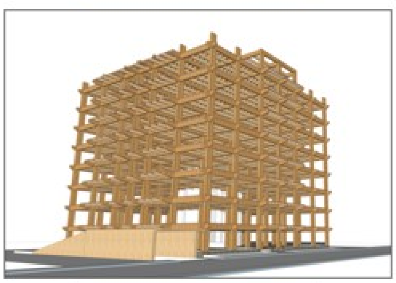
Option 1: Reinforced Concrete



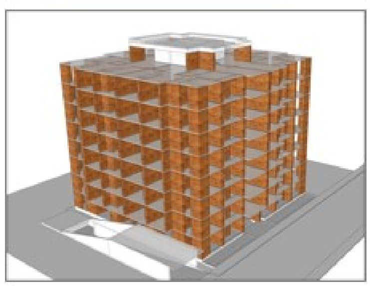
Option 2: Structural Steel



Typical Floor Plan



Option 3: Timber



Option 4: Reinforced Masonry

Table 3: Excel Template for Obtaining Criteria Weightage Using Fuzzy AHP

Table 3: Pairwise Comparision of Criteria to Obtain Weightage through Fuzzy AHP

Criteria	Durability (Life expectancy)	Constructability (Ease of construction)	Maintainability (Ease of maintenance)	Resistance to Water and Weather	Material Cost	Construction Cost	Maintenance Cost	End of Life Cost	Job Opportunity Creation	Fire Resistance and Safety	Skilled Labor Availability	Compatibility with Local Heritage	Greenhouse Gas Emission	Impact During Manufacturing	Impact During Construction	Recycle and Reuse Potential
Durability (Life expectancy)	1															
Constructability (Ease of construction)		1														
Maintainability (Ease of maintenance)			1													
Resistance to Water and Weather				1												
Material Cost					1											
Construction Cost						1										
Maintenance Cost							1									
End of Life Cost								1								
Job Opportunity Creation									1							
Fire Resistance and Safety										1						
Skilled Labor Availability											1					
Compatibility with Local Heritage												1				
Greenhouse Gas Emission													1			
Impact During Manufacturing														1		
Impact During Construction															1	
Recycle and Reuse Potential																1

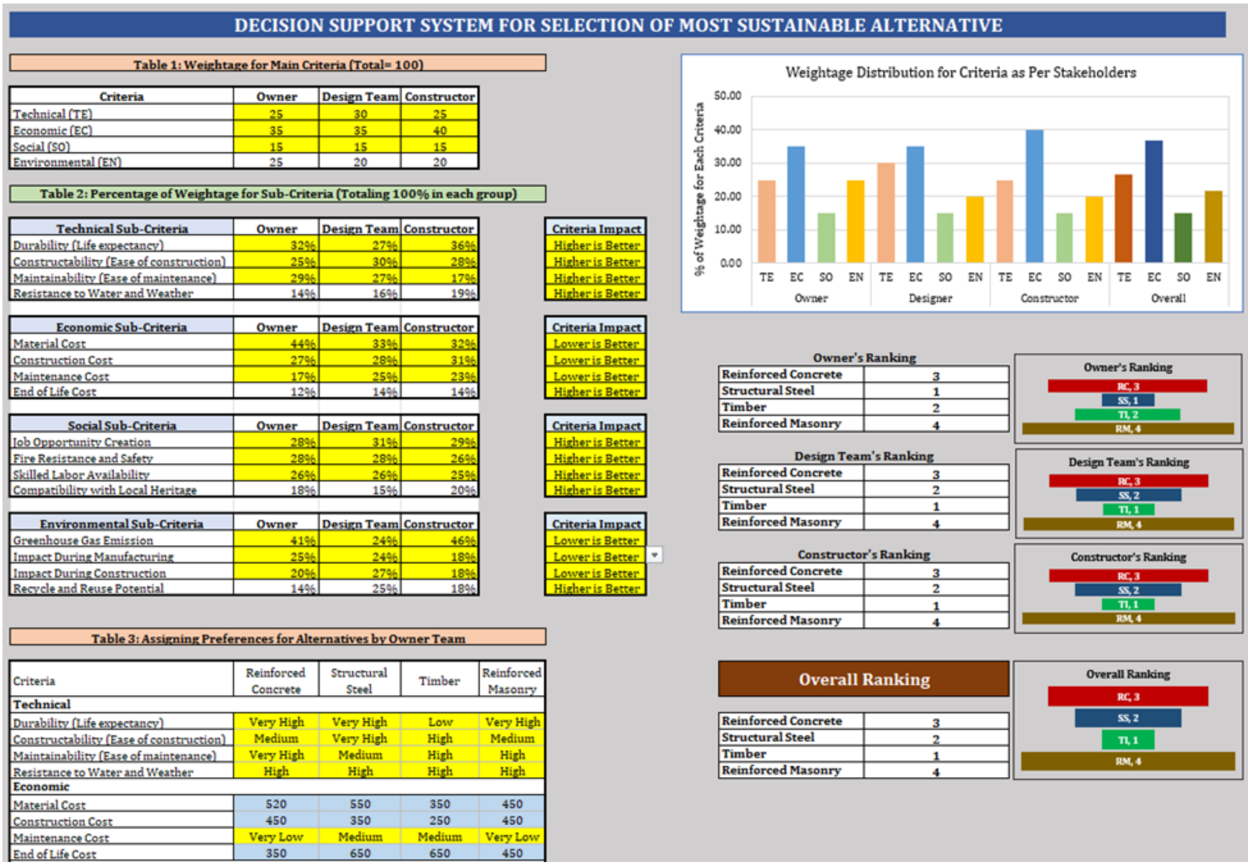
Fundamental Scale (Row vs Column)

