A systematic and objective approach for evaluating performance and selecting subcontractors in construction projects

by

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Abstract

The management of the contractor-subcontractor relationship is a pivotal component of supply chain management in the construction industry, significantly impacting project success. This thesis explores approaches to assess performance of subcontractor, select the best subcontractor and the critical role of subcontractors in construction projects. Traditionally, process of subcontractor assessment performance and selection have been influenced by subjective assessments, often leading to biased decision-making processes. To address this, the research develops a comprehensive framework that links performance assessment upon project completion with the selection process for new projects, using objective criteria and systematic evaluation methods.

The study begins with an extensive literature review and expert consultations to identify key indices and criteria for subcontractor evaluation, including time, cost, quality, safety, leadership, pricing, and experience. A hybrid approach is employed, combining Monte Carlo simulation and the Analytic Hierarchy Process (AHP) to weigh these criteria, ensuring statistical significance and reducing judgment uncertainty. This innovative method generates pairwise comparison matrices and utilizes probability distributions to establish objective weights for each criterion.

The developed evaluation model incorporates a Linear Additive Utility Model (LAUM) to calculate a Performance Index (PI) that quantifies subcontractor performance across various levels, from outstanding to poor. By integrating these assessments into a Decision Support System (DSS), the research provides a tool for general contractors to systematically evaluate subcontractors and make informed decisions. The DSS employs the Complex Proportional Assessment (COPRAS) method, a multi-criteria decision-making (MCDM) approach that ranks subcontractors based on comprehensive performance data, aligning selection decisions with empirical evidence and industry best practices.

This thesis demonstrates the potential for enhanced transparency, accuracy, and efficiency in subcontractor selection, contributing to improved project outcomes by optimizing subcontractor capabilities, resource allocation, and overall project delivery. By bridging the gap between performance assessment and selection processes, the research establishes a foundation for more informed and effective subcontractor management in the construction industry.

Preface

This thesis is an original work by Iyad Al Hasan 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. No part of this thesis has been previously published.

Acknowledgement

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List of Abbreviations

AI	Activeness Index
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
ANN	Artificial Neural Network
CT	Construction Time
CI	Consistency Index
CR	Consistency Ratio
CAOS	Construction Accident Occurrence Status
COPRAS	Complex Proportional Assessment
CFC	Cost and Finance Criterion
CDF	Cumulative Distribution Function
DM	Decision Makers
DSS	Decision Support System
ECDF	Empirical Cumulative Distribution Function
EFPC	Environmental-Friendly Project Capability
FC	Financial Claims
FSs	Fuzzy Sets
FMCDM	Fuzzy Multi-Criteria Decision-Making
GC	General Contractors
SCC	General Contractor Satisfaction (Communication) Criterion
GI	Growth
KS	Kolmogorov-Smirnov
LC	Leadership Criterion
LAUM	Linear Additive Utility Model
LD	Lognormal Distribution
MC-AHP	Monte Carlo and AHP
MCDM	Multi-Criteria Decision-Making
NCRs	Non-Conformance Reports
ND	Normal Distribution

NI	Normalization Index
OHS	Occupational Health and Safety
HSC	Occupational Health and Safety and Environmental Protection
OPA	Ordinal Priority Approach
PI	Performance Index
PEC	Pricing and Experience Criterion
PI	Profitability Index
QC	Quality Criterion
QFD	Quality Function Deployment
RI	Random Consistency Index
RUI	Relative Usage Index
RC	Resource Adequacy Criterion
RC	Revised Contract Period
RV	Revised Contract Value
RFI	Request for Information
SPI	Schedule Performance Index
SNA	Social Network Analysis
SI	Stability Index
SG	Subcontractors
STC	Time Criterion
SQL	Structured query language
TD	Triangular Distribution
C$	Canadian Dollar
%	Percentage

Chapter 1: Introduction

1.1 Background

One of the key components of supply-chain management is the management of the buyer-supplier (contractor- subcontractor) relationship (BSR). Undoubtedly, a company's competitive edge can be enhanced through efficient supplier-relationship management (Morgan & Hunt., 1994).

Furthermore, building strong bonds between contractors and subcontractors appears to be a viable solution for a variety of project difficulties, including delays and cost overruns. A subcontractor can provide a competitive advantage for a general contractor, such as having unique assets, advanced knowledge or technology, complementary resources, and effective management practices (Dyer & Singh., 1998).

In the past, general contractors independently handled entire projects using their in-house capabilities. However, the modern role of general contractors has evolved, emphasizing tasks like surveying, contract management, budget estimation, and the planning, direction, and control of projects.

About 70% of project work in construction is handled by subcontractors. This growing reliance is due to contractors leveraging the specialized skills of subcontractors to boost their overall capabilities while managing their resources more efficiently (Okunlola, 2015) . Another common reason for subcontracting is that qualified subcontractors are usually able to perform their work specialty more quickly and at a lesser cost than can the general contractor (Arditi & Chotibhongs, 2005).

Moreover, outsourcing offers companies the opportunity to enhance operational efficiencies by freeing up capacity and focusing on their core strengths, thereby increasing flexibility (Conner & Prahalad, 1996).

In the current system, the subcontractor may subcontract some of the work and have a series of sub-subcontractors. Additionally, they have contractual agreements with material suppliers, manufacturers, distributors, and manufacturer’s representatives (Arditi & Chotibhongs, 2005).

According to Pallikkonda et al. (2019), a subcontractor may be defined as any person or company stated in the contract document as a subcontractor, or any person designated as a subcontractor for a part of the works.

1.2 Problem Statement

The construction industry has a dynamic nature and is strongly associated with economic indicators. The nature and complexity of construction projects create the need for subcontractor involvement to effectively execute the projects.

The reasons for employing subcontractors vary across different countries and projects. One of the major challenges faced by general contractors is the objective selection of qualified subcontractors based on all relevant criteria and standards while minimizing bias. Additionally, there is a need to objectively assess subcontractor performance upon project completion to enhance management operations and use lessons learned to inform future selection decisions.

In this context, selecting subcontractors based on subjective criteria and neglecting objective performance assessments upon project completion can result in a range of adverse outcomes. The reliance on subjective judgment for subcontractor selection often leads to inconsistencies in work quality, manifesting as defects, delays, and overall compromised project outcomes. Such an approach not only undermines project integrity but also introduces significant bias and potential for corruption, as selection decisions may be influenced by personal preferences or relationships rather than objective performance metrics.

The financial repercussions of these practices are substantial. Subjective selection methods may result in increased costs due to inefficiencies, additional oversight, and necessary rework. The absence of objective performance evaluations exacerbates these issues by perpetuating the engagement of subcontractors with a history of underperformance, thereby leading to recurrent delays and ineffective resource utilization. Safety concerns are also heightened when subcontractors are not thoroughly assessed; those who fail to adhere to safety standards can elevate the risk of accidents and injuries on site.

Furthermore, the lack of objective performance assessments impacts the general contractor's reputation. Consistently poor subcontractor performance can lead to client dissatisfaction, damaging trust, and reducing future business opportunities. Ineffective resource management and missed opportunities for continuous improvement arise from the absence of structured feedback, which is essential for refining subcontractor selection criteria and enhancing project execution.

Legal and compliance risks are also amplified when subcontractors who do not meet regulatory or contractual obligations are selected based on biased criteria. In conclusion, the combination of subjective subcontractor selection and inadequate performance assessments contributes to increased bias, potential corruption, elevated costs, delays, safety risks, and diminished client satisfaction. This underscores the necessity for a more systematic and data-driven approach to subcontractor management.

1.3 Study Questions

The study is guided by the following research questions:

- Why are qualified subcontractors important in the construction industry?
- What are the relevant criteria to assess performance and select the best subcontractor?
- How can the performance of subcontractors be evaluated objectively upon project completion?
- How can the best subcontractor be selected objectively?
- What is the link between the process of assessing performance and selection?

1.4 Research Objectives

The following express the research objectives:

1- Identify and establish relevant criteria for assessing performance and selecting the best subcontractor and explore the relationship between these criteria.
2- Weigh the identified criteria using appropriate methods to minimize bias.
3- Develop a methodology and approach for objectively evaluating the performance of subcontractors upon project completion.
4- Create a framework and decision support system for objectively selecting the best subcontractor for new projects.
5- Explore and establish the link between performance assessment upon project completion and the subcontractor selection process for new projects.

1.5 Research Methodology

The research is divided into three main phases, each with detailed steps to ensure a comprehensive and objective process, as shown in Figure 1.1.

1.5.1 Phase 01: Data Collection and Analysis

This initial phase focuses on gathering relevant information and preparing it for analysis.

- Literature Review, Industry Practices, and Expert Opinions: The process begins with an extensive review of existing literature, current industry practices, and insights from experts. This step is crucial for understanding the landscape and identifying potential criteria.
- Data Collection and Preparation: Based on the information gathered, specific data relevant to subcontractor evaluation and selection is collected. This data is then organized and prepared for detailed analysis.
- Data Analysis: The prepared data is analyzed to identify key patterns, trends, and insights that will inform the subsequent phases. This step ensures that the criteria used for evaluation and selection are based on empirical evidence and industry standards.

1.5.2 Phase 02: Identification and Weighting of Criteria

This phase involves identifying the specific criteria for evaluation and selection determining their relative importance.

- Identification of Evaluation Indices and Selection Criteria: The relevant criteria for evaluating and selecting subcontractors are identified. These criteria could include factors such as cost, quality, time, safety, customer satisfaction, and sustainable practices.
- Weighting Indices and Criteria: Once the criteria are identified, they are weighted according to their importance. This involves using methodologies such as Monte Carlo simulations with the Analytic Hierarchy Process (AHP) to ensure that the weighting is objective and statistically valid.

1.5.3 Phase 03: Developing and Applying the Model

The final phase involves creating and implementing a model for evaluating and selecting subcontractors, incorporating the identified and weighted criteria.

- Formulating Criteria (Objectively): The identified criteria are formulated into a structured framework, ensuring that each criterion is clearly defined and objectively measurable.

- Developing the Evaluation Model: An evaluation model is developed based on the formulated indices. This model is designed to assess subcontractors' performance systematically and consistently.
- Developing Decision Support System: A Decision Support System (DSS) is developed to assist in the selection the best subcontractor process. The DSS integrates the evaluation model and allows for easy application of the criteria to different subcontractors, providing a user-friendly interface for decision-makers.

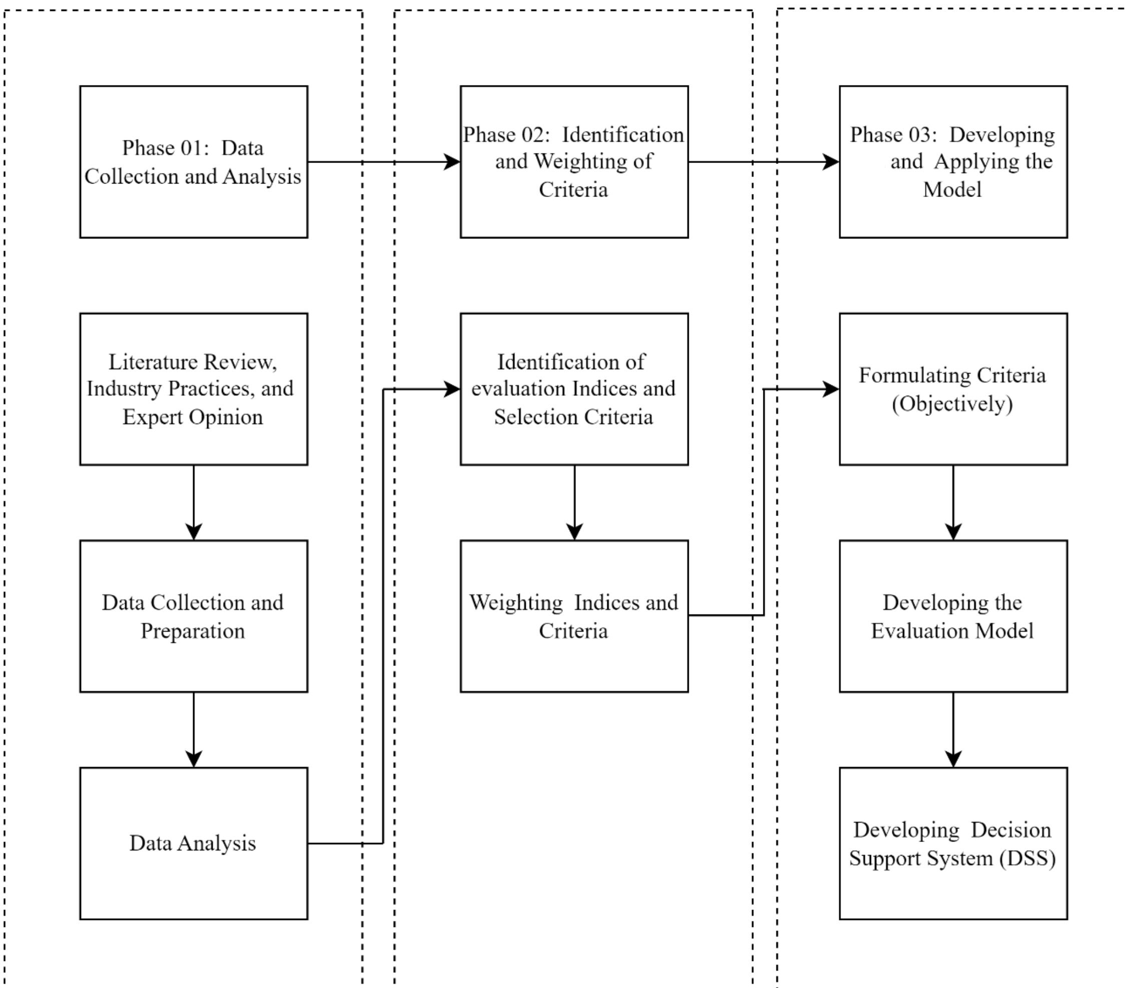


Figure 1.1. Research Methodology

1.6 Expected Contributions

1.6.1 Academic Contributions

The academic contributions of this research are:

- Comprehensive Identification of Criteria: This research combines literature reviews, expert opinions, and industry practices to identify the indices and criteria that impact the performance assessment and selection of subcontractors.
- Introduction of a Hybrid Methodology: The study introduces a hybrid methodology that combines Monte Carlo simulation with the Analytic Hierarchy Process (AHP) to weigh factors related to subcontractor selection. It proposes a mechanism for obtaining more accurate results by utilizing various probability distributions.
- Objective Formulation of Measurements: Measurements of indices and criteria are formulated objectively rather than subjectively, with validation from academic and industry experts.
- Integration of Performance Assessment and Selection: The research contributes to academic literature by establishing a theoretical link between performance assessment and the selection process, providing a more comprehensive understanding of subcontractor management in construction.
- Implementation of Normalization Techniques and Utility Models: The study implements three types of normalization approaches based on the level of tolerance of measurement values, along with linear additive utility models (LAUM) for performance measurement, offering a scalable methodology applicable to various fields beyond construction.
- Development of a Robust MCDM Framework: The thesis presents an advanced MCDM framework that incorporates both qualitative and quantitative criteria by employing the Complex Proportional Assessment (COPRAS) method, enhancing academic discourse on decision-making processes in complex environments like construction.

1.6.2 Industrial Contributions

The contributions to the industry are as follows:

- **Enhanced Subcontractor Selection Process:**
  - **Objective Evaluation Criteria:** By employing a systematic framework for subcontractor evaluation, The practical approach provides general contractors with a more objective and

transparent assessment process, reducing biases that often arise from subjective assessments.

- **Performance-Based Decision Making:** The approach enables contractors to increase objectivity in decision-making based on quantifiable performance metrics, thereby improving the overall efficiency and effectiveness of subcontractor selection and contributing to better project outcomes.
- **Improvement in Project Delivery:**
  - **Risk Mitigation:** The structured assessment of subcontractor performance helps mitigate risks associated with delays and cost overruns by ensuring that only qualified and reliable subcontractors are selected.
  - **Increased Accountability:** By linking performance assessments with future project opportunities, subcontractors are incentivized to deliver high-quality work, fostering a culture of accountability and excellence.
- **Strengthening contractor-subcontractor relationships:**
  - **Long-term Partnerships:** The use of objective metrics and performance data in subcontractor evaluation encourages stronger, long-term partnerships between general contractors and subcontractors, enhancing collaboration and project success.

1.7 Thesis Organization

This thesis is structured into seven chapters, commencing with the Introduction. A summary of the content for the following chapters is presented below:

- Chapter 2- Literature Review: Examines relevant prior research and journal articles to identify the research gap and lay the foundation for this study.
- Chapter3-Development of the Conceptual Model: Discusses methodologies and implementation of analysis methods (RUI , SNA) to determine the relevant criteria and SC.
- Chapter 4- Development of the Computerized Model – Calculates the weights of criteria using Monte Carlo and AHP techniques and develops an integrated model for evaluating subcontractor performance and decision support systems (DSS).
- Chapter 5- Application of An integrated Model and Decision Support System: Applies the methodologies, models, and weights discussed in Chapters 3 and 4 to a hypothetical example to generate the desired outputs.

- Chapter 6- Validation and Verification: Focuses on the validation and verification processes crucial for ensuring the integrity and reliability of the model and DSS.
- Chapter 7- Conclusions and Recommendations: This chapter addresses the conclusions, limitations, and recommendations for future research.

Chapter 2: Literature Review

2.1 Introduction

An extensive review of previous research and journal articles is pivotal in laying the groundwork for new initiatives. This chapter delves into literature from pertinent domains essential for the evaluation and selection of subcontractors in the construction industry. The discussion within this chapter is divided into six sections. The first section highlights the nature of the relationship between the main contractor and subcontractors, focusing on the facets of similarity and the differences between them. Secondly, the criteria and sub-criteria established by researchers for evaluating and selecting subcontractors in the construction industry are covered. The third section, dedicated to multi-criteria decision-making (MCDM), reviews several of the most relevant techniques employed in construction and elucidates the methods chosen for this research. The fourth section explores the application designed to facilitate the evaluation and selection process of subcontractors (SG) for general contractors (GC). Next section explores practical methods to alleviate bias in decision-making within the construction industry. Lastly, the chapter summarizes the findings from the literature, identifying research gaps.

2.2 The Nature of Relationship between the Main Contractor and Subcontractors

Subcontractors handle a substantial portion, approximately 85%, of all construction projects in the building industry. The ability of the main contractor and consultants to achieve project goals related to time, quality, and cost heavily depends on the performance of subcontractors (Mbachu, 2008).

The relationship between the general contractor and subcontractors is mutual. Consequently, the impact of subcontractors can extend beyond their specific portion to affect the entire project. For example, a delay by the electrical subcontractor may result in project delays or affect other subcontractors.

Some studies referred to various similarities and differences between GCs and SCs such as who will assign each of them. Figure 2.1 illustrates these variances between main contractor and subcontractors.

Figure 2.1. Variance between main contractors and subcontractors

Sr.N	Items	General Contractor (GC)	Subcontractor (SC)	Reference
1	Hiring	By owner	By general contractor	(PMBOOK® guide, 2001); (Nassar,2005); (Yu,2007); (Types subcontractors in construction,2022); (Subcontractor vs Contractor, 2023); (Başaran et al,. 2023)
2	Scope of Work	Is responsible for overseeing the entire construction project from start to finish and managing all aspects, including coordination of subcontractors.	Performing specific tasks or trades within the project, such as electrical work.	
3	Experience and Track Record	Expertise is evaluated based on tracking record of successfully completing similar projects within budget and on schedule.	Expertise is evaluated based on subcontractor specific trade or skill set and completing similar projects.	
4	Financial Stability	The financial stability to manage the project's budget effectively, pay subcontractors and suppliers promptly, and absorb any unexpected costs or delays.	The financial stability reflects SC ability to complete portion of the work without financial issues that could lead to delays or quality concerns.	
5	Capacity and Resources	Clients assess the main contractor's capacity to handle the scale and complexity of the project. This includes evaluating workforce and subcontractor management capabilities.	GC evaluates subcontractors based on criteria such as availability, skilled manpower, specialized equipment, as well as specific requirements like certificates or qualifications.	
6	Quality and Performance	Clients expect the GC to uphold high-quality standards throughout the project, ensuring that all work meets specifications and regulations.	Focusing on delivering quality work within specific trade or specialty.	
7	Legal and Regulatory Compliance	Clients need assurance that the main contractor understands and complies with all relevant laws, regulations, permits, and building codes governing the construction project.	GC expect subcontractors to also comply with all applicable regulations and standards related to their specific trades, such as electrical codes, plumbing regulations.	