Extremely more important	9
Very strongly more important	7
Strongly more important	5
Moderately more important	3
Equal Importance	**1**
Moderately less important	1/3
Strongly less important	1/5
Very strongly less important	1/7
Extremely less important	1/9

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, it dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
2,4,6,8 can be used to express intermediate values		

Instructions:
a. Please insert your choice of importance (from 9 - 1/9) in the **yellow shaded cells only.**
b. Criteria in each row needs to be compared with all columns (pairwise

Table 4: Excel Interface of Decision Support System for Selection of Most Sustainable Alternative



DECISION SUPPORT SYSTEM FOR SELECTION OF MOST SUSTAINABLE ALTERNATIVE

Table 1: Weightage for Main Criteria (Total= 100)

Criteria	Owner	Design Team	Constructor
Technical (TE)	25	30	25
Economic (EC)	35	35	40
Social (SO)	15	15	15
Environmental (EN)	25	20	20

Table 2: Percentage of Weightage for Sub-Criteria (Totaling 100% in each group)

Technical Sub-Criteria	Owner	Design Team	Constructor	Criteria Impact
Durability (Life expectancy)	32%	27%	36%	Higher is Better
Constructability (Ease of construction)	25%	30%	28%	Higher is Better
Maintainability (Ease of maintenance)	29%	27%	17%	Higher is Better
Resistance to Water and Weather	14%	16%	19%	Higher is Better

Economic Sub-Criteria	Owner	Design Team	Constructor	Criteria Impact
Material Cost	44%	33%	32%	Lower is Better
Construction Cost	27%	28%	31%	Lower is Better
Maintenance Cost	17%	25%	23%	Lower is Better
End of Life Cost	12%	14%	14%	Higher is Better

Social Sub-Criteria	Owner	Design Team	Constructor	Criteria Impact
Job Opportunity Creation	28%	31%	29%	Higher is Better
Fire Resistance and Safety	28%	28%	26%	Higher is Better
Skilled Labor Availability	26%	26%	25%	Higher is Better
Compatibility with Local Heritage	18%	15%	20%	Higher is Better

Environmental Sub-Criteria	Owner	Design Team	Constructor	Criteria Impact
Greenhouse Gas Emission	41%	24%	46%	Lower is Better
Impact During Manufacturing	25%	24%	18%	Lower is Better
Impact During Construction	20%	27%	18%	Lower is Better
Recycle and Reuse Potential	14%	25%	18%	Higher is Better