2.3 Determining Criteria and Sub-Criteria for Evaluating and Selecting Subcontractors

Researchers globally have extensively focused on rationalizing the evaluation and selection procedures of subcontractors. In the construction industry, a successful bid is commonly divided into multiple subcontracts (Wang et al., 2001). The contractor's overall success is heavily reliant on the performance of subcontractors (Arditi & Chotibhongs, 2005; Cox et al., 2006). Often, general contractors function as project agents, delegating actual project tasks to subcontractors for execution (Shash, 1998). Despite this, the evaluation and selection of subcontractors are frequently overlooked in the construction industry (Kumaraswamy & Matthews, 2000&; Ng & Wan, 2005).

Subpar performance by a subcontractor can result in defective work, necessitating additional costs and time for rectification (Kale & Arditi, 2001; Schaufelberger, 2003; Shaikh, 1999). General contractors commonly use historical subcontractor performance as a benchmark to identify suitable subcontractors for current and future projects (Bent, 1978; Ramirez et al., 2004). Typically, two scores, a primary and a final, are provided, with field superintendents initially tallying primary scores, and final scores evaluated by general contractors. However, these assessments often heavily rely on experience and intuition (Albino & Garavelli, 1998), highlighting the need for reliable scientific measurement in the field.

As general contractors increasingly prioritize the benefits of selecting the best subcontractors, the development of a technique becomes crucial for reliably predicting subcontractor performance (Kumaraswamy & Matthews, 2000). Numerous papers published over the past several decades have explored this topic. Nearly all prior studies have sought to comprehend the dynamics inherent in subcontractor selection processes by identifying the factors that should be considered for the evaluation of subcontractors. Detailed explanations for the seven main groups of criteria, along with their related sub-criteria, are provided below:

2.3.1 Related to Schedule/ Time

Time is considered the most important, exerting a significant influence on project outcomes. In the literature, this criterion has been identified under various names such as completion of the job within time (El-Mashaleh, 2009; Arslan et al., 2008; Afshar et al., 2022), delivery date (Hanák & Nekardová, 2020), or control time (Cheng & Wu, 2012). Researchers evaluate this criterion in diverse ways. Ng (2007) and Ng and Skitmore (2014) expressed it by calculating the percentage of deviation from subcontractors' project milestones, while another one introduced this criterion using a formula to calculate the schedule shortened ratio (Schedule shortened ratio = (schedule-changed schedule) / schedule × 100) (Eom, et al., 2008). Additionally, Pallikkonda et al. (2019) divided the time criterion into three sub-criteria: firstly, completion of a job within the allocated time; secondly, the scale of cooperation and flexibility when dealing with delays, defined as the subcontractor's attitude toward delays; and lastly, the percentage of work completed according to the planned schedule.

2.3.2 Related to Cost

The cost criterion encompasses numerous dimensions found in the literature, such as price, financial aspects, and payments. Pallikkonda et al. (2019) and Mbachu (2008) proposed three sub-criteria under the cost criterion. One of them is the subcontractor's bid offer to commence the construction project (tender price), completion of a job within budget, and whether the subcontractor has any financial problems that may cause future issues (Financial capacity). Additionally, Arslan et al. (2008) mentioned that timely payment to laborers is considered under the cost criterion umbrella.

On the other hand, the evaluation of the cost criterion is considered crucial for the operation of assessments. In this regard, Eom et al. (2008) proposed the most important indexes and distinguished between cost and finance and defined indexes related to finance, including profitability, growth, activeness, stability, and a cost index (cost-saving ratio = (cost - cost variance) / cost × 100). Meanwhile, Ng (2007) focused on determining the promptness of payment to discover the financial strength of subcontractors by calculating the number of days in delaying payment to workers and the number of days in delaying payment to sub-subcontractors.

2.3.3 Related to Quality

Achieving successful completion in construction projects entails meeting the quality standards outlined in contracts and specifications, along with adhering to the desired time and cost parameters for the project (Başaran et al., 2023). Consequently, the performance of the subcontractors involved in producing project items, in alignment with these quality standards, holds significant importance (Pallikkonda et al., 2019).

To underscore the significance of the quality criterion, Arslan et al. (2008) identified nine sub-criteria: 1. quality of production, 2. standard of workmanship, 3. team efficiency, 4. quality of materials used, 5. experience in similar works, 6. experience in the construction industry, 7. job safety, 8. personnel training, 9. number of qualified personnel. Meanwhile, Pallikkonda et al. (2019) considered the quality criterion to have the highest impact on the evaluation of subcontractors, assigning it the highest value (16.03), while the time criterion held the second-highest weight value (13.63). Additionally, Pallikkonda et al. (2019) proposed three sub-criteria under the quality criterion, which are quality certificates owned by the subcontractor (quality standard), a guide to assess the contractor's ability based on likely future performance (previous performance), and whether the subcontractor has a quality assurance staff (quality assurance programs).

Few studies used formulas to evaluate the quality criterion. Eom et al. (2008) utilized two formulas to calculate the defect occurrence ratio (DOR = (occurrence per unit)/participated projects × 100) and the rework occurrence rate (ROR = (rework occurrences)/participated works × 100) and used concept of five- point scale to assess executing quality management plan considering that DOR and ROR and quality management represent the quality criterion. On the other hand, Arslan at al. (2008) suggested evaluating this quality criterion based on the construction department of the main contractor without determining a specific methodology.

2.3.4 Related to Resource Adequacy

The concept of resource in construction encompasses workforces, materials, equipment, and technology applications. Consequently, researchers have delineated sub-criteria under the resource adequacy criterion. These include assessments related to the adequacy of labor resources, material resources, compliance with the company image, and alignment with other on-site employees (Başaran t al., 2023). Cheng et al. (2011) and Cheng et al. (2012) identified self-owned tools (or borrowed from the contractor), effective management capabilities, and material wastage as factors influencing the evaluation of subcontractors. In contrast, Arslan et al. (2008) went further by delineating nine sub-criteria, which include proposal accuracy, adequacy of experienced site (supervisor and staff), adequacy of labor resources, adequacy of material resources, adequacy of equipment, care of works and workers, compliance with site safety requirements, compliance with the contract, and compliance with the company image. Furthermore, Eom et al. (2008) focused on the technical side, giving importance to the number of technical patents held by the subcontractor, technical support capability (number of technicians), and awards and warnings (over the past three years).

In terms of evaluating resource adequacy, Cheng et al. (2011) specified that the assessment is the responsibility of the relevant field superintendents of main contractors. Meanwhile, Ng (2007) suggested calculating the number of permanent employees of the company (semi-skilled and skilled) and the quantity of physical resources owned by the subcontractor, including equipment and tools.

2.3.5 Related to Communication

The communication between the main contractor and subcontractor are crucial aspects of a successful construction project. Communication extends not only within the main contractor and subcontractors but also encompasses compatibility and communication between various subcontractors (Cheng et al., 2011; Cheng et al., 2012; El-Mashaleh., 2009). This criterion significantly influences the performance in other project categories (Başaran et al 2023). Pallikkonda et al. (2019) expressed the compatibility and communication criterion across three sub-criteria, which are compliance with the main contractor's vision, cooperation with other subcontractors during the project period, and knowledge of construction regulations.

In contrast, Başaran et al. (2023) defined four sub-criteria, namely, compliance with other subcontractors and employees on-site, communication and compliance with the main contractor, harmony within the subcontractor's own team, and the ability to adopt and respond to changes in the project. Some researchers have sought to identify indicators for assessing this criterion using quantitative or qualitative measurements. Ng and Skitmore (2014) examined the evaluation criterion in two main groups—namely, relationship and communication—by determining the number of unresolved disputes with clients or other parties, the percentage of unsuccessful claims, the percentage of site meetings not attended, the number of times not responding to the contractor's instructions, and the number of days delayed in responding to instructions.

On the other hand, Eom et al. (2008) emphasized the importance of evaluating the level of participation (collaborative work), the level of cooperation and communication (cooperation in work), and the appropriate organizational structure on-site, using a five-point scale.

2.3.6 Related to Occupational Health and Safety

In the construction industry, occupational health and safety are interconnected and crucial aspects of responsible and sustainable project management. By integrating both OHS and environmental protection measures into construction practices, main contractors and subcontractors can contribute to the well-being of workers, minimize the environmental footprint of projects. Therefore, the OHS and environmental protection criterion is frequently encountered in addition to time, cost, and quality dimensions (Başaran et al., 2023).

In this regard, some studies have researched to define this criterion within a practical vision. Ng & Tang (2008) proposed that sub-criteria representing this criterion in its two parties (OHS and environmental protection) include the rate of accidents/incidents on the contractor's project, purchase of insurance for staff and labor, existence of a safety manual and officer, compliance with the contractor's safety regulations, existence of an environmental manual and officer, and compliance with environmental regulations.

However, the research did not deeply interpret or provide a methodology to evaluate some sub-criteria, specifically compliance with environmental regulations. Meanwhile, Pallikkonda et al. (2019) summarized this criterion within three sub-criteria, which are the level of health and safety accreditation, conformity with environmental legal requirements, and construction waste material control. Additionally, an important study by Ng & Skitmore (2014) attempted to evaluate this criterion. It determined quantitative indicators to measure the criterion by calculating the number of fatal accidents per 100,000 man-hours, the number of reportable injuries per 100,000 man-hours, the number of prosecutions made by the Labour Department, the number of prosecutions related to environmental aspects, and the number of incidents damaging public utilities.

On the other hand, another study (Eom et al., 2008) measured indexes related to the OHS and environmental protection criterion by assessing environmental-friendly project capability (EFPC = order of correction / (participated works × 100)), construction accident occurrence status (CAOS = number of accidents (during three years)), and safety management/execution and training (SM/ET = level of execution (five-point scale)).

2.3.7 Related to Management Competencies

Achieving comprehensive success in projects now requires a thorough examination and evaluation of subcontractors' characteristics beyond the specified criteria. The social structures, life views, and personal traits of the parties involved can significantly influence collaborative efforts towards a common purpose (Başaran et al., 2023).

According to Ferdig (2007), leaders possess the ability to inspire a shared vision, build consensus, provide direction, and foster changes in beliefs and actions among followers. These qualities are deemed necessary to achieve the goals of the organization or community. Furthermore, Akinshipe et al. (2022) disclosed that innovative thinking style, problem-solving skills, reliability, emotional maturity and control, and trust from project stakeholders are crucial attributes necessary for the successful completion of projects.

In this context, Başaran et al. (2023) delineated the leadership criterion according five sub-criteria: 1. the ability to be creative and innovative and to set solid priorities for future work (vision and imagination), 2. ability to make short- and long-term assessments and anticipate opportunities and threats (strategic perspective), 3. the ability to assess situations, discern their advantages and disadvantages, exercise sound judgment, and make decisions grounded in factual information (critical analysis and judgment), 4. dedication to the project, active participation in resolving issues with the main contractor, contribution to the overall project beyond individual tasks, and a willingness to make sacrifices (Commitment), 5. exhibiting leadership that prioritizes collaboration with team members and the growth of subordinates (Transformational leadership). This study did not mention method to evaluate this criterion.

A frequency analysis was conducted by Başaran et al. (2023) to identify the criteria frequently mentioned in relation to evaluating and selecting subcontractors. The information was collected from 24 studies, and the results are presented in Figure 2.2. .

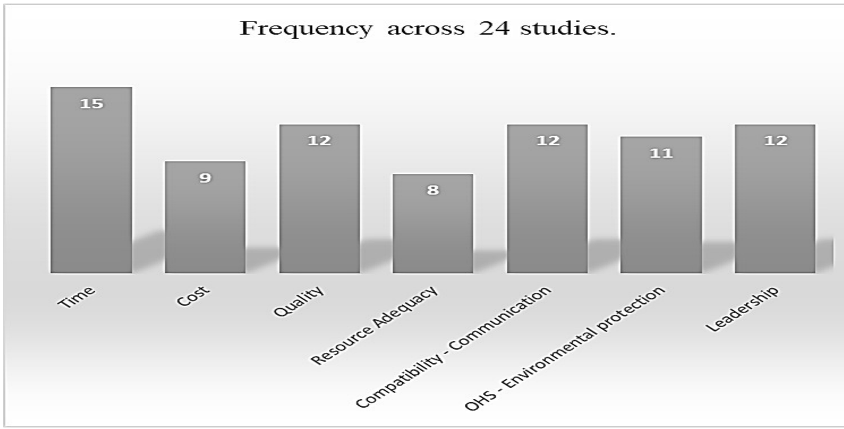


Figure 2.2. Results of a frequency analysis

2.4 Highlighting about Weighting of Criteria

Weighting criteria is a critical step in various decision-making processes. This process involves assigning numerical values (weights) to different criteria based on their relative importance. These weights help prioritize the criteria, ensuring that the more important ones have a greater influence on the final decision.

In this context, Shiau et al. (2003) conducted a survey of 400 contractors, scrutinizing the subcontractor selection process and the consistency of weight analyses. According to Shiau et al. (2003), five primary criteria and thirteen sub-criteria are assigned for selecting subcontractors. As indicated in Table 2.1, the highest weight assigned to a criteria are 0.299 (Construction Capability), while the highest weight assigned to a sub-criteria is 0.133 (Coordination).

Table 2.1. Criteria and Sub-Criteria for Selection SC with Weights (Shiau et al., 2003)

Criteria	Weight	Sub-Criteria	Weight
Construction Capability	0.299	Construction Quality	0.107
		Schedule Control	0.122
		Construction Capability	0.070
Management Capability	0.198	Coordination	0.133
		Safe Administration	0.065
Financial Condition	0.170	Capital	0.041
		Payment	0.070
		Banking History	0.059
Reputation Condition	0.126	Arbitration History	0.027
		Business Evaluation	0.037
		Trade History	0.062
Regional Condition	0.207	Material Regional Condition	0.128
		Subcontractor Regional	0.079

In this context, Arslan et al. (2008) strived to expand the criteria and sub-criteria for selecting the best subcontractor to cover a wide range of aspects required for the bidding process. Arslan et al. (2008) divided the main criteria into four groups, which include twenty-five sub-criteria and considered all weights of criteria and sub-criteria to be equal initially, with the understanding that the GC may set different weights for the criteria depending on the specific requirements of each project. Table 2.2 illustrates all criteria with weights and sub-criteria.

Table 2.2 Criteria with Weights and Sub-Criteria for Selection SC (Arslan et al., 2008)

Criteria	Weight	Sub-Criteria	Criteria	Weight	Sub-Criteria
A.Cost	0.25	A1. Financial capacity	C.Time	0.25	C1. Accessibility to the firm
		A2. Timely payment to labourers			C2. Time accuracy in submitting bids
		A3. Completion of job within the budget			C3. Completion of job within the time
B. Quality	0.25	B1.Quality of production			C4. Adherence to program
		B2. Standard of workmanship	D. Adequacy	0.25	D1. Proposal accuracy
		B3. Team efficiency			D2. Adequacy of experienced site superv.staff
		B4. Quality of materials used			D3. Adequacy of labor resources
		B5. Experience in similar works			D4. Adequacy of material resources
		B6. Experience in the construction industry			D5. Adequacy of equipment
		B7. Job safety			D6.Care of works & workers
		B8. Personnel training			D7. Compliance with site safety requirements
		B9. Number of qualified personnel			D8. Compliance with contract
					D9. Compliance with company image

On the other hand, Pallikkonda et al. (2019) employed a theoretical framework to select twenty-five factors out of forty-seven, aiming to determine the most crucial factors in subcontractor selection as shown in Table 5.3. Pallikkonda et al. (2019) delineated eight categories as the main criteria and placed significant emphasis on technical capability and management capability. According to Pallikkonda et al. (2019), the triangle of project management, comprising Quality, Cost, and Time, has emerged as the first three important factors. Following closely is the critical category of 'Health and Safety,' with a weight of 0.13. 'Technical Capability' and 'Experience and Reputation' rank as the fifth and sixth important categories. 'Adequacy' is then identified as the eighth important category, as shown in Figure 2.3, while the highest weight assigned to a sub-criterion is 0.07 (Completion of a job within the time), as illustrated in Figure 2.4.

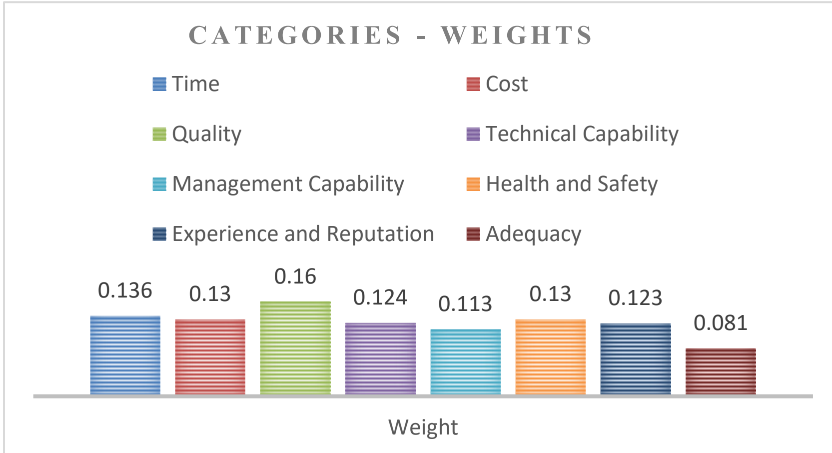


Figure 2.3. Main Categories with weights (Pallikkonda et al., 2019)

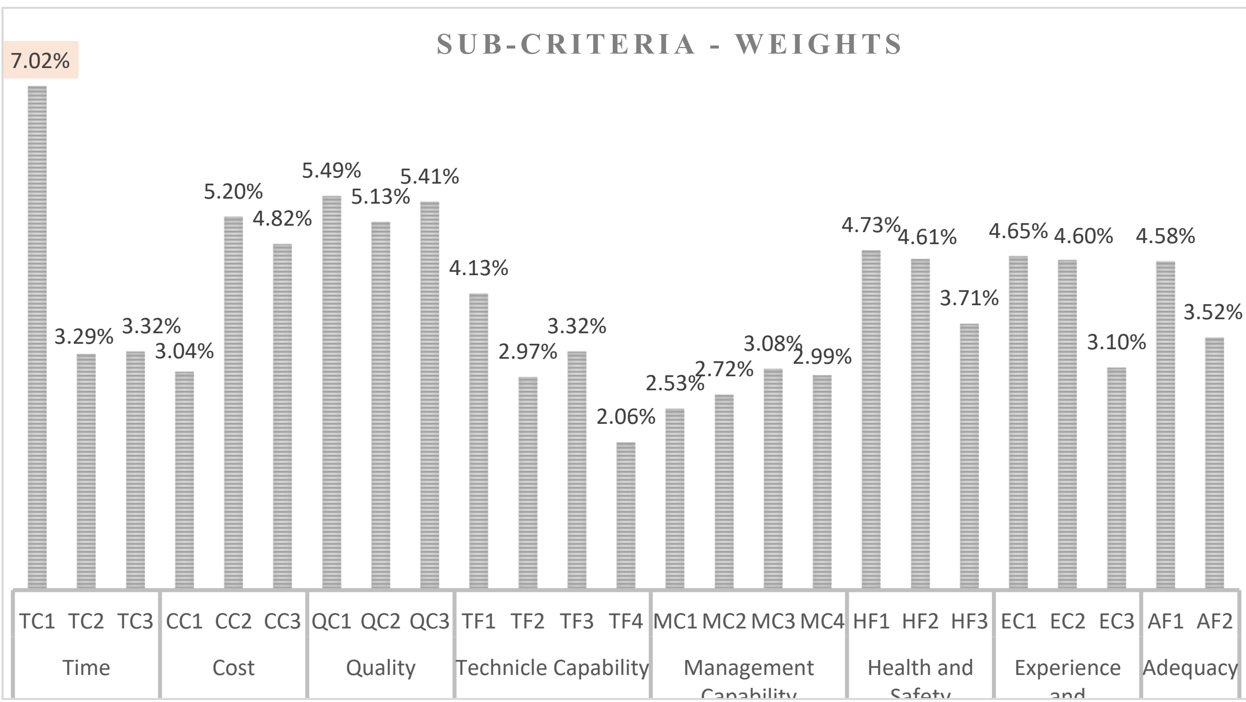


Figure 2.4. Sub-Criteria with weights (Pallikkonda et al., 2019)

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

Generally, decision-making is a cognitive process that engages individuals throughout their lives. This process relies on elements such as culture, perceptions, belief systems, values, attitudes, personality, knowledge, and the insights of the decision-maker(s) (Delazer et al., 2011). Shahsavarani and Azad (2015) determined that the main processes involved in decision-making consist of situation identification, option generation, evaluation and choice, follow-up, and execution, as illustrated in Figure 2.5. It should be noted that in the process of decision-making, the closer the decision authority is to the origin of the problem, the better decision they can make.