Table 3: Assigning Preferences for Alternatives by Owner Team

Criteria	Reinforced Concrete	Structural Steel	Timber	Reinforced Masonry
Technical				
Durability (Life expectancy)	Very High	Very High	Low	Very High
Constructability (Ease of construction)	Medium	Very High	High	Medium
Maintainability (Ease of maintenance)	Very High	Medium	High	High
Resistance to Water and Weather	High	High	High	High
Economic				
Material Cost	520	550	350	450
Construction Cost	450	350	250	450
Maintenance Cost	Very Low	Medium	Medium	Very Low
End of Life Cost	350	650	650	450

Owner's Ranking

Reinforced Concrete	3
Structural Steel	1
Timber	2
Reinforced Masonry	4

Design Team's Ranking

Reinforced Concrete	3
Structural Steel	2
Timber	1
Reinforced Masonry	4

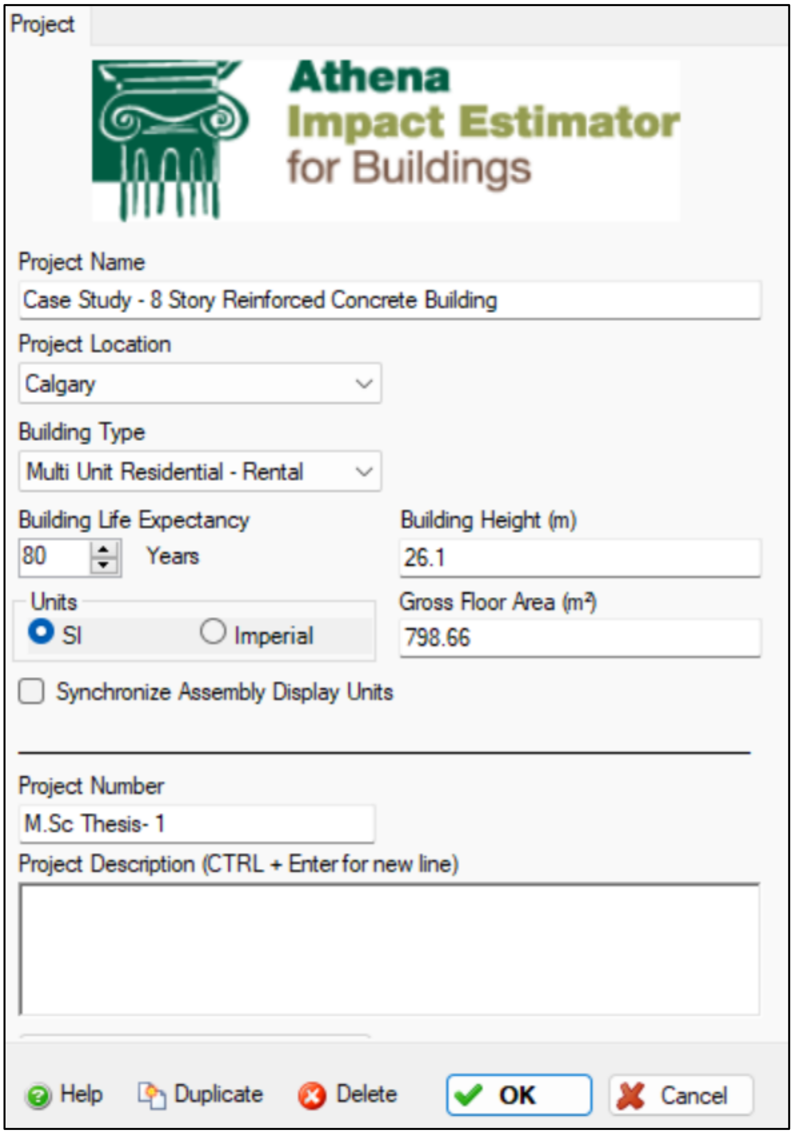
Constructor's Ranking

Reinforced Concrete	3
Structural Steel	2
Timber	1
Reinforced Masonry	4

Overall Ranking

Reinforced Concrete	3
Structural Steel	2
Timber	1
Reinforced Masonry	4

Appendix B: LCA and LCCA Calculations Using 'Athena Impact Estimator for Building' Software