Figure 2.5. Involved processes in decision-making.

In this context, Taherdoost and Madanchian (2023) explains the term Multi-Criteria Decision Making (MCDM) (also known as multicriteria decision-analysis or MCDA (Triantaphyllou & Baig, 2005)), which is a field of study, and a set of methods used to evaluate and prioritize alternative solutions or options when facing decision-making problems that involve multiple, often conflicting criteria. It is particularly useful in situations where several factors need consideration, and these factors may vary in terms of importance or weight. Figure 2.6 shows the steps of MCDM (Taherdoost & Madanchian, 2023).

Figure 2.6. Steps of MCDM

Additionally, Deng et al. (2000) emphasizes that there are two types of weighing techniques: subjective (qualitative) methods and objective (quantitative) methods. Subjective methods establish weights based on the preferences or judgments of decision-makers.

In contrast, objective techniques, including the entropy method, multiple objective programming, etc., determine weights by solving mathematical models without considering the decision maker's preferences.

According to Jato-Espino et al. (2014), methods within the scope of MCDM vary, ranging from individual approaches to combined approaches known as the hybrid method. Researchers have developed several individual methods to assist decision makers (DM) in making the best decisions, with the most popular ones being ANP, PROMETHEE, AHP, TOPSIS, VIKOR, and ELECTRE (Hwang et al., 1981; Saaty, 1990; Brans & Mareschal, 1986; Brans & Mareschal, 1995); Brans & Vincke, 1985; Opricovic & Tzeng, 2004; Saaty& Vargas, 2013).

Furthermore, some researchers have employed hybrid methods that involve the extension or combination of single processes with other techniques, such as AHP + FSs (Fuzzy Sets) + PROMETHEE, FSs + TOPSIS, AHP + MIVES + MCS (Monte Carlo Simulations), AHP + FSs + TOPSIS, ELECTRE + FSs, etc. (Lin et al., 2008; Gervásio & Da Silva, 2012; Ali-Mohammad et al., 2010; Chou et al., 2013). Brief overviews of various widely acknowledged MCDM methods are presented in the following paragraphs.

2.4.1 Analytic Hierarchy Process (AHP)

AHP stands as a MCDM method that enables decision-makers to navigate choices in the assessment of multiple competing criteria (Zahedi, 1986). Pioneered by Saaty (1980), it focuses on establishing the relative importance of activities in a multi-criteria decision-making context. AHP involves the execution of numerous pairwise comparisons using a standard nine-level comparison scale, as illustrated in Table 2.3.

Table 2.3. standard nine-level comparison scale (Saaty & Vargas, 2012)

Intensity of Importance	Definition	Explanation
1	**Equal Importance**	**Two activities contribute equally to the objective**
2	Weak	
3	**Moderate importance**	**Experience and judgment slightly favor one activity over another**
4	Moderate plus	
5	**Strong importance**	**Experience and judgment strongly favor one activity over another**
6	Strong plus	
7	**Very strong or demonstrated importance**	**An activity is favored very strongly over another; its dominance demonstrated in practice**
8	Very, very strong	
9	**Extreme importance**	**The evidence favoring one activity over another is of the highest possible order of affirmation**

Within the framework of AHP, individual preferences undergo a transformation into ratio-scale weights, subsequently amalgamated into linear additive weights for the alternatives. With these weights, the decision-maker (DM) can more effectively rank the alternatives and anticipate outcomes (Forman et al., 2001). This approach effectively manages the inherent uncertainty and imprecision inherent in human decision-making processes, providing an optimal level of flexibility and robustness. This enables a decision-maker to grasp and comprehend a decision problem more thoroughly (Albayrak et al., 2004).

2.4.2 Analytic Network Process (ANP)

The analytic network process (ANP) technique, also crafted by Thomas L. Saaty, represents a versatile adaptation of AHP that accommodates more intricate and interdependent relationships, including feedback among elements within the hierarchy (Saaty et al., 2013). Over the past decade, ANP has found application in various decision-making scenarios, particularly in exploring risk and uncertainty (Sipahi & Timor, 2010). Büyüközkan and Çifçi (2012) clarifies the difference between AHP and ANP, whereas AHP employs a one-way hierarchical relationship between decision levels and more extensive interconnections between decision levels and attributes. In contrast to a hierarchy, the ANP-based system operates as a dependent and feedback-based network, replacing single-direction relationships.

2.4.3 Fuzzy Set Theory

The Fuzzy set theory was developed by Zadeh, who introduced the concept of fuzzy sets in 1965 as a mathematical framework (Zadeh,1965). It 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 (Nieto-Morote et al., 2012). By transitioning gradually from membership to non-membership, the Fuzzy set introduces vagueness by diminishing the sharp boundary that separates set members from non-members. These contrasts with traditional crisp set theory, which asserts that elements are either within or outside the set, as shown in Figure 2.7 (Kruse et al., 1994).

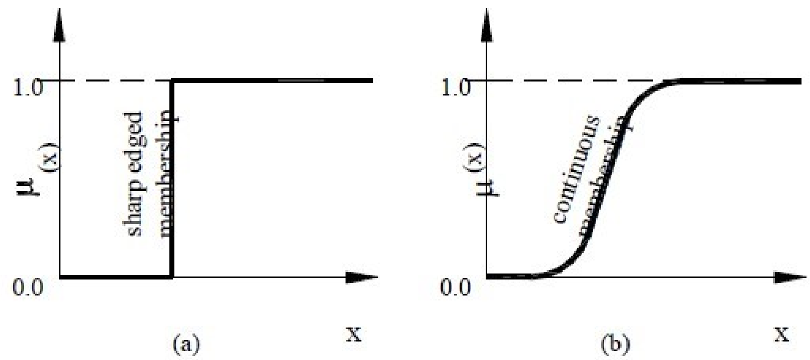


Figure 2.7. Membership functions for (a) a crisp set and (b) a fuzzy set

Kishk and Al-Hajj, (1999, September) referred to the membership function of a fuzzy set, which is a curve that illustrates how each point in the input space can be allocated a membership value ranging from 0 to 1, indicating the extent of that element's membership.

A triangular fuzzy is easy for decision-makers (DMs) to use and calculate. it is defined as (a, b, c), where a ≤ b ≤ c. The parameters a, b, and c represent the smallest possible value, the most promising value, and the largest possible value, respectively (Abbasianjahromi et al., 2018).

2.4.4 Technique for Order Performance by Similarity to Ideal Solution (TOPSIS)

TOPSIS was developed by Hwang and Yoon in 1981 and later popularized by Chen and Hwang in 1992, as an MCDM technique designed to discern solutions within a finite set of alternatives (Büyüközkan & Çifçi, 2012; Dağdeviren et al., 2009).

Wang & Elhag (2006) clarified that the fundamental principle of this method is for the selected alternative to be close to the positive ideal solution while being distant from the negative ideal solution. The positive ideal solution is characterized by maximizing benefit criteria and minimizing cost criteria, while the negative ideal solution involves maximizing cost criteria and minimizing benefit criteria. In the classical TOPSIS method, precise weights for criteria and ratings of alternatives are known, utilizing crisp values in the evaluation process.

However, under many conditions, crisp data proves inadequate for modeling real-life decision problems. Therefore, the fuzzy TOPSIS method is introduced, where criteria weights and alternative ratings are assessed using linguistic variables represented by fuzzy numbers, addressing the limitations of the traditional TOPSIS (Ertuğrul & Karakaşoğlu, 2008).

2.4.5 Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE)

PROMETHEE was developed by Jean-Pierre Brans and Bertrand Mareschal in the early 1980s. It belongs to the class of outranking methods in multicriteria analysis (Brans et al., 1986). Mergias et al. (2007) clarified that the application of PROMETHEE necessitates two additional forms of information namely, the weights assigned to the considered criteria, indicating their relative importance, and information about the preference function used by the decision-maker when assessing the contributions of alternatives for each distinct criterion. The preference function (Pj) converts the difference in evaluations between two alternatives (a and b) for a specific criterion into a preference degree, which ranges from 0 to 1. Figure 2.8 depicts preference functions of PROMETHEE.

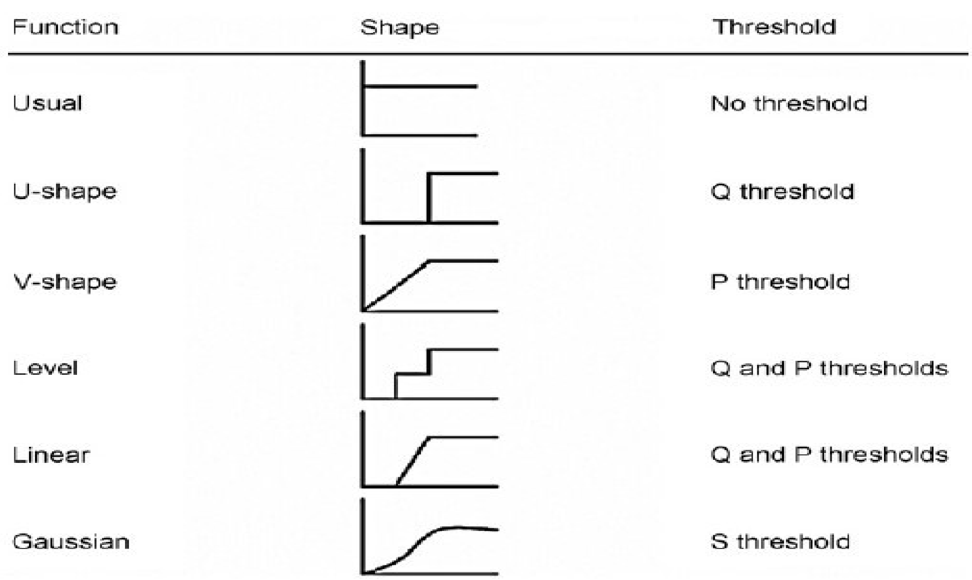


Figure 2.8. Preference functions of PROMETHEE (Mergias et al., 2007)

Brans et al. introduced PROMETHEE I for a partial ranking of alternatives and PROMETHEE II for the complete ranking of alternatives in 1982. Subsequently, several versions of the PROMETHEE methods were introduced. These include PROMETHEE III for ranking based on an interval, applicable to complete or partial ranking when the set of viable solutions is continuous. Additionally, PROMETHEE IV is designed for problems with segmentation constraints, PROMETHEE V for human brain representation, PROMETHEE VI, and PROMETHEE GDSS for group decision-making (Brans & Mareschal, 1995; Brans et al., 1986).

2.4.6 Choosing by Advantage (CBA)

CBA is an MCDM technique developed by Suhr in1999. It considers the advantages of alternatives and makes comparisons based on these advantages (Parrish & Tommelein, 2009, July).

Suhr, J. (1999) clarified that the fundamental principle of CBA is to initially concentrate exclusively on identifying the advantages of alternatives, deviating from the conventional method of simultaneously evaluating both advantages and disadvantages. This approach helps prevent double-counting and omissions. The second guideline underscores the importance of differentiating between cost and value; cost is regarded as a constraint, not a factor, and requires careful consideration before arriving at a decision. CBA fosters transparency in the decision-making process by explicitly taking into account multiple alternatives and considering various influencing factors (Parrish & Tommelein, 2009, July; Arroyo et al 2012, July; Espinoza et al 2021).

Parrish and Tommelein (2009, July) emphasized that the CBA method establishes a database that clearly and systematically articulates how and why a decision was made. This database can serve as a valuable reference point for future projects.

2.5 Applications of Multi-Criteria Decision-Making (MCDM) in Construction Industry

This section is divided into two parts. The first part covers applications implemented in the construction industry in general. The second part focuses on applications utilized in the selection of subcontractors in construction projects.

2.5.1 Application of MCDM in the Construction Industry: A General Overview

The researchers employed diverse methods and techniques within the realm of MCDM, adapting to the specific needs and requirements of their studies. Consequently, some researchers opted for a singular method, such as AHP or ANP, while others embraced hybrid approaches like FSs + TOPSIS, AHP + MIVES + MCS.

In this regard, Chen and Pan (2021) conducted a comprehensive review and analysis of the literature on fuzzy multi-criteria decision-making (FMCDM) in construction management from 2007 to 2017. Initially, 165 published journal articles were selected, encompassing 37 single-hybrid and 17 multiple-hybrid FMCDM methods. FMCDM is gaining popularity as an efficient approach to address complex problems with diverse decision-makers' interests, conflicting objectives, and abundant but uncertain information (Chen & Pan, 2021). Figure 2.9 illustrates the development of FMCDM applications in construction management (Chen & Pan, 2021).

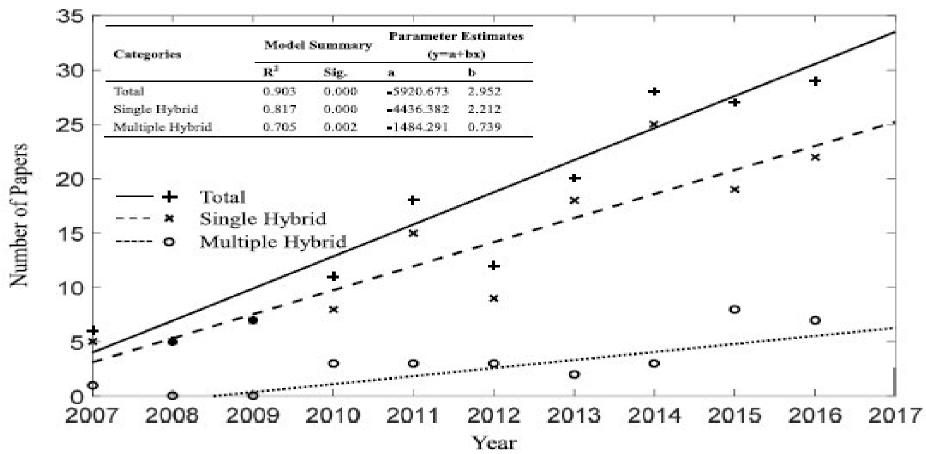


Figure 2.9. Development of FMCDM applications in construction management

On the other hand, a study by Zhu et al. (2021) investigated 530 civil engineering construction articles published between 2000 and 2019, examining the application of MCDM in construction. The researchers identified the use of 29 single methods and 94 hybrid methods. The study reveals that the two largest hybrid categories are methods that incorporate fuzzy logic, utilized in 159 articles (30.00 percent), and methods that involve AHP, applied in 104 papers (19.62 percent). Figure 2.10 provides a visual representation of the top five single MCDM methods and the top six hybrid MCDM methods that were utilized in articles.

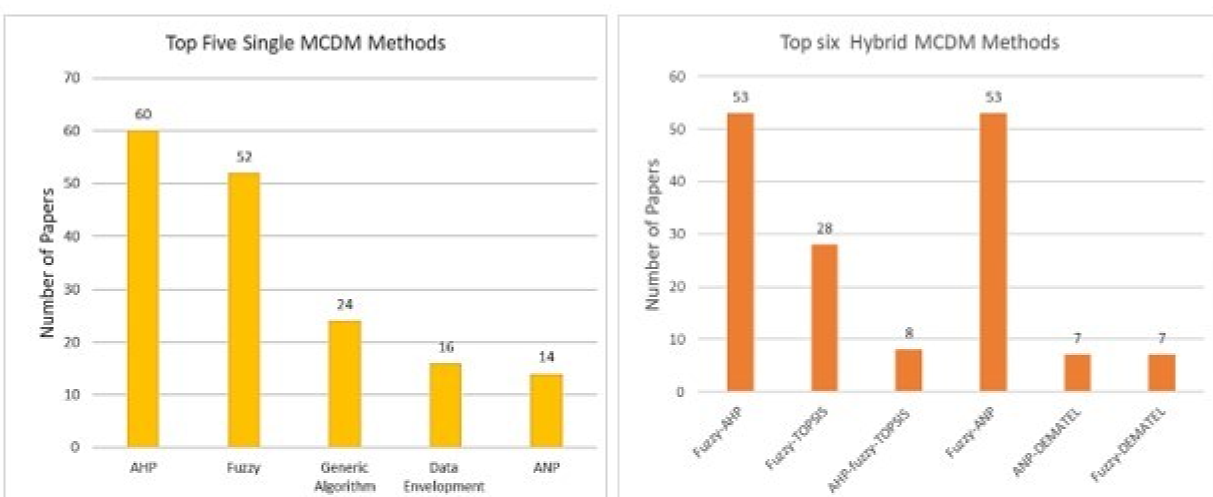


Figure 2.10. Single and Hybrid MCDM Methods

5.2 Application of MCDM in the Selection and Evaluation of Subcontractors

Generally, there are not many existing studies related to the evaluation and selection of subcontractors. According to a study by Abbasianjahromi et al. (2018), the researcher found that the number of papers about subcontractor selection from 2000 to 2014 is 13, as shown in Figure 2.11.

Authors	Study purpose	Findings
Elazouni and Metwally (2000)	Decision support system for subcontracting construction works	Their model optimized the selection process based on time and cost
D. Wang, Yung, and Ip (2001)	A heuristic genetic algorithm for subcontractor selection in a global manufacturing environment	They used a hybrid model of fuzzy logic and genetic algorithm for SC selection after dividing a project into subprojects
Ng and Luu (2008)	Modeling subcontractor registration decisions through case-based reasoning approach	The selection of SCs with characteristics like successful past experience
Arslan, Kivrak, Birgonul, and Dikmen (2008)	Improving subcontractor selection process in construction projects: WEBSES	They proposed a web-based model with 25 criteria for SCs selection. The shortcoming of their model was using the same weight for all criteria
Mbachu (2008)	Conceptual framework for the assessment of subcontractors' eligibility and performance in the construction industry	He found that the quality is the most important criterion in SCs prequalification and selection
Hartmann, Ling, & Tan (2009)	Relative importance of subcontractor selection criteria: evidence from Singapore	They considers price as the most important criterion in SC selection, though criteria such as technical know-how, cooperation, and quality are also effective in SC selection
Yin, Wang, Yu, Ji, and Ni (2009)	Application of DEA cross-evaluation model in project dynamic alliance subcontractors selection	They showed correct selection of SCs leads to an increase in the probability of the project success
Enshassi, Arain, and Tayeh (2010)	Subcontractor prequalification practices in Palestine	Their research was on the criteria for SC selection in Palestine, as commitment to contract, good planning, price, reputation, and proficiency in one or more tasks
Marzouk, El Kherbawy, and Khalifa (2013)	Factors influencing subcontractors selection in construction projects	They used 10 criteria for SC selection as cost, quality, time, staff behavior, safety, repair and warranty, equipment, risk avoidance, and the company's past experience
Abbasianjahromi, Rajaie, & Shakeri (2013)	A framework for subcontractor selection in the construction industry	They developed FPSI SC selection without criteria weight
Laryea and Lubbock (2013)	Tender pricing environment of subcontractors in the United Kingdom	They studied 94 SCs in the United Kingdom and they found the price is not the sole factor in SCs evaluation in the United Kingdom
Abbasianjahromi, Rajaie, Shakeri, and Chokan (2014)	A new decision-making model for subcontractor selection and its order allocation	They applied continuous ant colony and fuzzy set theories to find the best SCs, while optimizing project risk and cost. They showed that SCs selection without attention to the type of subcontract work is not suitable

Figure 2.11.Summary of SC Selection Literature Review (Abbasianjahromi et al., 2018)

In this context, Shahvand et al. (2016) identified the criteria for the evaluation of two types of suppliers in the construction industry, which are first, material and equipment suppliers (referred to as suppliers), and second, service suppliers (referred to as subcontractors). A fuzzy approach through Mamdani's inference mechanism (Mamdani's inference is a type of fuzzy logic inference system developed by Lotfi Zadeh in the 1970s) has been utilized to develop a new methodology for a fuzzy expert system.

In contrast, Polat (2016) clarified that a low bid price is not a sufficient criterion for selecting a subcontractor. The study employed an integrated decision-making approach, utilizing both AHP and PROMETHEE. AHP was applied to determine the weights of the criteria, while PROMETHEE was used to achieve a complete ranking.

Another study introduced an Artificial Neural Network (ANN) with the capability to generalize data. The objective of the study was to develop an ANN model for subcontractor selection and to identify significant criteria related to the company's strategic goals (Husin, 2017).

Abbasianjahromi et al. (2018) applied the Kano model (The Kano Model is a theory for product development and customer satisfaction developed by Professor Noriaki Kano in the 1980s) to classify the selection criteria into five categories: must-be, reverse, one-dimensional, attractive, and indifferent. Following this categorization, the weight of criteria is extracted by applying the Analytic Hierarchy Process. Subsequently, a fuzzy multi-attribute decision framework is developed to select the best subcontractor (SC).

Kishore et al. (2020) integrated all criteria with equal importance in subcontractor selection and employed AHP for weighting, followed by the SAW model for ranking the alternatives. While Chen et al. (2021) proposed a subcontractor selection model that comprehensively considers the impact of construction enterprise demands, designed the model based on quality function deployment (QFD), AHP, and improved grey correlation analysis (IGCA). The QFD method was employed to translate specific enterprise demands, while the IGCA determined the weights of the criteria. AHP was used to quantify the experts' experience and construct the judgment matrix, serving as input for the grey correlation analysis. Mahmoudi & Javed (2022) attempted post-qualification performance evaluation of subcontractors using the Ordinal Priority Approach (OPA). This approach allows for the simultaneous estimation of weights for evaluation criteria, subcontractors to be evaluated, and the experts evaluating them.

2.6 Alleviating Bias in Decision-Making

According to the Oxford English Dictionary (2002), the term “bias” was originally used to describe a slanting line. Bias refers to the presence of prejudice or favoritism in the way information is presented, interpreted, or decision-making processes.

In various contexts, bias can manifest as a systematic error or deviation from an objective standard, often influenced by personal beliefs, stereotypes, or external factors. Koehler and Harvey (2008) explained two distinctions related to biases. Firstly, biases are often used to describe deviations from a norm; they can also simply indicate a tendency to slant in one way rather than another. For instance, the term 'positivity bias' has been used to describe a preponderance of positive over negative evaluations in person perception. Secondly, bias can be considered both as a cause and as an effect.

The bias of the bowl may result from its shape or loading, causing it to deviate from a straight run. In the psychology of judgment, biases were originally conceived more as effects than as causes. In fact, it has been reported that the application of unconscious heuristics could lead to bias (Cheung and Li, 2019).

In this context, Stingl and Geraldi (2017) discovered that biased decision-making jeopardized the success of construction projects. This resulted in the escalation of commitment (Cheung and Li 2019; Wang et al., 2017), an inefficient risk management system (Kutsch and Hall, 2005, 2010), suboptimal project planning (Pinto, 2013), and a failure to heed early warnings in projects.

Javidmehr and Ebrahimpour (2015) referred to that Performance appraisal is a crucial issue in human resource management and represents an important responsibility for managers and supervisors and bias in performance appraisal is problematic as it complicates the process of making appropriate personnel decisions, such as promotions (Moers, 2005) and also evaluation errors and biases may occur at various stages, including judgment, observations, or information processing. These factors can significantly impact the appropriateness and accuracy of performance evaluations. Javidmehr and Ebrahimpour (2015) provided a typology of errors and biases in performance evaluation, which are halo error, leniency and severity errors, contrast, proximity error, central tendency, spill-over effect, recency error, personal bias, and rater attitudes and values.

Furthermore, Zhang et al. (2021) clarified that One way to correct the bias is by using resampling techniques such as Jackknife and Bootstrap. Two well-known methods for first-order bias correction using the Taylor series are those proposed by Cox and Snell (1968) and Firth (1993).

2.7 Identifying the Research Gap and Defining the Chosen Research Area

Based on the findings from the literature reviews, it has been identified that numerous studies have been conducted on the evaluation and selection of subcontractors in the construction industry. Some researchers have highlighted the evaluation and selection of subcontractors during the bidding stage, without taking into account their performance in past projects.

Others have focused on evaluating subcontractors during the execution stage of a project, while others have established criteria and sub-criteria for evaluating subcontractors at the project's completion. In some cases, these evaluations rely on subjective information and qualitative scales, without addressing the potential bias in these evaluation methods. As noted in the literature reviews, researchers did not sufficiently highlight sustainable practices of subcontractors during the execution of projects. Additionally, no research has provided any application that links the evaluation of subcontractors at the stage of completion of projects with the selection process for a new project.

Therefore, this research will develop an MCDM model that aligns with the research goals. The research aims to address several aspects. First, it aims to determine significant criteria and sub-criteria related to the evaluation and selection of subcontractors, including the triangle in construction management (time, cost, quality), and other criteria such as safety, customer satisfaction, and sustainable practices…. etc. Next, the research aims to utilize quantitative scales and objective measurements as much as possible to evaluate preferences and achieve the highest degree of transparency. It also seeks to employ methods to alleviate bias concerning qualitative scales and subjective measurements. Third, the research aims to develop a model for evaluating subcontractors at project completion and creating a dataset that takes into account the final reasonable evaluation of subcontractors who have worked on multiple projects with the same construction company, each with different evaluations, with the purpose of considering each factor in each project. Lastly, the research aims to retrieve this data for selecting the best subcontractors when a construction company is looking for suitable subcontractors for a new project through the implementation of an appropriate MCDM method.

Chapter 3: Methodology for Performance Evaluation and Decision Support Systems

3.1 Introduction

The aim of this research is to develop a model with two significant functions (evaluating function and selecting function). Firstly, after the completion stage of construction projects, the first function assists general contractors (GCs) in objectively assessing subcontractors (SCs) performance regarding critical aspects. Secondly, the study aims to create a decision support system to aid GCs in selecting the most qualified subcontractor for specific works within a project, utilizing the COPRAS Method (MCDM).

This model will establish a connection between the evaluation and selecting functions from the side of aspects because of their commonalities. To be more precise, the selecting function will utilize the database of subcontractors created by the evaluation function to establish preferences among competing subcontractors (further elaboration on this will follow).

The methodology for developing the model is illustrated in Figure 3.1 and encompasses several phases. Firstly, it involves data collection, understanding industry practices, reviewing existing methods for assessing and selecting subcontractors (SCs), and exploring important criteria and sub criteria.

In the subsequent phase, performance indexes will be identified specifically for evaluating SCs upon project completion. Additionally, criteria and sub-criteria for selecting SCs for new projects will be established, with any commonalities being identified, and the weighting of performance indexes, criteria, and sub-criteria will be conducted through industry expert meetings and implementing a combination of Analytic Hierarchy Process (AHP) and Monte Carlo simulations to minimize bias.

The third phase will entail the development of the model using Python and SQL, linking of common indexes and criteria, and implementing Pre-evaluation inquiries and the COPRAS method for selection competent SC. Finally, two interfaces will be employed for the implementation phase.

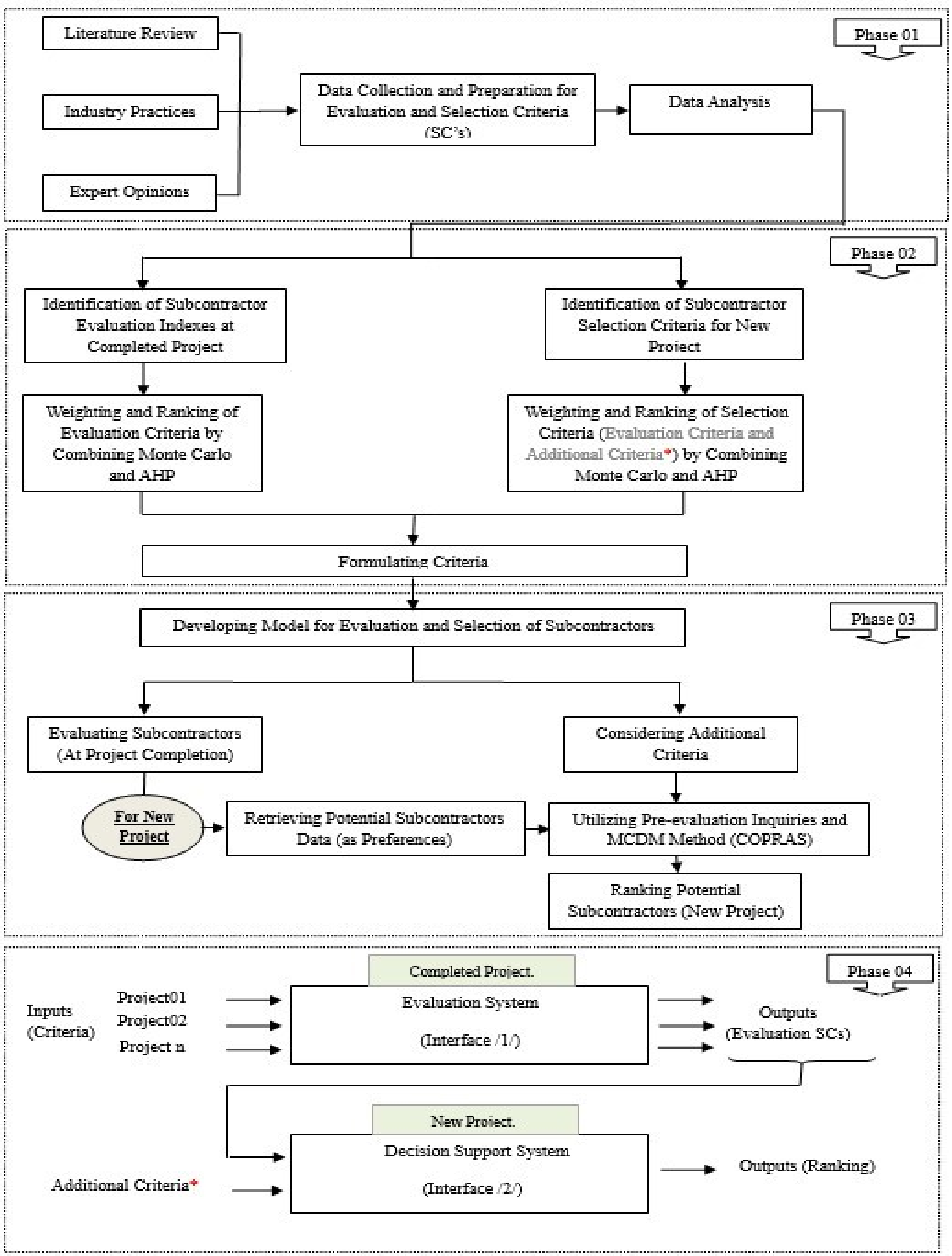


Figure 3.1. Methodology of Developing the Model

3.2 Hierarchy of Evaluation System and Decision Support System for SCs

The core of the research is two key applications: the performance evaluation system and the decision support system. The hierarchy of performance evaluation problem and decision problem is illustrated in Figure 3.2, Figure 3.3, and Figure 3.2.

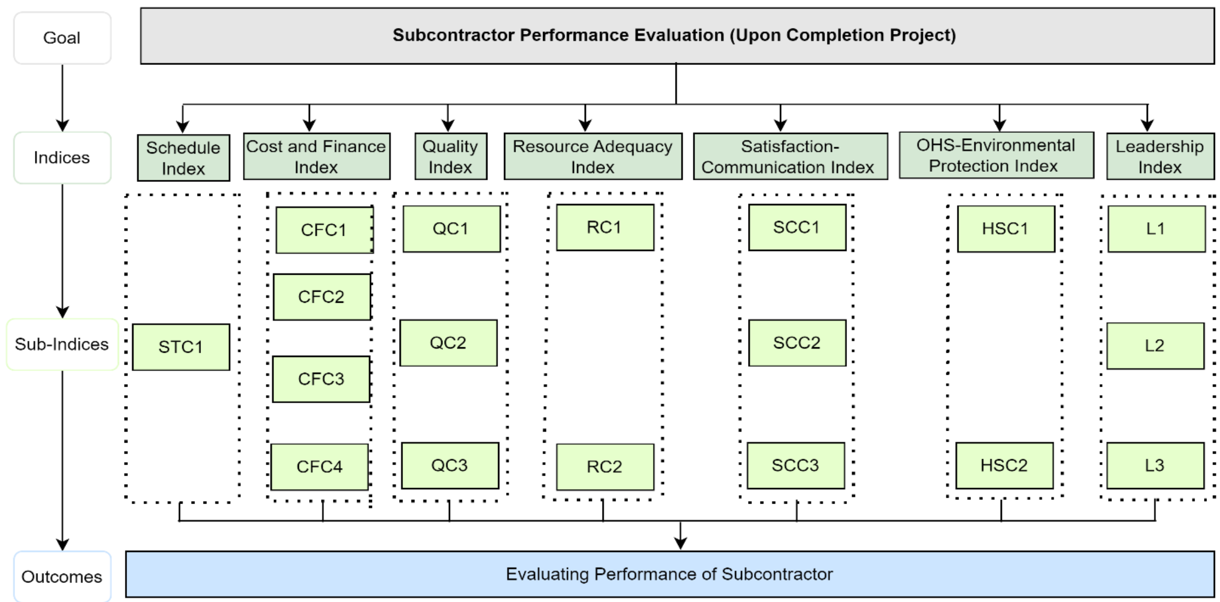


Figure 3.2. Hierarchy of Performance Evaluation Problem

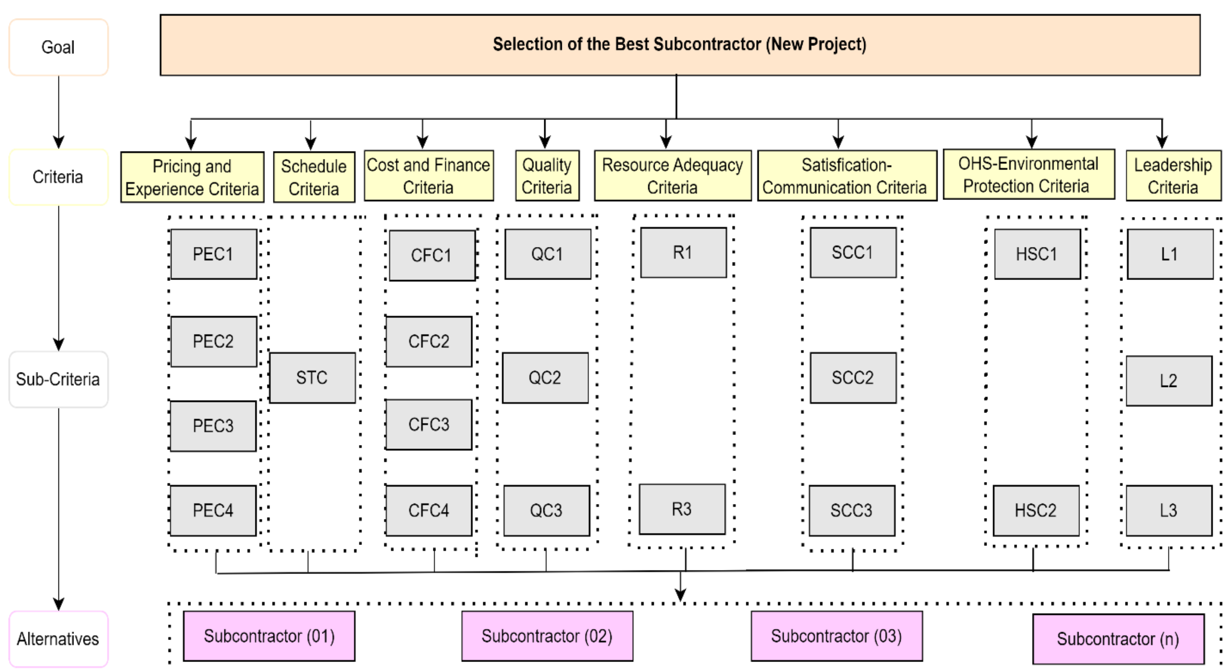


Figure 3.3. Hierarchy of Decision Problem

3.3 Significant Criteria and Sub-criteria for Evaluating SC Performance and Selection of the Best Subcontractor

3.3.1 Methodology

The literature review on subcontractors was conducted to gain an understanding of how to evaluate the performance of subcontractors upon project completion, select the best subcontractor for new projects, and identify the relationships between the criteria.

The review and identification of criteria are accomplished through a multi-step process executed as illustrated in Figure 3.4. The procedure begins with the selection of an appropriate search engine platform. Google Scholar is chosen for its comprehensive coverage and inclusivity, encompassing a diverse range of research found in other databases such as Scopus and Web of Science (Martín-Martín et al., 2021).

Additionally, Scopus and Web of Science are queried using the same keywords to ensure a thorough review of relevant sources. Once a suitable search engine is identified, a systematic review is conducted using predefined keywords: subcontractor evaluation, on-site subcontractor assessment method, criteria for subcontractor appraisal, and Framework for Subcontractor Selection. These keywords are meticulously selected to encompass the entire process of performance evaluation and selection. The title, abstract, and conclusion of each article retrieved in the search are then screened.

The second step involves reviewing the full papers to determine if their content is sufficient for analysis and to characterize the relationships between evaluation and selection criteria.

Next, analyze the content of the selected articles, as shown in Table 3.2, to identify the criteria and sub-criteria for both performance assessment and the selection of the best SC. These articles are classified into two categories based on their objectives: evaluation of subcontractor performance and selection of subcontractors. The body of knowledge was analyzed using both the Relative Usage Index (RUI) and Social Network Analysis (SNA) to define the significant criteria. Finally, a shortlist of significant criteria was identified.