REINFORCED CONCRETE BUILDING

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls
Concrete Benchmark CAN 25 MPa	m3	865.53	0.00	0.00	487.27	0.00	378.26
Concrete Benchmark CAN 30 MPa	m3	2042.99	352.00	1187.17	0.00	403.73	0.00
Galvanized Studs	Ton	17.71	0.00	0.00	0.00	0.00	17.71
Rebar, Rod, Light Sections	Ton	350.41	211.00	66.81	20.67	21.18	9.95
Screws Nuts & Bolts	Ton	0.55	0.00	0.00	0.00	0.00	0.55
Welded Wire Mesh / Ladder Wire	Ton	2.30	0.00	0.00	2.30	0.00	0.00

Total Cost	438966	$
Unit Cost (Sqm)	549.63	$
Construction Cost (Sqm)	152.39	$

LCA Measures		Unit	Foundations	Walls	Columns and Beams	Roofs	Floors	Total
Greenhouse Gas Emission	Total	kg CO2 eq	327351.7	14320.47	734767.2	0	354048.59	1430487.99
	Emission/ Sqm	kg CO2 eq	51.21	2.24	114.95	0	55.39	223.79

STAINLESS STEEL BUILDING

Material	Unit	Total Quantity	Wall, Columns & Beams	Floors	Foundations	Roofs	Wall
Concrete Benchmark CAN 25 MPa	m3	865.8479	0.0000	0.0000	487.59	0.0000	378.25
Galvanized Studs	Ton	17.7067	0.0000	0.0000	0.00	0.0000	17.70
Hollow Structural Steel	Ton	21.1579	21.1579	0.0000	0.00	0.0000	0.000
Rebar, Rod, Light Sections	Ton	28.1958	0.0000	0.0000	18.24	0.0000	9.94
Screws Nuts & Bolts	Ton	11.4343	10.8812	0.0000	0.00	0.0000	0.55
Welded Wire Mesh / Ladder Wire	Ton	2.2991	0.0000	0.0000	2.29	0.0000	0.00
Wide Flange Sections	Ton	192.2411	192.2411	0.0000	0.00	0.0000	0.00

Total Cost	3,071,489.18	$
Unit Cost (Sqm)	480.72	$
Construction Cost (Sqm)	115.37	$

LCA Measures		Unit	Foundations	Walls	Columns and Beams	Roofs	Floors	Total
Greenhouse Gas Emission	Total	kg CO2 eq	313119.04	13697.8	702820.8	0	338655.17	1368292.8
	Emission/Sqm	kg CO2 eq	48.98	2.142	109.95	0	52.98	214.06