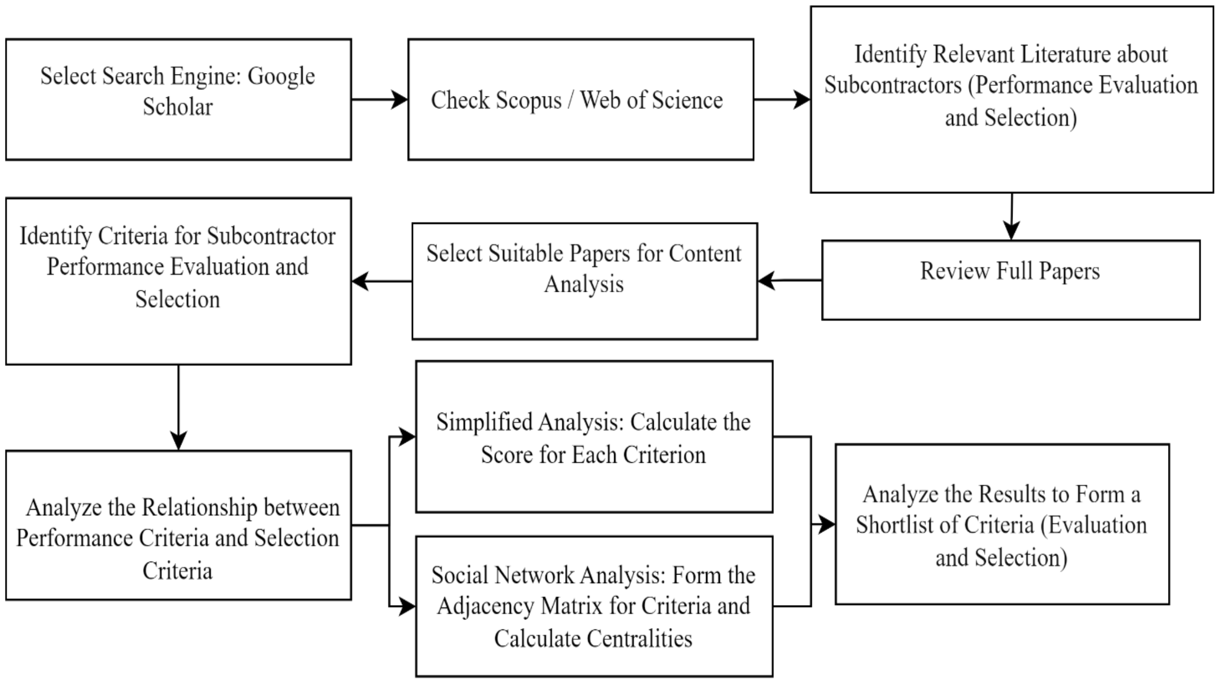


Figure 3.4. Methodology for Identification of Indices and Criteria

Table 3.1. List of Selected Articles and Studies

Item	Studies / Formats	Evaluation of Performance SC	Selection of SC
R1	Okoroh and Torrance (1999)		☑
R2	Hudson et al. (2001)	☑	
R3	Shiau et al. (2003)		☑
R4	Rahman and Kumrswamy (2005)		☑
R5	Dulung and Pheng (2005)		☑
R6	Ng (2007)	☑	
R7	Maturana et al. (2007)	☑	
R8	Ng and Tang (2008)	☑	
R9	Eom et al. (2008)		☑
R10	Arslan et al. (2008)		☑
R11	Mbachu (2008)	☑	
R12	El-Mashaleh (2009)		☑
R13	Yin et al. (2009, May)		☑
R14	Hartmann and Caerteling (2010)		☑
R15	Cheng et al. (2011)	☑	
R16	Cheng and Wu (2012)	☑	
R17	Abbasianjahromi et al. (2013)		☑

R18	Ng and Skitmore (2014)	☑	
R19	Chamara et al. (2015)	☑	
R20	Polat (2016)		☑
R21	Pallikkonda et al. (2019)		☑
R22	El-khalek et al. (2019)		☑
R23	Demirkesen and Bayhan (2019)		☑
R24	Hanák and Nekardová (2020)		☑
R25	Chen et al. (2021)		☑
R26	Zhong and Elzarka (2022)		☑
R27	Afshar et al. (2022)		☑
R28	Peansupap and Nov(2022)		☑
R29	Mahmoudi and Javed (2022)	☑	
R30	Koprivica (2022)		☑
R31	Putri and Nusraningrum (2022)		☑
R32	Liu et al. (2023)		☑
R33	Başaran et al. (2023)	☑	
R34	Lumanauw et al (2023)	☑	
R35	Abdull Rahman et al. (2024)	☑	
R36	Hansen et al (2024)		☑

3.3.2 Identification of Criteria and the Relationship Between Evaluation and Selection Criteria

An examination of the selected articles (referenced in Table 3.1) indicates two categories of criteria from a usage perspective. Eight criteria, comprising 25 sub-criteria, are employed to select the best subcontractor. Meanwhile, seven criteria, including 20 sub-criteria, are used to evaluate subcontractor performance.

It is worth mentioning that the selected articles reveal that the criteria for selecting the best subcontractor are essentially the same as those for assessing subcontractor performance, with the addition of criteria related to pricing and experience. In this context, Mbachu (2008) states that the criteria and sub-criteria used to assess subcontractors' overall performance can be documented as lessons learned and retrieved for future use in selecting the best subcontractor. As a result, Table 3.2 illustrates criteria comprising both categories.

Table 3.2. Identification of Criteria and Sub-Criteria

Sr.N	Criteria	Sub- Criteria	Identification
1	Pricing and Experience (PEC)	Bid Offer (PEC1)	The SC's bid offer to commence the construction project.
		Financial capacity (PEC2)	Refers to the profitability, growth, activeness, and stability of the subcontractor.
		Experience of similar works (PEC3)	Number of similar projects that the SC has accomplished
		Experience in the construction industry (PEC4)	Number of years of experience in construction.
		Time accuracy in submitting bids (PEC5)	Refers to the precision and timeliness with which a subcontractor submits their bid proposals.
2	Time Criterion (STC)	Compliance and flexibility of project schedule (STC)	The SC's ability to adhere to the project schedule and to demonstrate flexibility when dealing with delays and schedule shorten that is amount of time that SC saves the schedule for the GC across all project stages.
3	Cost and Finance (CFC)	Ensuring subcontractor budget compliance (CFC1)	The ability of the subcontractor to stay within the budget limits agreed upon in the contract, without submitting claims that are not dependent on contractual documents and ensuring that the actual cost of the work performed remains within the allocated budget.
		Adaptability and invoice timeliness (CFC2)	The capacity of the SC to adapt to circumstances in cases of payment delays attributed to specific conditions, and the punctual submission of invoices to the GC in accordance with contractual obligations.
		Cost -saving (CFC3)	This sub-criterion concerns the cost-saving measures implemented by the SC for the GC across all project stages. For example, the SC may achieve cost reductions for the GC through the adoption of particular technologies.
		Timely payment from SC (CFC4)	The timely payment performance of SC workers at each stage of project execution and timely payment to material suppliers for SC work.
4	Quality (QC)	Upholding material quality (QC1)	Ensuring the quality of material usage status complies with the standards specified in the contract and general and specific specifications.
		Level of workmanship (QC2)	The quality of construction workmanship during project execution.
		The quality of the end product (QC3)	The compliance status of the accomplished production with the project general and particular specifications.
5	Resource Adequacy (RC)	Technical competence (RC1)	The sub-criterion (RC1) concerns the technical competence of employees and the availability of adequate resources such as technicians, equipment, and software.
		Materials available (RC2)	Ensuring that the materials required for production are sufficiently available at the proper time .

6	Occupational Health and Safety and Environmental Protection Criterion (HSC)	Adhere to the health and safety regulations (HSC1)	Assessing the attitude towards occupational health and safety requirements and ensuring that subcontractors adopt and comply with the health and safety rules requested by the GC.
		Environmental awareness (HSC2)	The environmental compliance of subcontractors during the project, which involves maintaining a clean workspace and adhering to the GC's waste management plan.
7	General Contractor Satisfaction (Communication) (SCC)	Effective communication compliance with GC (SCC1)	Communication and compliance with the GC through the use of coordinated work execution skills and information exchange during the project execution with the GC.
		Adaptability in Responding to Project Changes (SCC2)	The ability to flexibly respond to changes in the project is the second sub-criterion.
		Effective communication with other (SCC3)	Ensuring adherence to coordination with other subcontractors and on-site employees guarantees smooth collaboration without causing delays.
		Ability to communicate orders electronically (SCC4)	Refers to the capability of a subcontractor to receive, process, and respond to orders through digital means.
		Ability to receive complaints electronically (SCC5)	Refers to the capability of a subcontractor to accept and manage complaints or feedback through digital channels.
8	Leadership Criterion (LC)	Collaborative Leadership (LC1)	leadership is evaluated based on its focus on fostering collaboration and facilitating the development of subordinates.
		Dedication (LC2)	Dedication to the project is gauged by assessing the extent of effort dedicated to resolving issues with the GC.
		Effective leadership (LC3)	The ability to conduct short- and long-term assessments and anticipate opportunities and threats is considered as an indicator of effective leadership (LC3).

3.3.3 Analysis and Distribution of Criteria Among Listed Studies and Resources

A matrix, as shown in Table 3.3, is constructed with the 25 sub-criteria from Table 3.2 as rows and the 36 studies as columns. Each cell at the intersection of a row and column is marked with a value of 1 if the criterion is mentioned in the study and left blank if it is not. This matrix illustrates the agreement among academics and professionals regarding the criteria. Subsequently, the matrix is divided into two separate matrices: one for evaluating performance and one for selecting the best subcontractor.

Table 3.3. Matrix of Criteria- Studies

	Evaluation of Performance SC													Selection oF SC																						
	R2	R6	R7	R8	R11	R15	R16	R18	R19	R29	R33	R34	R35	R1	R3	R4	R5	R9	R10	R12	R13	R14	R17	R20	R21	R22	R23	R24	R25	R26	R27	R28	R30	R31	R32	R36
PEC1														1	1	1	1			1	1			1	1	1		1	1	1				1	1	1
PEC2														1	1	1	1	1		1			1	1	1	1	1	1	1					1		
PEC3																1	1			1	1		1	1		1	1		1	1				1		1
PEC4														1			1						1	1	1							1	1	1	1	1
PEC5																							1													
STC	1	1	1		1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1				1	1	1	1		1	1	1	1	1		
CFC1		1			1					1	1		1		1			1	1				1		1			1		1						
CFC2													1													1								1		
CFC3																		1								1										
CFC4									1		1								1	1			1													
QC1			1		1				1	1	1	1	1	1		1	1	1	1	1		1	1		1	1						1		1	1	
QC2		1	1		1			1	1	1	1	1	1	1	1		1	1	1	1		1	1		1	1						1		1	1	1
QC3	1	1	1		1				1	1	1	1	1	1	1			1	1	1		1	1		1	1						1		1	1	
RC1		1		1			1				1					1		1	1		1	1	1	1	1	1	1		1	1	1		1	1		1
RC2		1		1							1	1			1	1			1		1		1		1	1					1		1			1
HSC1		1	1	1	1	1	1				1		1	1	1	1		1	1	1	1		1		1	1	1		1				1	1	1	
HSC2		1	1	1	1	1	1	1			1		1		1										1	1			1		1		1	1		
SCC1		1		1	1		1	1			1		1	1	1			1		1		1			1	1			1		1		1	1		
SCC2				1	1					1	1							1				1			1			1								
SCC3	1	1			1	1	1	1			1		1		1			1							1	1			1		1		1			
SCC4										1																										
SCC5										1																										
LC1					1						1							1								1										
LC2			1		1						1					1		1				1									1	1	1			
LC3											1							1																		

Note: The details of each studies and sub-criteria are mentioned in Table 3.2 and Table 3.3 respectively.

3.3.4 Implementation of Analysis Methods

The purpose of applying analysis methods is to determine the frequency of criteria illustrated in Table 3.3 among the listed studies (referenced in Table 3.1) and to help highlight the most commonly used criteria. Two methods are implemented as follows:

3.3.4.1 Relative Usage Index (RUI) Method:

The RUI method begins by calculating the frequency by summing the values in each row of the matrix (referenced in Table 3.3.) to determine how often each sub-criterion is mentioned.

Next, the RUI values are calculated using Equation 3.1. These values are then analyzed to identify the most and least frequently mentioned criteria. It is worth mentioning that the interconnections among the various sub-criteria have not been accounted for in the analysis.

$$\mathrm{RUI} = \frac{\text{(Frequency of Criteria)}}{\text{(Total Number of Studies)}} \quad (3.1)$$

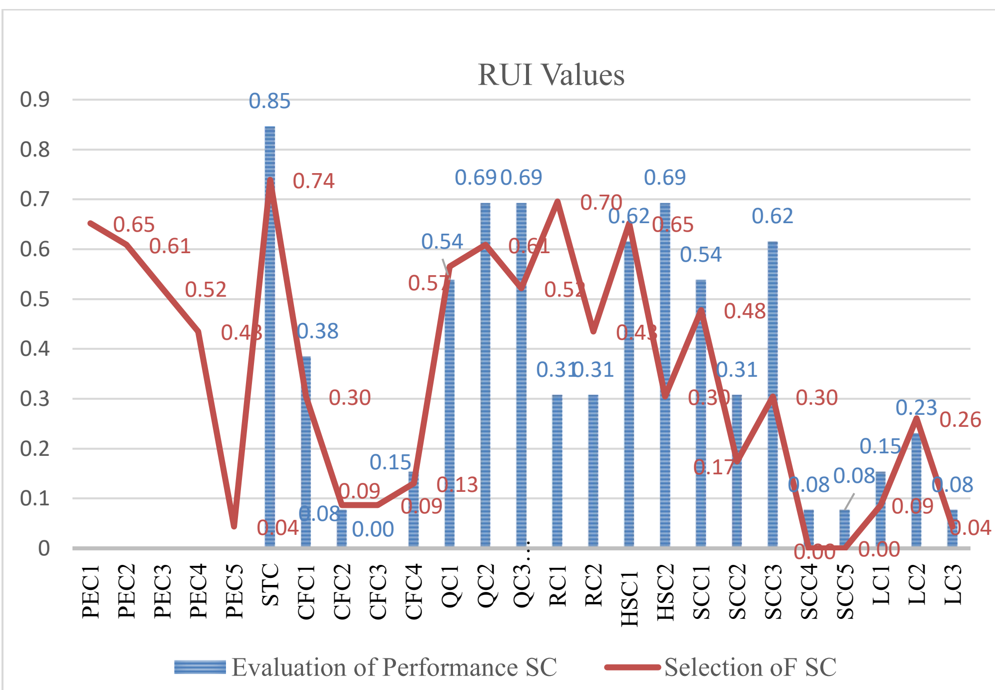
The calculation of the RUI is completed for both separate matrices (evaluation and selection), as shown in Table 3.4 Table 3.5 and Figure 3.5. It is noteworthy that sub-criteria related to the pricing criterion are not mentioned in the evaluation matrix.

Table 3.4. Calculation RUI for Evaluation Matrix

	Evaluation of Performance SC														
	R2	R6	R7	R8	R11	R15	R16	R18	R19	R29	R33	R34	R35	Sum	RUI
STC	1	1	1		1	1	1	1	1	1	1		1	11	0.85
CFC1		1			1					1	1		1	5	0.38
CFC2													1	1	0.08
CFC3														0	0.00
CFC4									1		1			2	0.15
QC1			1		1				1	1	1	1	1	7	0.54
QC2		1	1		1			1	1	1	1	1	1	9	0.69
QC3	1	1	1		1				1	1	1	1	1	9	0.69
RC1		1		1			1				1			4	0.31
RC2		1		1							1	1		4	0.31
HSC1		1	1	1	1	1	1				1		1	8	0.62
HSC2		1	1	1	1	1	1	1			1		1	9	0.69
SCC1		1		1	1		1	1			1		1	7	0.54
SCC2				1	1					1	1			4	0.31
SCC3	1	1			1	1	1	1			1		1	8	0.62
SCC4										1				1	0.08
SCC5										1				1	0.08
LC1					1						1			2	0.15
LC2			1		1						1			3	0.23
LC3											1			1	0.08

Table 3.5. Calculation RUI for Selection Matrix

	Selection oF SC																								
	R1	R3	R4	R5	R9	R10	R12	R13	R14	R17	R20	R21	R22	R23	R24	R25	R26	R27	R28	R30	R31	R32	R36	Sum	RUI
PEC1	1	1	1	1			1	1			1	1	1		1	1	1				1	1	1	15	0.65
PEC2	1	1	1	1	1		1			1	1	1	1	1	1	1					1			14	0.61
PEC3			1	1			1	1		1	1		1	1		1	1				1		1	12	0.52
PEC4	1			1						1	1	1							1	1	1	1	1	10	0.43
PEC5										1														1	0.04
STC	1	1	1	1	1	1	1	1				1	1	1	1		1	1	1	1	1			17	0.74
CFC1		1			1	1				1		1			1		1							7	0.30
CFC2													1								1			2	0.09
CFC3					1								1											2	0.09
CFC4						1	1			1														3	0.13
QC1	1		1	1	1	1	1		1	1		1	1						1		1	1		13	0.57
QC2	1	1		1	1	1	1		1	1		1	1						1		1	1	1	14	0.61
QC3	1	1			1	1	1		1	1		1	1						1		1	1		12	0.52
RC1			1		1	1		1	1	1	1	1	1	1		1	1	1		1	1		1	16	0.70
RC2		1	1			1		1		1		1	1					1		1			1	10	0.43
HSC1	1	1	1		1	1	1	1		1		1	1	1		1				1	1	1		15	0.65
HSC2		1										1	1			1		1		1	1			7	0.30
SCC1	1	1			1		1		1			1	1			1		1		1	1			11	0.48
SCC2					1				1			1			1									4	0.17
SCC3		1			1							1	1			1		1		1				7	0.30
SCC4																								0	0.00
SCC5																								0	0.00
LC1					1								1											2	0.09
LC2			1		1				1									1	1	1				6	0.26
LC3					1																			1	0.04



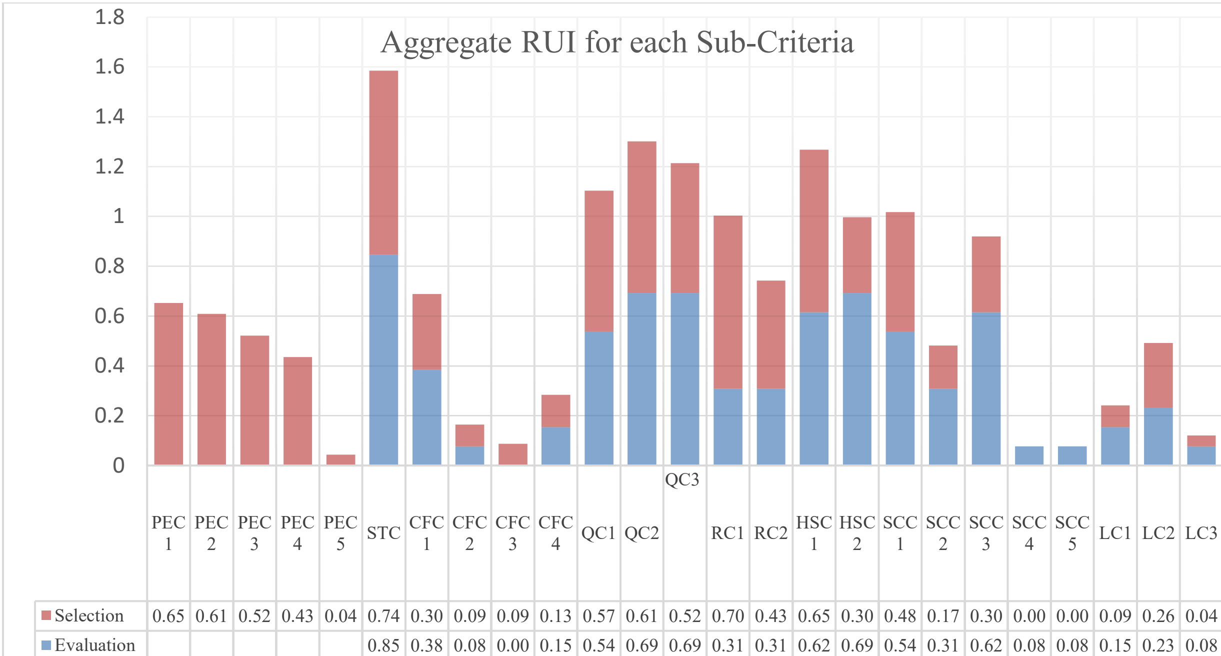


Figure 3.5.RUI Values and Aggregate RUI

3.3.4.2 Social network analysis (SNA):

SNA is a methodological approach used to study the structure and dynamics of social networks (Wasserman & Faust, 1994). It involves mapping and measuring relationships and flows between people, groups, organizations, computers, or other information/knowledge processing entities (Scott & Carrington, 2011). By visualizing and analyzing these networks, SNA helps to identify key players, understand the flow of information, and uncover the underlying patterns and structures within the network.

In the current study, the network construction utilizes previously established matrices (both selection and evaluation). Each criterion is represented as a node within the network. A relationship (edge) between two nodes is inferred if the criteria are co-mentioned within the same source. This network is categorized as undirected since it examines the concurrent occurrence of two criteria rather than the directional influence of one criterion on another.

To implement SNA, Gephi is utilized for analyzing linkages. Gephi is a powerful open-source tool designed for network analysis and visualization across various domains. It supports the calculation of centrality measures (degree, betweenness, closeness), clustering coefficients, and community detection algorithms (Bastian et al., 2009).

Measures used in social network analysis are categorized into two types: those that provide information about individual positions and interactions between nodes, and those that offer insights into the overall structure of the social network (Hanneman & Riddle, 2005). For this study, the focus is on the first category (individual positions). Centrality, a measure of prestige, is employed for undirected networks.

Centrality is a key concept in SNA used to identify the most important or influential nodes (individuals, entities, or criteria) within a network. Centrality measures provide insights into the structure and dynamics of the network by quantifying the significance of each node (Bastian et al., 2009). There are several types of centrality measures, such as degree centrality, betweenness centrality, and others.

In this study, degree centrality is adopted, which is defined as the number of direct connections (edges) a node has. In other words, degree centrality indicates which criteria are most frequently mentioned together with other criteria.

Table 3.6 illustrates an example of creating edges for use in Gephi. The edges consist of a node source (criterion1), a node target (criterion2), and an edge type. The undirected edge type indicates that the relationship between node 1 and node 2 is bidirectional. The number of edges regarding to evaluation matrix is 389 edges and regarding to selection is 915 edges.

Table 3.6. An Example of Edges

Edges - Evaluation (SC)				**Edges - Selection (SC)**			
Source	Target	Studies	Edge Type	Source	Target	Studies	Edge Type
STC	QC3	R2	Undirect	PEC1	PEC2	R1	Undirect
STC	SCC3	R2	Undirect	PEC1	PEC4	R1	Undirect
STC	CFC1	R6	Undirect	PEC1	STC	R1	Undirect
STC	QC2	R6	Undirect	PEC2	QC1	R1	Undirect
STC	QC3	R6	Undirect	PEC2	QC2	R1	Undirect
STC	RC1	R6	Undirect	PEC2	QC3	R1	Undirect
CFC1	HSC2	R35	Undirect	PEC2	HSC1	R1	Undirect
CFC1	SCC1	R35	Undirect	PEC1	QC3	R32	Undirect
CFC1	SCC3	R35	Undirect	PEC1	HSC1	R32	Undirect
CFC2	QC1	R35	Undirect	PEC1	PEC3	R36	Undirect
CFC2	QC2	R35	Undirect	SCC3	LC2	R27	Undirect
SCC3	LC3	R33	Undirect	SCC3	LC2	R30	Undirect
SCC4	SCC5	R29	Undirect	LC1	LC2	R9	Undirect
LC1	LC2	R11	Undirect	LC1	LC3	R9	Undirect
LC2	LC3	R33	Undirect	LC2	LC3	R9	Undirect

After importing the edges into Gephi, the network visualizations of degree centrality were generated, as illustrated in Figure 3.6 and Figure 3.8. Each node represents a criterion, and the size of the node corresponds to the number of connections it has with other criteria. In other words, a criterion that is connected to many other criteria will appear larger, indicating its high level of interaction.

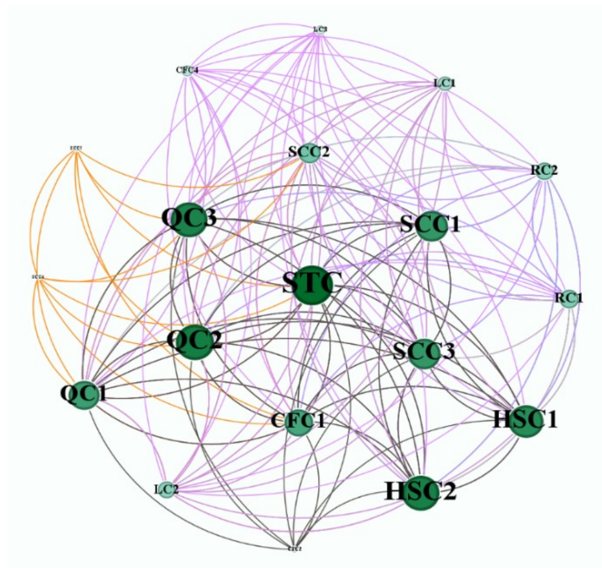


Figure 3.6. Social Network for Evaluation of Performance SC

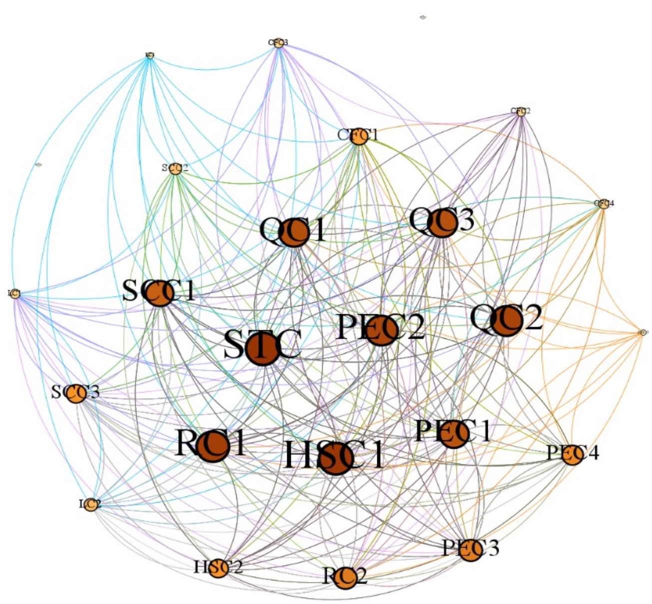


Figure 3.7. Social Network for Selection SC

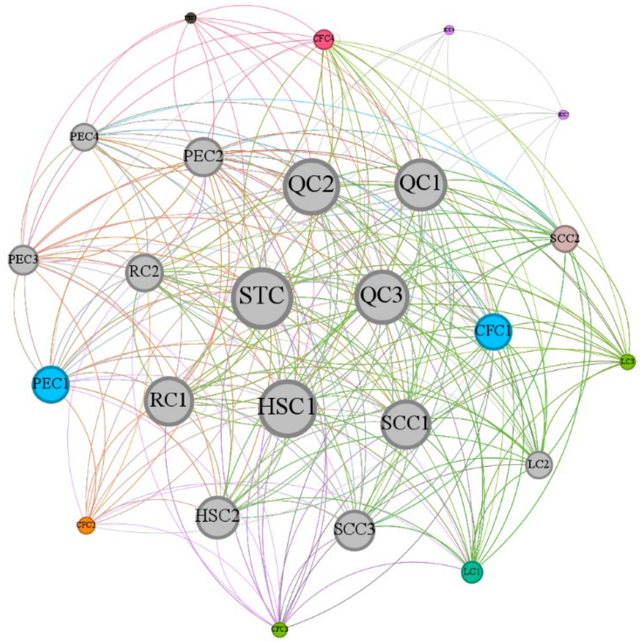


Figure 3.8. Social Network for Aggregate Evaluation and Selection SC

3.3.5 Analysis of Results

As illustrated in Table 3.3, the number of studies related to the evaluation of performance SC is 13, while the number of studies related to the selection of the best SC is 23. To analyze the 36 studies and reveal the significant criteria for SC, two methods have been implemented. The analysis of results from these two methods aims to provide an in-depth understanding of the significance and application of each criterion in the evaluation and selection processes.

3.3.5.1 Results from the RUI Method

The results from Figure 3.5 provide a comprehensive comparison of the Relative Usage Index (RUI) for different criteria. The criteria are categorized into eight groups.

3.3.5.1.1 Pricing and Experience (PEC):

The RUI for bid offer (PEC1) is 0 for evaluation but 0.65 for selection. This indicates that while the bid offer is not considered during performance evaluation, it is a significant factor in the selection process. This criterion is crucial as it directly impacts the financial feasibility of subcontractor engagement.

Similar to PEC1, financial capacity (PEC2) has an RUI of 0 for evaluation and 0.61 for selection. This shows that while financial stability is not evaluated during performance reviews, it plays a vital role in the selection of subcontractors. Ensuring that a subcontractor has sufficient financial resources is essential to mitigating the risks associated with project completion.

The criterion (PEC3), with an RUI of 0 for evaluation and 0.52 for selection, emphasizes the importance of prior experience in similar projects. This indicates that subcontractors with a track record of relevant work are preferred during the selection process.

Experience in the construction industry (PEC4) with an RUI of 0 for evaluation and 0.43 for selection, experience in the construction industry is highlighted as a crucial selection criterion. This experience ensures that subcontractors are familiar with industry standards and practices, which can contribute to the successful execution of projects.

Time accuracy in submitting bids (PEC5) has the lowest RUI values of 0 for evaluation and 0.04 for selection, indicating that it is considered the least important among the pricing and experience criteria. While timely bid submission is relevant, it does not heavily influence the evaluation or selection process.

3.3.5.1.2 Time Criterion (STC):

The criterion STC stands out with high RUI values of 0.85 for evaluation and 0.74 for selection. It underscores the critical importance of adherence to project schedules and flexibility in managing project timelines. This flexibility is essential for maintaining project timelines and ensuring timely completion.

3.3.5.1.3 Cost and Finance (CFC):

Ensuring subcontractor budget compliance (CFC1) has an RUI of 0.38 for evaluation and 0.30 for selection, indicating its moderate importance in both contexts. Ensuring that subcontractors adhere to budget constraints is crucial for project cost management.

The RUI for CFC2 is 0.08 for evaluation and 0.09 for selection, this criterion is less emphasized. While important, adaptability in handling invoices does not significantly influence the evaluation or selection process.

The criterion (CFC3) has an RUI of 0 for evaluation and 0.09 for selection; suggesting it is not a priority during evaluation but has some significance in selection. Cost-saving measures are beneficial, but they do not heavily impact the overall decision-making process.

Timely payment from SC (CFC4) with RUI values of 0.15 for evaluation and 0.13 for selection reflects moderate importance. Timely payments are essential for ensuring project continuity.

3.3.5.1.4 Quality (QC):

The criterion (QC1) has RUI values of 0.54 for evaluation and 0.57 for selection; this criterion is consistently important in both processes. Ensuring high-quality materials is crucial for project success and longevity.

Level of workmanship (QC2), with RUI values of 0.69 for evaluation and 0.61 for selection, highlights the importance of skilled workmanship. High-quality workmanship ensures that projects meet the required standards and specifications.

Quality of the end product (QC3) also has high RUI values of 0.69 for evaluation and 0.52 for selection, indicating its critical role in both evaluation and selection. The quality of the end product is a significant factor in determining the overall success of a project.

3.3.5.1.5 Resource Adequacy (RC):

Technical competence (RC1) has an RUI of 0.31 for evaluation and a high 0.70 for selection, this criterion is particularly important in the selection process. Technical competence ensures that subcontractors have the necessary skills and knowledge to perform their tasks effectively.

The RUI of RC2 is 0.31 for evaluation and 0.43 for selection, showing its relevance in both areas. Having adequate materials is essential for project execution and avoiding delays.

3.3.5.1.6 Occupational Health and Safety and Environmental Protection (HSC):

Adherence to health and safety regulations (HSC1) with RUI values of 0.62 for evaluation and 0.65 for selection is crucial in both contexts. Ensuring compliance with health and safety regulations is vital for protecting workers and minimizing project risks.

Environmental awareness (HSC2) has an RUI of 0.69 for evaluation and 0.30 for selection, indicating its higher importance in evaluation. Environmental awareness is increasingly important for sustainable project management.

3.3.5.1.7 General Contractor Satisfaction (Communication) (SCC):

The RUI of SCC1 is 0.54 for evaluation and 0.48 for selection; this criterion is important in both processes. Effective communication ensures that project requirements are clearly understood and executed.

Adaptability in responding to project changes (SCC2) has lower RUI values of 0.31 for evaluation and 0.17 for selection, indicating less emphasis. While important, adaptability in responding to changes is not a primary deciding factor.

The criterion SCC3, with RUI values of 0.62 for evaluation and 0.30 for selection, is more significant in evaluation. Effective communication with other stakeholders is crucial for smooth project execution.

Ability to communicate orders electronically (SCC4) and ability to receive complaints electronically (SCC5) both have low RUI values (0.08 for evaluation and 0 for selection), indicating minimal importance. While electronic communication is beneficial, it does not significantly impact the overall decision-making process.

3.3.5.1.8 Leadership Criterion (LC):

Collaborative leadership (LC1) has RUI values of 0.15 for evaluation and 0.09 for selection, showing its low importance. Collaborative leadership helps in building effective teams and ensuring project success.

Dedication (LC2) with RUI values of 0.23 for evaluation and 0.26 for selection, this criterion is somewhat important in both contexts.

Effective leadership (LC3) has low RUI values (0.08 for evaluation and 0.04 for selection), indicating lesser significance. While leadership is important, it is not a primary criterion in the evaluation and selection process.

The results analysis reveals that certain criteria, such as compliance and flexibility of the project schedule (STC), level of workmanship (QC2), and adherence to health and safety regulations (HSC1), are highly valued in both evaluation and selection processes. Other criteria, like bid offer (PEC1) and financial capacity (PEC2), are crucial in the selection process but not in performance evaluation. On the other hand, some criteria, like time accuracy in submitting bids (PEC5), ability to communicate orders electronically (SCC4), and ability to receive complaints electronically (SCC5), are of very low importance for both processes, with the lowest RUI value. Understanding these distinctions helps in prioritizing the criteria based on their importance in different stages of subcontractor management.

3.3.5.2 Results from the Social network analysis (SNA) Method

The network visualizations, as shown in Figure 3.6 and Figure 3.8, reveal significant insights into the criteria that play pivotal roles in both the evaluation and selection of subcontractors. The criteria are categorized according to their degree of centrality into two categories.

3.3.5.2.1 Central Criteria

- Time criterion (STC) emerges as a central criterion in both evaluation and selection networks. This criterion's high centrality indicates its critical importance in ensuring that project schedules are adhered to. The frequent connections with other criteria underscore the pivotal role of time management in both assessing subcontractor performance and making selection decisions. STC is strongly connected with various quality criteria (QC1, QC2, QC3) and effective communication with GC (SCC1), indicating that effective time management is closely linked with maintaining high-quality standards and communication.
- Quality sub-criteria (QC1, QC2, QC3) are consistently central in both networks, highlighting the importance of material quality, workmanship, and the quality of the end product. These criteria are essential in ensuring that subcontractors meet the required performance standards and deliver high-quality outputs.
- Effective communication compliance with the general contractor (SCC1) and effective communication with other parties (SCC3) are central criteria in both networks. These criteria's high centrality underscores their importance in ensuring seamless collaboration and responsiveness in project execution. SCC1 and SCC3 are frequently connected with

both quality and time management criteria, indicating their integral role in facilitating project success through clear and effective communication.

- Health and safety criteria (HSC1, HSC2) are more pronounced in the evaluation network, while HSC1 is more pronounced in the selection network, reflecting their importance in maintaining safe working conditions and adhering to safety regulations during project execution.
- Competitive pricing (PEC1), financial capacity (PEC2), and relevant experience (PEC3) are more central in the selection network. These criteria ensure that selected subcontractors are not only cost-effective but also possess the necessary experience and financial stability to complete the project successfully.

3.3.5.2.2 Peripheral Criteria

- Leadership criteria (LC1, LC2, LC3) and additional communication criteria (SCC2, SCC4, SCC5) appear more peripheral in both networks. The peripheral positioning suggests that leadership and communication (SCC2, SCC4, and SCC5) are considered secondary factors. They are essential for smooth project execution and effective teamwork, but they are not the primary determinants in the evaluation and selection processes.
- Cost and finance criteria (CFC1, CFC2, CFC3) show moderate centrality, indicating their balanced importance in both evaluation and selection processes. Ensuring subcontractor budget compliance and cost-saving measures are necessary for project cost management but are not as critical as time and quality criteria.
- Resource adequacy criteria (RC1, RC2) exhibit moderate centrality, indicating their balanced importance in both evaluation and selection processes.
- Time accuracy in submitting bids (PEC5) has a relatively low centrality in selection networks. It is not as critical as other criteria like pricing, quality, and time management.

STC, QC1, QC2, QC3, SCC1, and HSC1 are consistently central in both the evaluation and selection processes. Meanwhile, PEC1 and PEC2 are central in the selection process, whereas HSC2 is central in the evaluation process. On other hand, PECS, SCC4, and SCC5 have the lowest degree of centrality.

Based on the matching results derived from implementing the RUI and SNA methods, a shortlist of criteria and sub-criteria has been identified. This list includes all criteria as illustrated in Table 3.2 except those with the lowest RUI values and the lowest degree of centrality, which are time accuracy in submitting bids (PEC5), ability to communicate orders electronically (SCC4), and ability to receive complaints electronically (SCC5).

3.3.3 Reflection of industrial Experts Perspective

The Short list was presented to a panel of experts with broad experience in construction, representing the viewpoints of general contractors (GCs). The experts did not add any new one and emphasized the importance of all criteria, not just price, time, and quality. Resource adequacy, communication, and managerial practices play a significant role in the evaluating process and successful selection of the best subcontractor.

3.3.4 Identification and Measurement of Significant Criteria and Sub-criteria

The short list, as shown in Table 11.3 and Figure 23.3, comprises eight main criteria and 22 sub-criteria for selecting the best subcontractor (SC), while for the evaluation process, the short list includes seven main criteria with 18 sub-criteria, as follows:

3.3.4.1 Time Criterion (STC):

Time refers to the duration required to complete specific construction work. It is scheduled to enable the SC to deliver work according to a date determined by the GC’s plans. Time (STC) divides not two sub- criteria namely, schedule performance (STC1) that is a crucial criterion for evaluating the SC's ability to adhere to the project schedule (Başaran et al., 2023) and to demonstrate flexibility when dealing with delays (Pallikkonda et al., 2019) and schedule shorten that is amount of time that SC saves the schedule for the GC across all project stages.

The measurement of STC1 expresses the performance of construction schedule, engineering schedule, and procurement schedule (Nassar & AbouRizk, 2014). Time criterion (STC) is derived from historical data of SC and is considered a quantitative beneficial input. Nassar and AbouRizk (2014) measured STC1 by calculating the Schedule Performance Index (SPI) during the execution stage of the GC’s work.