TIMBER BUILDING

Material	Unit	Total Quantity	Walls, Column Beam	Floors	Foundations	Roofs
#15 Organic Felt	100sf	2,555.59	635.18	0.00	0.00	1,920.40
1/2" Regular Gypsum Board	sf	195,712.66	140,211.59	0.00	0.00	0.00
6 mil Polyethylene	sf	32,473.04	0.0000	0.00	32,473.04	0.00
Air Barrier	sf	59,103.85	59,103.85	0.00	0.00	0.00
Blown Cellulose	sf (1")	545,878.92	319,246.91	0.00	0.00	0.00
Concrete Benchmark USA 3000 psi	yd^3	122.62	14.64	0.00	107.98	0.00
Double Glazed Hard Coated Argon	sf	17,128.05	17,128.05	0.00	0.00	0.00
Expanded Polystyrene	sf (1")	5,357.19	5,357.19	0.00	0.00	0.00
Fiber Cement	sf	75,665.82	61,287.93	0.00	0.00	0.00
Galvanized Sheet	Tons (short)	11.68	0.00	5.29	0.00	6.38
Glass Based shingles 30yr	100sf	1,415.03	0.00	0.00	0.00	1,415.03
Glass Fibre	lbs	13,889.10	13,889.10	0.00	0.00	0.00
Glazing Panel	Tons	7.93	7.93	0.00	0.00	0.00
Joint Compound	Tons	14.33	14.33	0.00	0.00	0.00
Laminated Veneer Lumber	ft3	235.40	235.40	0.0000	0.00	0.00
Large Dimension Softwood Lumber, kiln-dried	Mbfm large dimension	140.56	0.00	6.41	0.00	0.0000
Nails	Tons (short)	6.45	4.78	0.69	0.00	0.98
Oriented Strand Board	msf (3/8")	1,246.25	77.80	105.95	0.00	0.00
Paper Tape	Tons (short)	0.16	0.16	0.00	0.00	0.00
Polyiso Foam Board (unfaced)	sf (1")	12,105.05	12,105.05	0.00	0.00	0.00
PVC Window Frame	lbs	63,967.49	63,967.49	0.00	0.00	0.00
Rebar, Rod, Light Sections	Tons (short)	70.93	3.24	0.00	67.69	0.00
Roofing Asphalt	lbs	2,302.76	0.0000	0.0000	0.0000	0.00
Small Dimension Softwood Lumber, kiln-dried	Mbfm small dimension	227.17	110.65	43.32	0.0000	73.19

Softwood Plywood	msf (3/8")	74.47	0.00	0.00	0.0000	74.47
Solvent Based Alkyd Paint	Gallons (us)	14.35	14.35	0.00	0.0000	0.00
Water Based Latex Paint	Gallons (us)	2,530.25	767.88	0.00	0.0000	0.00
Welded Wire Mesh / Ladder Wire	Tons (short)	0.78	0.00	0.00	0.78	0.00

Total Cost	1918125.75	$
Unit Cost (Sqm)	300.21	$
Construction Cost (Sqm)	84.59	$

LCA Measures		**Unit**	**Foundations**	**Walls**	**Columns and Beams**	**Roofs**	**Floors**	**Total**
Greenhouse Gas Emission	Total	kg CO2 eq	71163.41	3113.14	159732	0	76967.08	310975.65
	Emission/Sqm	kg CO2 eq	11.13	0.48	24.98	0	12.041	48.65

<u>**REINFORCED MASONRY**</u>

Material	Unit	Total Quantity	Wall, Columns & Beams	Floors	Foundations	Roofs
Concrete Benchmark CAN 25 MPa	m3	173.11	33.40	0.00	97.45	0.00
Concrete Benchmark CAN 30 MPa	m3	408.60	0.00	237.43	0.00	80.75
Brick Block	Thousand	0.00	1070.00	0.00	0.00	0.00
Galvanized Studs	Tonnes	3.54	0.00	0.00	0.00	0.00
Rebar, Rod, Light Sections	Tonnes	70.08	58.20	13.36	4.13	4.24
Screws Nuts & Bolts	Tonnes	0.11	0.00	0.00	0.00	0.00
Welded Wire Mesh / Ladder Wire	Tonnes	2.30	0.00	0.00	2.30	0.00

Total Cost	2426547.2	$
Unit Cost (Sqm)	379.78	$
Construction Cost (Sqm)	179.56	$

LCA Measures		Unit	Foundations	Wall, Columns and Beams	Roofs	Floors	Total
Greenhouse Gas Emission	Total	kg CO_2 eq	270420.99	606981.6	0	292474.92	1181707.47
	Emission/Sqm	kg CO_2 eq	42.306	94.960	0	45.75	184.87