On the other hand, Chan and Chan, A (2004) determined STC1 based on the speed of construction and the time variation at project completion for the GC's work as shown in Table 3.7. Meanwhile, Ng and Skitmore (2014) referred to the percentage deviation from subcontractors' project milestones without providing clarification on the calculation method.

Table 3.7. Formulas and equations to determine time criterion from previous studies

Item	Formula	For	Author
Schedule Performance Index	Budgeted cost of work performed ÷ Budgeted cost of work scheduled	GC	(Nassar & AbouRizk, 2014)
Speed of construction	Gross floor area (m2) ÷ Construction time (days/weeks)	GC	(Chan & Chan, A, 2004)
Time variation	(Construction time - Revised contract period) ÷ (Revised contract period)		
Percentage deviation	No Formula (qualitative)	SC	(Ng & Skitmore, 2014)
Completion of a job within the time.	No Formula (qualitative)	SC	Pallikkonda et al., 2019)

Based on previous studies and expert reviews, the time criterion (STC) can be calculated using Equation 3.2:

$$\text{Schedule performance (STC1)} = \frac{\text{Revised Contract Period (RC)}}{\text{Construction Time (CT)}} \tag{3.2}$$

Where:

- Construction Time (CT)= practical completion date – work commencement date
- Revised contract period (RC)= original contract period + Change Order Time granted by the GC (may be increasing or decreasing)

3.3.4.2 Cost and Finance Criterion (CFC):

Cost is an important measure. The cost extends beyond the tender price alone. It encompasses the entirety of costs incurred by a project from inception to completion. This encompasses costs arising from variations and modifications during the construction period, as well as expenses resulting from legal claims, such as litigation and arbitration (Chan & Chan, A, 2004).

The evaluation of the cost and finance criterion requires the evaluation of four sub-criteria. Firstly, it involves assessing the ability of the subcontractor to stay within the budget limits agreed upon in the contract, without submitting claims that are not dependent on contractual documents and ensuring that the actual cost of the work performed remains within the allocated budget (Pallikkonda et al., 2019). It is considered a quantitative cost input. For the quantitative measurement of this sub-criterion (CFC1), it is reasonable to follow the same principle used for calculating the time criterion (STC). Nassar and AbouRizk (2014) calculated the Cost Performance Index (CPI) during the execution stage and Chan and Chan, A (2004) considered that cost performance can be measured in terms of unit cost and percentage of net variation over final cost.

Table 3.8. formulas and equations to determine (CFC1) from previous studies

Item	Formula	For	Author
Cost Performance Index	Budgeted cost of work performed ÷ Actual cost of work performed	GC	(Nassar & AbouRizk, 2014)
Net Variation	Net value of variations ÷ Final contract sum	GC	(Chan & Chan, A, 2004)
Completion of a job within budget	No Formula (qualitative)	SC	(Pallikkonda et al., 2019)
Ability to adhere to the project budget	No Formula (qualitative)	SC	(Başaran et al., 2023)

Based on previous studies and expert reviews, for measuring the ability of the SC to stay within the budget limits (CFC1) can be calculated using Equation 3.3:

$$\text{CFC1}=\frac{\text{SC Financial Claims (FC)}}{\text{Revised Contract Value (RV)}} \tag{3.3}$$

Where:

- SC Financial Claims (FC) are claims that are not dependent on contractual documents. For example, an SC may submit a financial claim as a result of a mistake in the bill of quantities.
- Revised contract Value (RV)= original contract value + change order value granted by the GC (may be increasing or decreasing)

Secondly, the capacity of the SC to adapt to circumstances in cases of payment delays attributed to specific conditions (Putri & Nusraningrum, 2022), and the punctual submission of invoices to the General Contractor (GC) in accordance with contractual obligations, constitute the second sub-criterion (CFC2). This element elucidates the financial capability of the SC. It constitutes a quantitative cost input, assessed by determining the frequency of SC submissions of invoices to the GC prior to the contractual dates.

Subsequently, this sub-criterion (CFC3) concerns the cost-saving measures implemented by the SC for the GC across all project stages (Eom et al., 2008). For example, the SC may achieve cost reductions for the GC through the adoption of particular technologies. This constitutes a quantifiable benefit, measurable through the utilization of Equation 3.4 as derived from Eom et al. (2008).

$$\text{Cost Saving (CFC3)} = \frac{\sum \text{Cost Saving (Item or Task)}}{\sum \text{Contractual Cost (Item or Task)}} \tag{3.4}$$

Where:

Cost Saving (Task) = Contractual Cost (Task) – Modified Cost (Task)

The last sub-criterion (CFC4) is the timely payment performance of SC workers at each stage of project execution and timely payment to material suppliers for SC work (Başaran et al., 2023; El-Khalek et al., 2019). It is important to determine the number of times the SC delayed payments to its labor force or material suppliers during the project, as it also reflects the financial ability of the SC. This aspect serves as a quantitative cost sub-criterion and is measured by assessing the frequency of delayed payments (workers and material suppliers) throughout the project.

3.3.4.3 Quality Criterion (QC):

In construction, quality criteria are essential standards and measures that ensure that the completed project meets the required standards of quality. Assessing the quality criterion (QC) involves measuring three sub-criteria as follows: Firstly, ensuring the quality of material usage status complies with the standards specified in the contract and general and specific specifications (Arslan et al., 2008). This sub-criterion (QC1) is measured using a method derived from Cha and Kim (2011), which involves assessing the number of non-conformance reports (NCRs) regarding materials. These reports are issued by the quality controller from the GC side throughout the project.

Next, QC2 pertains to the quality of construction workmanship during project execution (Başaran et al., 2023). QC2 is assessed by determining the number of non-conformance reports (NCRs) related to work requiring rework.

Lastly, QC3 refers to the compliance status of the accomplished production with the project general and particular specifications (Başaran et al., 2023). QC3 is crucial as it influences most stakeholders, including other subcontractors, the general contractor (GC), and the end-user. QC3 is measured by assessing the number of non-conformance reports (NCRs) related to finished production. QC1 with QC2 and QC3 sub-criteria is considered a quantitative cost input.

3.3.4.4 Resource Adequacy Criterion (RC):

Resource adequacy criteria in construction refer to the evaluation of whether the available resources, including labor, materials, and equipment, are sufficient to meet the demands of a construction project. Identifying resource adequacy criteria involves assessing various sub-criteria to ensure that the project has the necessary resources to be completed successfully and within the specified constraints.

The first sub-criterion (RC1) concerns the technical competence of employees and the availability of adequate resources such as technicians, equipment, and software (Pallikkonda et al., 2019). RC1 is measured using Equations 3.5, 3.6, 3.7, and 3.8 derived from Pallikkonda et al. (2019) and Eom et al. (2008).

$$\text{RC1-1} = \frac{\text{Number of technicians and technical certificates (SC)}}{\text{Number of required technicians and certificates according to contract}} \tag{3.5}$$

$$\text{RC1-2} = \frac{\text{Number of specialized equipment (SC)}}{\text{Number of specialized equipment according to contract}} \tag{3.6}$$

$$\text{RC1-3} = \text{Number of software issues encountered throughout the project} \tag{3.7}$$

$$\text{RC1} = 0.33\ \text{RC1-1} + 0.33\ \text{RC1-2} + 0.33\ \text{RC1-3} \tag{3.8}$$

Secondly, the sub-criterion (RC2) involves ensuring that the materials required for production are sufficiently available at the proper time (Başaran et al., 2023). RC2 is measured using Equation 3.9.

$$\text{RC2} = \frac{\text{Total of days of delay in the delivery of materials}}{\text{Revised Contract Period (RC)}} \tag{3.9}$$

Where:

- Revised contract period (RC)= original contract period + Change Order Time granted by the GC (may be increasing or decreasing)

All resource adequacy sub-criteria are considered a quantitative beneficial inputs, except RC1-3 and RC2.

3.3.4.5 Occupational Health and Safety and Environmental Protection Criterion (HSC):

Health and safety are defined as the extent to which general conditions promote the completion of a project without major accidents or injuries (Bubshait & Almohawis, 1994). Construction projects impact the environment in numerous ways throughout their life cycle (Shen et al., 2000). HSC criterion issues are among the most important issues in construction projects (Başaran et al., 2023).

$$HSC1 = 0.25\ HSC1\text{-}1 + 0.25\ HSC1\text{-}2 + 0.25\ HSC1\text{-}3 + 0.25\ HSC1\text{-}4 \tag{3.10}$$

The HSC criterion encompasses three sub-criteria. Firstly, it involves assessing the attitude towards occupational health and safety requirements and ensuring that subcontractors adopt and comply with the health and safety rules requested by the GC (Ng & Tang, 2008; Arslan et al., 2008; Başaran et al., 2023). This sub-criterion (HSC1) is measured by methods deriving from Ng and Skitmore (2014) and Eom et al. (2008):

- HSC1-1= Number of incidents of damaging utilities, works or materials by SC workers during project
- HSC1-2= Number of fatal incidents by SC workers during project
- HSC1-3= Number of reportable safety violation and injuries during project
- HSC1-4= Number of prosecutions made by Labor Department or Union during project

The second sub-criterion pertains to the environmental compliance of subcontractors during the project, which involves maintaining a clean workspace and adhering to the GC's waste management plan (Başaran et al., 2023). This sub-criterion (HSC2) is measured by determining the number of warnings issued by the GC site officer.

3.3.4.6 General Contractor Satisfaction (Communication) Criterion (SCC):

Meeting the expectations of the client is essential for ensuring that a contracting company will continue to receive repeat business (Nassar & AbouRizk, 2014). Similarly, a subcontractor should maintain an ongoing working relationship with its clients (Sims & Anderson, 2003). The satisfaction of the general contractor is achieved by meeting expectations regarding the level of quality and communication. Quality expectations are covered under the quality criterion. Therefore, SCC specifically focuses on the satisfaction of the general contractor with the communication process with subcontractors.

In this context, the SCC is divided into three sub-criteria. Firstly, it involves communication and compliance with the GC through the use of coordinated work execution skills and information exchange during the project execution with the GC (Başaran et al., 2023). Ng & Tang (2008) partially measured this sub-criterion through the rate of attendance at site meetings and prompt responses to contractor correspondence. SCC1 can be quantitatively measured using Equations 3.11, 3.12, 3.13, and 3.14.

$$\text{SCC1-1} = \frac{\text{Number of RFI's + official letters (sent + responded) from SC}}{\text{Number of official letters (sent + responded) from GC}} \quad (3.11)$$

$$\text{SCC1-2} = \frac{\text{Number of attendance meetings by SC}}{\text{Number of meetings that SC should be attended as contract}} \quad (3.12)$$

$$\text{SCC1-3} = \frac{\text{Number of submitting documents by SC for closing project}}{\text{Number of documents as contract for closing project}} \quad (3.13)$$

$$\text{SCC1} = 0.33\ \text{SCC1} - 1 + 0.33\ \text{SCC1-2} + 0.33\ \text{SCC1-3} \quad (3.14)$$

Next, the ability to flexibly respond to changes in the project is the second sub-criterion (SCC2). In other words, when a change is requested by the client or GC in the production process, the subcontractor's reactions and analytical skills are assessed (Hanák & Nekardová, 2020; Başaran et al., 2023). SCC2 is quantitative input and can be measured using Equations 3.15.

$$\text{SCC2} = \frac{\text{Number of accepted changes by SC}}{\text{Number of changes required by GC}} \times 100\% \quad (3.15)$$

Lastly, ensuring adherence to coordination with other subcontractors and on-site employees guarantees smooth collaboration without causing delays. This sub-criterion (SCC3) is measured by determining the number of incidents, complaints, or conflicts reported by GC engineers.

3.3.4.7 Leadership Criterion (LC):

Effective leadership is indispensable in every construction project, with leadership behavior serving as a crucial variable that significantly influences project management success (Gharehbaghi & McManus, 2003). There is an increasing necessity to scrutinize and assess social structures, individual perspectives, and personal characteristics, as they can also exert an impact in collaborative endeavors aimed at achieving common objectives (Başaran et al., 2023).

Limsila and Ogunlana (2008) defined the style leadership and concluded that transformational leadership style is better than transactional leadership style because the transformational leadership style has significant relationships with work quality and creativity in problem solving of workforces.

The leadership criterion (LC) is assessed through a qualitative evaluation of three sub-criteria (Başaran et al., 2023). First, leadership is evaluated based on its focus on fostering collaboration and facilitating the development of subordinates (LC1). Secondly, commitment to the project is gauged by assessing the extent of effort dedicated to resolving issues with the GC (LC2). Lastly, the ability to conduct short- and long-term assessments and anticipate opportunities and threats is considered as an indicator of effective leadership (LC3).

LC1, LC2, and LC3 are considered subjective evaluations because the GC team's opinions are the source of evaluation. To measure LC, the rating scale method is implemented with a scale of 1 to 10. This method provides a simple and intuitive way to quantify qualitative data (Nassar, 2005). To obtain the final aggregated value, the weighted average with the expert calibration method (WAEC) is utilized.

WAEC is a robust method for aggregating expert opinions. By assigning appropriate weights to each GC team's rating based on their expertise, the evaluation is considered fair and more accurate.

Furthermore, WAEC helps to reduce bias by assigning more weight to the opinions of more experienced or reliable GC teams; this method reduces the impact of less informed opinions (Shahar, 2017). Additionally, the final aggregated value is more likely to be accurate since it reflects the insights of the most knowledgeable GC teams.

3.3.4.7.1 Implement the Rating Scale and Weighted Average with GC team Calibration Method:

3.3.4.7.1.1 Step 1: Develop a Rating Scale

- Create rating scale: Develop a rating scale from 1 to 10 for each , where 1 represents the lowest level of performance and 10 represents the highest level.

3.3.4.7.1.2Step 2: Gather GC Team Opinions

- Collect GC team ratings: Obtain ratings from a panel of GC team for each criterion using the developed scale.

$$R_{ij}\text{=Rating given by GC team i for criterion j}$$

3.3.4.7.1.3 Step 3: Assign Weights to GC Team

- Assign GC team weights: Evaluate and assign weights to each GC team based on their expertise and experience.

$$W_i\text{=Weight assigned to GC team i from 1 to 10}$$

3.3.4.7.1.4 Step 4: Calculate Weighted Ratings

- Calculate weighted ratings by utilizing Equation 3.16.

$$W\,R_j = \sum_{i=1}^{n} (R_{ij} \times W_i) \tag{3.16}$$

Where WR_j is the weighted rating for criterion j, R_{ij} is the rating given by GC team i for criterion j, and Wi is the weight of GC team i.

3.3.4.7.1.5 Step 5: Sum the Weights

- Sum the weights by utilizing Equation 3.17.

$$TW = \sum_{i=1}^{n} (W_i) \tag{3.17}$$

Where TW is the total weight.

3.3.4.7.1.6 Step 6: Calculate the Weighted Average (Final Aggregated Value)

- Calculate the final aggregated value by using Equation 3.18.

$$W\,A_j = \sum_{i=1}^{n} (W\,R_j \div TW) \tag{3.18}$$

3.3.4.8 Pricing and Experience Criterion (PEC):

The PEC is divided into two categories: the pricing category, which encompasses two sub-criteria. Firstly, the tender price, defined as the SC's bid offer to commence the construction project (El-Mashaleh, 2009; Pallikkonda et al., 2019). Increasing the tender price will negatively influence the selection of the SC. Therefore, it is considered a quantitative cost input.

Secondly, financial capacity encompasses four factors (Eom et al., 2008). Firstly, profitability (PI) refers to the ability of a subcontractor to generate earnings relative to its expenses and investments (Akintoye & Skitmore, 1991). Next, the growth (GI) indicates to the expansion of a subcontractor's business over time, typically measured in terms of revenue. Third, activeness (AI) refers to the level of engagement and involvement of a subcontractor in pursuing opportunities, adapting to market changes, and proactively addressing challenges. Lastly, stability (SI) defines as the ability of a subcontractor to maintain consistent performance and withstand external shocks or disruptions without significant negative impact. These factors are considered quantitative beneficial inputs and are measured using Equations 3.19, 3.20, 3.21, 3.22, 3.23, and 3.24 as proposed by Eom et al. (2008).

$$\text{PI} = \frac{\text{Operation Profit (SC)}}{\text{Revenue}} \times 100\% \tag{3.19}$$

$$\text{GI} = \frac{\text{Current Financial Year Revenue (SC)}}{\text{Previous Financial Year Revenue-1}} \times 100\% \tag{3.20}$$

$$\text{AI} = \frac{\text{Current Financial Year Revenue (SC)}}{\text{Current Financial Year Total Capital}} \times 100\% \tag{3.21}$$

$$\text{SI-1} = \text{3 year average annual revenue} \tag{3.22}$$

$$\text{SI-2} = \text{credit rating score} \tag{3.23}$$

$$\text{PEC2} = 0.2\times \text{PI} + 0.2\times \text{GI} + 0.2\times \text{AI} + 0.2\times \text{SI-1} + 0.2\times \text{SI-2} \tag{3.24}$$

The experience category includes the experience of similar works, assessed through the number of similar projects that the SC has accomplished, considering the volume and nature of the works. Next is experience in the construction industry, representing the number of years of experience in construction. The experience category is a quantitative beneficial input.