Appendix C: C Sharp Coding and Computation Algorithm

1. To Register a New Team:

```
private void button1_Click(object sender, EventArgs e)
        {
            try
            {
                if (txtname.Text != "" && txtloc.Text != "" && txtheight.Text != "" &&
txtgrossarea.Text != "" && txtnofloor.Text != "" && txtowner.Text != "" && txtpid.Text != ""
&& txtpass.Text != "" && txtcpass.Text != "" && txtqsn.Text != "" && txtans.Text != "")
                {
                    if (txtpass.Text == txtcpass.Text)
                    {
                        string query;
                        query = "insert into
[MCDM].[dbo].[Reg](name,location,height_building,gross_area_floor,number_floor,owner_project,p
rojectID) values('" + txtname.Text + "','" + txtloc.Text + "','" + txtheight.Text + "','" +
txtgrossarea.Text + "','" + txtnofloor.Text + "','" + txtowner.Text + "','" + txtpid.Text +
"')";

                        int row = DataAccess.ExecuteQuery(query);

                        //login access
                        string query1;
                        query1 = "insert into [MCDM].[dbo].[UserLogin](projectID,pass,qsn,ans)
values('" + txtpid.Text + "','" + txtpass.Text + "','" + txtqsn.SelectedItem + "','" +
txtans.Text + "')";

                        int row1 = DataAccess.ExecuteQuery1(query1);
```

… … … Continued

2. To Login into the System:

```
private void button1_Click(object sender, EventArgs e)
        {
            DataTable table1 = DataAccess.LoadData("select * from [MCDM].[dbo].[UserLogin]
where projectID = '" + UserIdTextBox.Text + "' AND pass = '" + PasswordTextBox.Text + "'");


            if (table1.Rows.Count != 1)
            {
                MessageBox.Show("wrong user Id or Password");

                UserIdTextBox.Clear();
                PasswordTextBox.Clear();
                return;
```

… … … Continued

3. Calculation to Find Minimum, Maximum and Average Values (Generation of Combined Decision Matrix):

```
//step 2 calculation
                //Math.Max(x, Math.Max(y, z));
                //Math.Min(x, Math.Min(y, z));
                //Average(n1, n2, n3);
```

```
                //technical
                s2rct1[0] = Math.Min(orct1[0], Math.Min(drct1[0], crct1[0]));
                s2rct1[1] = Average(orct1[1], drct1[1], crct1[1]);
                s2rct1[2] = Average(orct1[2], drct1[2], crct1[2]);
                s2rct1[3] = Math.Max(orct1[3], Math.Max(drct1[3], crct1[3]));

                s2rct2[0] = Math.Min(orct2[0], Math.Min(drct2[0], crct2[0]));
                s2rct2[1] = Average(orct2[1], drct2[1], crct2[1]);
                s2rct2[2] = Average(orct2[2], drct2[2], crct2[2]);
                s2rct2[3] = Math.Max(orct2[3], Math.Max(drct2[3], crct2[3]));
```

… … … Continued

4. Identify Benefit (Positive) and Cost (Negative) Criteria and Compute the Normalized Fuzzy Decision Matrix:

```
//step 3 calculation
                //Math.Max(a, Math.Max(b, Math.Max(c, d)));
                //Math.Min(a, Math.Min(b, Math.Min(c, d)));
                min1 = Math.Min(s2rct1[0], Math.Min(s2sst1[0], Math.Min(s2tt1[0],
s2rmt1[0])));
                min2 = Math.Min(s2rct2[0], Math.Min(s2sst2[0], Math.Min(s2tt2[0],
s2rmt2[0])));
                min3 = Math.Min(s2rct3[0], Math.Min(s2sst3[0], Math.Min(s2tt3[0],
s2rmt3[0])));
                min4 = Math.Min(s2rct4[0], Math.Min(s2sst4[0], Math.Min(s2tt4[0],
s2rmt4[0])));
                min5 = Math.Min(s2rce1[0], Math.Min(s2sse1[0], Math.Min(s2te1[0],
s2rme1[0])));
                min6 = Math.Min(s2rce2[0], Math.Min(s2sse2[0], Math.Min(s2te2[0],
```

… … … Continued

```
//technical
                s3rct1[0] = s2rct1[0] / max1;
                s3rct1[1] = s2rct1[1] / max1;
                s3rct1[2] = s2rct1[2] / max1;
                s3rct1[3] = s2rct1[3] / max1;
```

… … … Continued

5. Step 4 Calculation:

```
//step 4 calculation

                //Math.Min(a, Math.Min(b, Math.Min(c, d)));
                //Math.Min(y, z);
                //Math.Max(y, z);
                //Math.Max(a, Math.Max(b, Math.Max(c, d)));
                //technical
                s4rct1[0] = Math.Min(s3rct1[0], Math.Min(s3rct1[1], Math.Min(s3rct1[2],
s3rct1[3])));
                s4rct1[1] = Math.Min(s3rct1[1], s3rct1[2]);
                s4rct1[2] = Math.Max(s3rct1[1], s3rct1[2]);
                s4rct1[3] = Math.Max(s3rct1[0], Math.Max(s3rct1[1], Math.Max(s3rct1[2],
s3rct1[3])));
                s4rct2[0] = Math.Min(s3rct2[0], Math.Min(s3rct2[1], Math.Min(s3rct2[2],
s3rct2[3])));
                s4rct2[1] = Math.Min(s3rct2[1], s3rct2[2]);
                s4rct2[2] = Math.Max(s3rct2[1], s3rct2[2]);
```

```
                s4rct2[3] = Math.Max(s3rct2[0], Math.Max(s3rct2[1], Math.Max(s3rct2[2],
s3rct2[3])));
```

… … … **Continued**

6. Compute the Normalized Fuzzy Decision Matrix for Particular Types of User (Owner):

```
//owner technical
//first col
 //ot11

                if (ot11.Text == "Very High")
                {
                    os5rct1[0] = s4rct1[0] * 7;
                    os5rct1[1] = s4rct1[1] * 8;
                    os5rct1[2] = s4rct1[2] * 9;
                    os5rct1[3] = s4rct1[3] * 10;

                }
                else if (ot11.Text == "High")
                {
                    os5rct1[0] = s4rct1[0] * 5;
                    os5rct1[1] = s4rct1[1] * 6;
                    os5rct1[2] = s4rct1[2] * 7;
                    os5rct1[3] = s4rct1[3] * 8;
                }
                else if (ot11.Text == "Medium")
                {
                    os5rct1[0] = s4rct1[0] * 3;
                    os5rct1[1] = s4rct1[1] * 4;
                    os5rct1[2] = s4rct1[2] * 5;
                    os5rct1[3] = s4rct1[3] * 6;
                }
                else if (ot11.Text == "Low")
                {
                    os5rct1[0] = s4rct1[0] * 1;
                    os5rct1[1] = s4rct1[1] * 2;
                    os5rct1[2] = s4rct1[2] * 3;
                    os5rct1[3] = s4rct1[3] * 4;
                }
                else if (ot11.Text == "Very Low")
                {
```

… … … **Continued**

7. Calculation to Assign Weightage Distribution Values:

```
//step 6 calculation owner
                //technical
                for (int i = 0; i < 4; i++)
                {
                    os6rct1[i] = os5rct1[i] * owt1;
                }
                for (int i = 0; i < 4; i++)
                {
                    os6rct2[i] = os5rct2[i] * owt2;
                }
                for (int i = 0; i < 4; i++)
                {
```

```
                    os6rct3[i] = os5rct3[i] * owt3;
                }
                for (int i = 0; i < 4; i++)
```

… … … **Continued**

8. Calculation to Find Minimum and Maximum Array (Owner):

```
//step 7 calculation owner


                opt1 = FindMax(os6rct1, os6sst1, os6tt1, os6rmt1);
                opt2 = FindMax(os6rct2, os6sst2, os6tt2, os6rmt2);
                opt3 = FindMax(os6rct3, os6sst3, os6tt3, os6rmt3);
                opt4 = FindMax(os6rct4, os6sst4, os6tt4, os6rmt4);

                ope1 = FindMax(os6rce1, os6sse1, os6te1, os6rme1);
                ope2 = FindMax(os6rce2, os6sse2, os6te2, os6rme2);
                ope3 = FindMax(os6rce3, os6sse3, os6te3, os6rme3);
                ope4 = FindMax(os6rce4, os6sse4, os6te4, os6rme4);
```

… … … **Continued**

9. Calculation to Find the Distance (Owner):

```
//step 8 calculation owner
                //Math.Pow(b, 2);
                //Math.Sqrt(x)
                //rc pos
                os8rct1[0] = Math.Sqrt(0.25 * (Math.Pow((opt1[0] - os6rct1[0]), 2) +
Math.Pow((opt1[1] - os6rct1[1]), 2) + Math.Pow((opt1[2] - os6rct1[2]), 2) + Math.Pow((opt1[3]
- os6rct1[3]), 2)));
                os8rct2[0] = Math.Sqrt(0.25 * (Math.Pow((opt2[0] - os6rct2[0]), 2) +
Math.Pow((opt2[1] - os6rct2[1]), 2) + Math.Pow((opt2[2] - os6rct2[2]), 2) + Math.Pow((opt2[3]
- os6rct2[3]), 2)));
                os8rct3[0] = Math.Sqrt(0.25 * (Math.Pow((opt3[0] - os6rct3[0]), 2) +
Math.Pow((opt3[1] - os6rct3[1]), 2) + Math.Pow((opt3[2] - os6rct3[2]), 2) + Math.Pow((opt3[3]
- os6rct3[3]), 2)));
                os8rct4[0] = Math.Sqrt(0.25 * (Math.Pow((opt4[0] - os6rct4[0]), 2) +
```

… … … **Continued**

10. Final Calculation for Owner:

```
//step 9 calculation owner

                orcdi1 = (os8rct1[0] + os8rct2[0] + os8rct3[0] + os8rct4[0]) + (os8rce1[0] +
os8rce2[0] + os8rce3[0] + os8rce4[0]) + (os8rcs1[0] + os8rcs2[0] + os8rcs3[0] + os8rcs4[0]) +
(os8rcen1[0] + os8rcen2[0] + os8rcen3[0] + os8rcen4[0]);
                orcdi2 = (os8rct1[1] + os8rct2[1] + os8rct3[1] + os8rct4[1]) + (os8rce1[1] +
os8rce2[1] + os8rce3[1] + os8rce4[1]) + (os8rcs1[1] + os8rcs2[1] + os8rcs3[1] + os8rcs4[1]) +
(os8rcen1[1] + os8rcen2[1] + os8rcen3[1] + os8rcen4[1]);
                orccc = orcdi2 / (orcdi1 + orcdi2);
```

… … … **Continued**

11. Calculation to Determine the Rank Using CC Values:

```
//rank
                double orank1 = 0, orank2 = 0, orank3 = 0, orank4 = 0;
                double[] or = new double[4];

                or[0] = orccc;
                or[1] = osscc;
                or[2] = otcc;
                or[3] = ormcc;

                Array.Sort(or);
                Array.Reverse(or);
```

… … … **Continued**

12. Generate Final Chart Using Importance of Opinion from Each Stakeholder:

```
private void button1_Click(object sender, EventArgs e)
        {
            if(c==0)
            {
                try
                {
                    try
                    {
                        double pt = Double.Parse(txtOT.Text) + Double.Parse(txtDT.Text) +
Double.Parse(txtCT.Text);
                        if (pt == 100)
                        {
                            f1 = Double.Parse(otxtcc1.Text) * (Double.Parse(txtOT.Text) / 100)
+ Double.Parse(dtxtcc1.Text) * (Double.Parse(txtDT.Text) / 100) + Double.Parse(ctxtcc1.Text) *
(Double.Parse(txtCT.Text) / 100);
                            f2 = Double.Parse(otxtcc2.Text) * (Double.Parse(txtOT.Text) / 100)
+ Double.Parse(dtxtcc2.Text) * (Double.Parse(txtDT.Text) / 100) + Double.Parse(ctxtcc2.Text) *
(Double.Parse(txtCT.Text) / 100);
                            f3 = Double.Parse(otxtcc3.Text) * (Double.Parse(txtOT.Text) / 100)
+ Double.Parse(dtxtcc3.Text) * (Double.Parse(txtDT.Text) / 100) + Double.Parse(ctxtcc3.Text) *
(Double.Parse(txtCT.Text) / 100);
```

… … … **Continued**