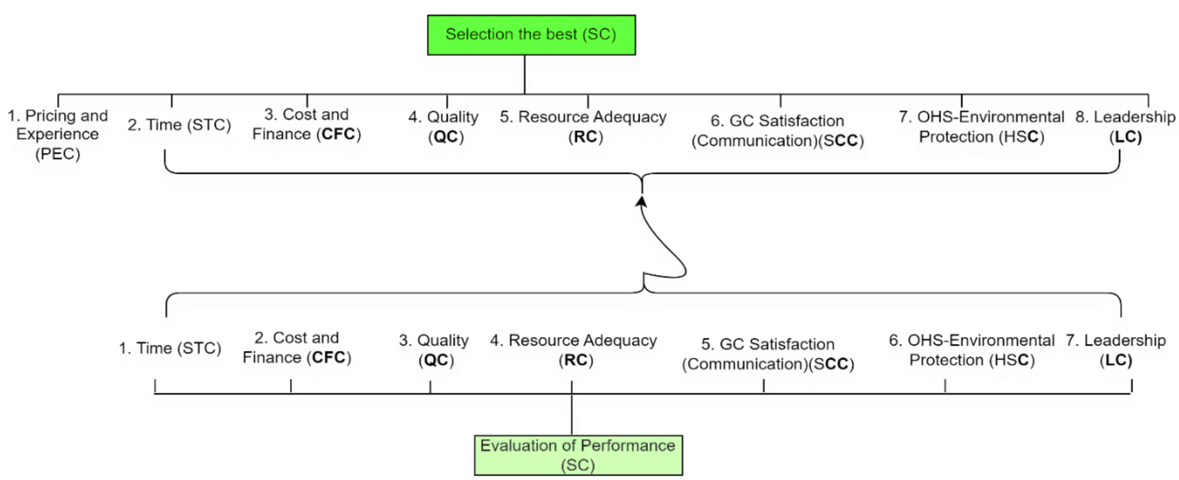


Figure 3.9. Relationship between Evaluation Indices and Selection Criteria

Table 3.9. Short List of Criteria and Sub-criteria

Sr.N	Criteria	Sub- Criteria	Equations
1	Pricing and Experience Criterion (PEC)	The SC's bid offer to commence the construction project (PEC1)	No Equation
		Financial capacity (PEC2)	$PI = \frac{\text{Operation Profit (SC)}}{\text{Revenue}} \times 100\%$
			$GI = \frac{\text{Current Financial Year Revenue (SC)}}{\text{Previous Financial Year Revenue-1}} \times 100\%$
			$AI = \frac{\text{Current Financial Year Revenue (SC)}}{\text{Current Financial Year Total Capital}} \times 100\%$
			SI-1 = 3 year average annual revenue
			SI-2 =credit rating score
		Experience of similar works (PEC3)	Number of years
		Experience in the construction industry (PEC4)	Number of years
2	Time Criterion (STC)	Compliance and flexibility of project schedule (STC)	$(STC) = \frac{\text{Revised Contract Period (RC)}}{\text{Construction Time (CT)}}$
3	Cost and Finance Criterion (CFC)	Ensuring subcontractor budget compliance (CFC1)	$FC1 = \frac{\text{SC Financial Claims (FC)}}{\text{Revised Contract Value (RV)}}$
		Adaptability and invoice timeliness (CFC2)	Determining the frequency of SC submissions of invoices to the GC prior to the contractual dates

		Cost -saving (CFC3)	$\text{Cost Saving (CFC3)} = \frac{\sum \text{Cost Saving (Item or Task)}}{\sum \text{Contractual Cost (Item or Task)}}$
		Timely payment from SC (CFC4)	Assessing the frequency of delayed payments (workers and material suppliers) throughout the project.
4	Quality Criterion (QC)	Upholding material quality (QC1)	Assessing the number of non-conformance reports (NCRs) regarding materials.
		Level of workmanship (QC2)	Determining the number of non-conformance reports (NCRs) related to work requiring rework.
		The quality of the end product (QC3)	Assessing the number of non-conformance reports (NCRs) related to finished production
5	Resource Adequacy Criterion (RC)	Technical competence (RC1)	$\text{RC1-1} = \frac{\text{Number of technicians and technical Certificates(SC)}}{\text{Number of required technicians and certificates contract}}$
			$\text{RC1-2} = \frac{\text{Number of specialized equipment (SC)}}{\text{Number of specialized equipment according contract}}$
			RC1-3 =Number of software issues encountered throughout the project
		Materials available (RC2)	$\text{RC2} = \frac{\text{Total of days of delay in the delivery of materials}}{\text{Revised Contract Period (RC)}} \times 100\ \%$
6	Occupational Health and Safety and Environmental Protection Criterion (HSC)	Adhere to the health and safety regulations (HSC1) HSC1= 0.25 × HSC1-1+ 0.25 × HSC1-2+ 0.25 × HSC1-3+ 0.25 × HSC1-4	HSC1-1= Number of incidents of damaging utilities, works or materials by SC workers during project
			HSC1-2= Number of fatal incidents by SC workers during project
			HSC1-3= Number of reportable safety violation and injuries during project
			HSC1-4= Number of prosecutions made by Labor Department or Union during project
		Environmental awareness (HSC2)	Determining the number of warnings issued by the GC site officer
7	General Contractor Satisfaction	Effective communication	$\text{SCC1-1} = \frac{\text{Number of RFI's + official letters (sent + responded) from SC}}{\text{Number of official letters (sent + responded) from GC}}$
			$\text{SCC1-2} = \frac{\text{Number of attendance meetings by SC}}{\text{Number of meetings that SC should be attended as contract}}$

	(Communication) Criterion (SCC)	compliance with GC (SCC1) SCC1 = 0.33 ×SCC1-1+0.33 ×SCC1-2+0.33× SCC1-3	$\text{SCC1-3} = \frac{\text{Number of submitting documents by SC for closing project}}{\text{Number of documents as contract for closing project}}$
		Adaptability in Responding to Project Changes (SCC2)	$\text{SCC2} = \frac{\text{Number of accepted changes by SC}}{\text{Number of changes required by GC}} \times 100\%$
		Effective communication with other (SCC3)	Determining the number of incidents, complaints, or conflicts reported by GC engineers
8	Leadership Criterion (LC)	Collaborative Leadership(LC1)	Implementing the rating scale and weighted average with GC team calibration method
		Dedication (LC2)	Implementing the rating scale and weighted average with GC team calibration method
		Effective leadership (LC3)	Implementing the rating scale and weighted average with GC team calibration method

Chapter 4: Development of the Computerized Model for Performance Evaluation and Selection of Subcontractors

4.1 Introduction

The assessment of the performance of subcontractors (SCs) upon completion of a project and the selection process for the best SC for a new project require the determination of significant criteria, including sub-criteria and their respective weights. Certainly, the process of evaluating and selecting SCs demands precision and foresight to ensure optimal project outcomes.

The development of a computerized model for performance evaluation and SC selection represents a significant advancement in project management practices. In Chapter 3, the criteria and sub-criteria are identified and formulated based on scientific studies and expert review.

In this chapter, the weights of criteria and sub-criteria are assigned, and an automated analytical model is developed using formulas for assessing subcontractors upon project completion. This data is then utilized to select the best subcontractor for a new project.

4.2 Calculating Weights of Criteria and Sub-Criteria Using Monte Carlo and AHP

4.2.1 Background

The Analytic Hierarchy Process (AHP), pioneered by T. L. Saaty in 1980, stands as a valuable decision-making tool for effectively managing and resolving multiple criteria decision problems (Momani & Ahmed, 2011). By engaging in a structured process of pairwise comparisons of the criteria, facilitated by the decision maker by using (*3.4*.2, the Analytic Hierarchy Process determines the weights for the evaluation criteria (Saaty & Vargas, 2012; Banzon et al., 2016).

In the other hand, Monte Carlo Simulation is a mathematical technique that allows people to account for the risks involved in a quantitative analysis and decision making (Banzon et al., 2016).

According to Banzon et al. (2016), Numerous studies globally have utilized the conventional Analytic Hierarchy Process (AHP) to address multi-criterion decision challenges. However, relying solely on the conventional AHP presents limitations as it provides only a singular point estimate for preferences. This singular approach heightens the risk of inaccurate decision-making and poses challenges to achieving precise decisions. To mitigate or ideally eliminate these inaccuracies, several studies have advocated for the integration of the Monte Carlo-Analytic Hierarchy Process (MC-AHP) hybrid. This hybrid approach aims to identify the most efficient decision across various criteria by representing the assessment of each criterion as random variables within a distribution.

4.2.2 Implementing Monte Carlo and AHP (MC-AHP) Hybrid

Situated below is Figure 4.1, which outlines the steps describing the hybrid Monte Carlo and Analytic Hierarchy Process (MC-AHP) method for weighting criteria and sub-criteria. This hybrid approach was developed using the Python programming language.

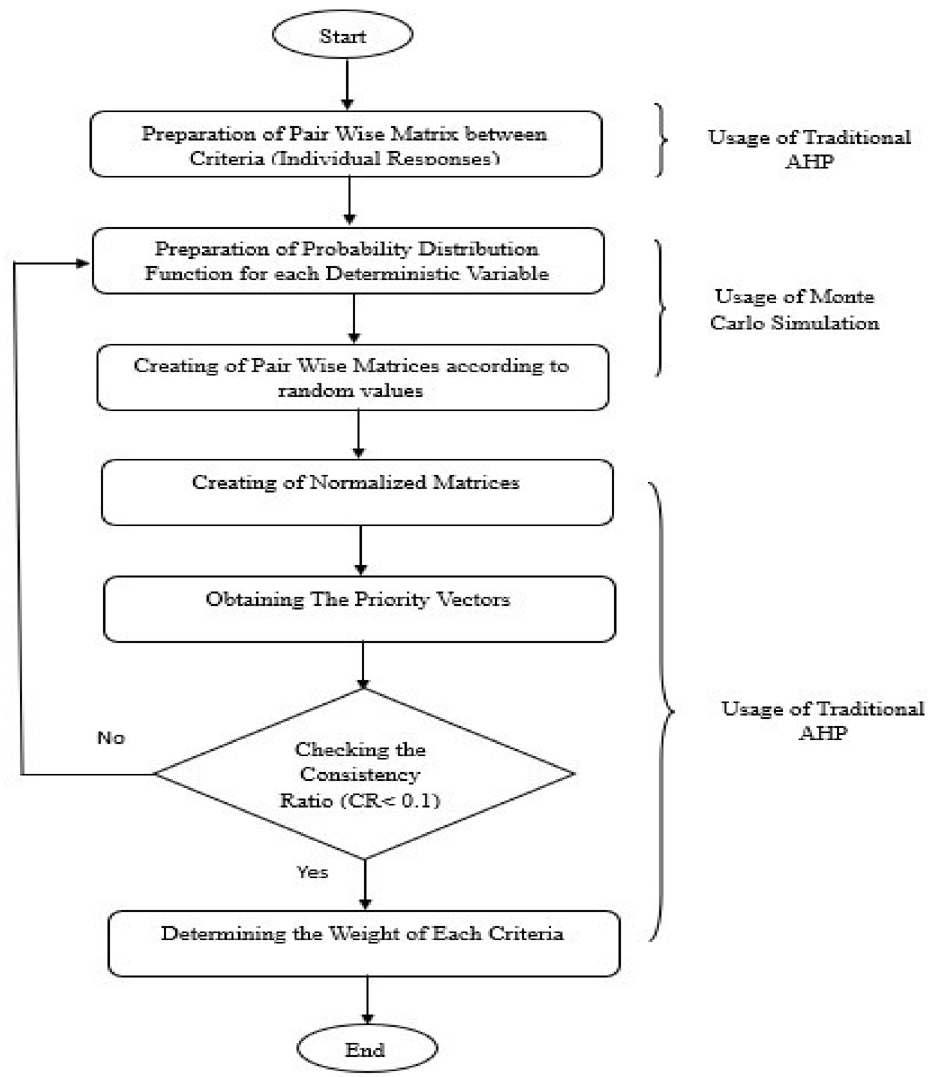


Figure 4.1. Steps of (MC- AHP) Hybrid for Weighting Criteria and Sub-Criteria

4.2.2.1 Step 01: Generate a Pairwise Comparison Matrix for *m* experts

The data collection process involves gathering input from experts and assessing the importance of each criterion and sub-criterion relative to one another through pairwise comparisons, utilizing a scale ranging from 1 to 9 to express the strength of preference or importance (De Felice & Petrillo, 2023). This process is repeated for all pairs of criteria and sub-criteria, incorporating each expert opinion.

In order to reduce bias and facilitate expert engagement in creating pairwise comparisons, range judgment is employed instead of point judgment, particularly with the standard nine-level comparison scale, as illustrated in Table 4.1.

The comparison matrix (**M**) is formed from the comparison matrix elements denoted as $c_{i,j}$. .Equation 4.1 is used to define $c_{i,j}$.

$$c_{i,j} = Wi / Wj \quad (i, j = 1,2,3,\ldots n) \tag{4.1}$$

where $c_{i,j}$ refers to the importance degree of element i relative to element j under evaluation criteria and n denotes the number of criteria compared

Table 4.1. standard nine-level comparison scale

Intensity of Importance	Definition	Range
1	Equal Importance	0 - 10
2	Week	11 - 20
3	Moderate Importance	21 - 30
4	Moderate Plus	31 - 40
5	Strong Importance	41 - 50
6	Strong Plus	51 - 60
7	Very Strong	61 - 70
8	Very Very Strong	71 - 80
9	Extreme Importance	81 - 90

$\mathbf{M}$ (expert $_{1,2,\ldots\, m}$) =

	C1	C2	C…	Criterion n (C_n)
C1	1	W1/W2	…..	W1/W_n
C2	$C_{2,1}$= W2/W1	1	…..	W2/W_n
C…	…..	…..	1	…..
Criterion n (C_n)	$C_{n,1}$= W_n/W1	W_n/W2	…..	1

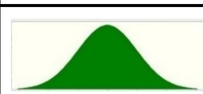
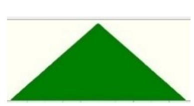
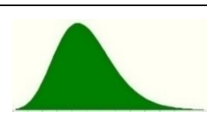
4.2.2.2 Step 02: Create Probability Distribution

4.2.2.2.1 Introduction

A Probability Distribution describes how the values of a random variable are spread out or distributed across the range of possible values (Wild, 2006) .

In Monte Carlo simulations, probability distributions are essential for modeling and analyzing complex systems and processes that involve uncertainty and variability.

One of the primary purposes of using probability distributions in Monte Carlo simulations is to generate a large number of random samples for each input variable. These samples are drawn from the defined probability distributions, ensuring that the simulation accurately reflects the true variability and stochastic nature of the system being modeled.
Kotulski et al., (2010) and Wanke et al., (2016) and Thomopoulos et al., (2018) explained detailly characteristics of distribution and parameters and shape and use cases as illustrated in Table 4.2.
Table 4.2. various probability distribution

Distribution	**Parameters**	**Shape**	**Use Cases**
Normal	Mean (μ), Standard Deviation (σ)		Used in natural and social sciences to represent real-valued random variables.
Uniform	Minimum(a), Maximum (b)		Used in simulations, random sampling, and scenarios where all outcomes are equally likely. Examples: rolling a fair die.
Triangular	Minimum (a), Maximum (b), Mode (c)		Used in project management and risk analysis where only minimum, maximum, and most likely values are known. Examples: cost and time estimates.
Lognormal	Location (μ), Scale (σ)		Used to model non-negative skewed data. Examples: stock prices, income distribution, time to failure of mechanical systems.

4.2.2.2.2 Probability Distribution

Based on experts' opinions, each matrix element ($c_{i,j}$) has *m* values. In other words, each expert opinion creates a pairwise comparison matrix. According to Gorripati et al. (2022), Monte Carlo simulation employs various probability distribution functions to augment inputs from various experts. These $c_{i,j}$ values are then used to form a probability distribution. According to Ataei et al. (2013), the number of distribution function is obtained from Equation 4.2.

$$N=\frac{n\,(n-1)}{2} \tag{4.2}$$

In order to determine the fit distribution of each set of ci,j values, Kolmogorov-Smirnov (KS) is implemented (Schaefer et al., 2019). The Kolmogorov-Smirnov test is a convenient method for investigating whether two underlying univariate probability distributions can be regarded as undistinguishable from each other or whether an underlying probability distribution differs from a hypothesized distribution (Olea et al., 2009).

KS test defines the maximum absolute difference between the empirical cumulative distribution function (ECDF) of the sample and the cumulative distribution function (CDF) of the reference distribution as a measure of disagreement (Lopes et al., 2007). The parameters of the distribution are considered when determining this difference.

Furthermore, the p-value plays a crucial role in determining whether to reject the null hypothesis. In other words, if the p-value is larger than the level of significance (α), the null hypothesis (H_0) is accepted (Olea et al., 2009). For instance, if the p-value is 0.08 and α is 0.05, H_0 is not rejected, suggesting there is no significant difference between the distributions of the two samples.

Given the diversity of expert opinions, the Kolmogorov-Smirnov (KS) test has been implemented using Python to determine the best-fit distribution. It has been observed that three types of distributions -Normal (ND), Triangular (TD), and Lognormal (LD)- are suitable fits for all sets of ci,j. It is important to note that the normal distribution (ND) extends infinitely in both directions, meaning it can generate negative values, even when the actual data (such as expert opinions) should only be positive. Negative values can have a high probability in a normal distribution, particularly when the mean is close to zero or the standard deviation is large. Despite this, Gorripati et al. (2022) and Diwakar (2019) state that ND, triangular distribution (TD), and lognormal distribution (LD) can be used in implementing MC-AHP, considering the minimum and maximum values of ci,j as informed by expert opinions.

The utilization of ND, TD, and LD distributions is accomplished by generating a set of random values (samples) that adhere to the characteristics of the specified distribution. A total of 100,000 random values have been generated separately using parameters for ND, TD, and LD. This means generating 100,000 values for each $c_{i,j}$.

4.2.2.3 Step 03: Re-generate a Pairwise Comparison Matrix

In this step, a pairwise comparison matrix is regenerated according to step 01 using 100,000 random values for each $c_{i,j}$. As a result, a total of 100,000 matrices are formed.

4.2.2.4 Step 04: Creating of Normalized Matrices

After generating m pairwise comparison matrices, the subsequent step entails normalizing each matrix. This process involves dividing every cell ($c_{i,j}$) by the sum of its respective column values, according to Equation 4.3.

$$x_{i,j} = c_{i,j} / \sum c_{i,j} \tag{4.3}$$

4.2.2.5 Step 05: Obtaining The Priority Vectors (Weights)

Average the normalized values across each rows to obtain the priority vector ($\ddot{y}_i$) for each element. This step has been implemented for 10,000 matrices utilizing Equation 4.4.

$$\ddot{y}_i = \frac{\sum x_{i,j}}{n} \tag{4.4}$$

4.2.2.6 Step 06: Checking for Consistency

Step 06 involves checking the consistency of the pairwise comparisons made by the decision-makers (Saaty, 1987). This step is crucial because it ensures that the judgments provided do not contain unacceptable levels of inconsistency, which can undermine the reliability of the decision-making process. The breakdown of how to check for consistency is as follows:

4.2.2.6.1 Calculate Principal Eigenvalue (λ_{max})

The process of calculating the eigenvalue (λ_{max}) involves several steps. First, multiply the pairwise comparison matrix (M) by the priority vector to obtain a new vector. Then, divide each element of the new vector by the corresponding element of the priority vector. Finally, the average of these eigenvalue estimates is λ_{max}, as shown in Equation 4.5.

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n} (M * \ddot{y})_i / \ddot{y}_i \tag{4.5}$$

4.2.2.6.2 Calculate the Consistency Index (CI):

The calculation of the consistency index using the principal eigenvalue (λmax) of the matrix. CI has been calculated by Equation 4.6.

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \tag{4.6}$$

Where:

- n is the number of criteria or elements being compared.

4.2.2.6.3 Determine the Random Consistency Index (RI)

RI is an average consistency index derived from a large number of randomly generated pairwise comparison matrices. RI values help determine if the level of inconsistency in your judgments is acceptable or if it might be due to a random error.

Table 4.3 shows the commonly used RI values for matrices of order 1 to 10, based on a large number of simulations.

Table 4.3. RI values (Saaty, 1987)

Size of Matrix	1	2	3	4	5	6	7	8	9	10
RI	0.0	0.0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

4.2.2.6.4 Calculate the Consistency Ratio (CR)

The consistency ratio (CR) compares the consistency index (CI) with the random consistency index (RI) to assess the consistency of the matrix. A CR of 0.1 (10%) or less is generally considered acceptable. If the CR exceeds 0.1, the pairwise comparisons may need to be reviewed and adjusted to reduce inconsistency. The CR is calculated using Equation 4.7.

$$CR = \frac{CI}{RI} \tag{4.7}$$

4.2.2.7 Step 07: Develop the Weight of Each Criteria

In this step, any matrix among the 10,000 matrices that does not comply with the condition of the consistency ratio (CR) is not considered. The final weight of each criterion is calculated by taking the mean of the weights resulting from the acceptable matrices that meet the CR condition (Banzon et al., 2016).

4.2.3 Implementing Traditional AHP

Referring to Figure 4.1, the AHP is implemented using steps 01, 04, 05, 06, and 07. According to Schaefer et al. (2019), in the traditional AHP method, the final weights are determined by averaging the weights obtained from each expert.

4.2.4 Application of All Steps Using Python for MC-AHP

The data was collected from three experts who represent a general contractor. These experts have extensive experience in the construction industry within Canada.

All steps of MC-AHP are coded in Python to automate the entire process. Three Python files are developed for the Normal (ND), Triangular (TD), and Lognormal (LD) distributions. After inputting the type of distribution, number of experts, number of criteria, number of iterations, and experts' opinions, the final outputs include a plot of the probability density of the chosen distribution, a histogram of frequencies for each criterion, pairwise comparison matrices, the weights of the criteria, and a chart of ranking criteria. The Figure 4.2 shows a pseudocode for MC-AHP steps.

```
In [ ]: MC-AHP Steps

1. Import necessary libraries

2. Get expert opinions:
    - Input: number of criteria, number of experts
    - Output: list of expert opinions
    - For each pair of criteria, get and validate opinions from each expert

3. Generate comparison matrices:
    - Input: number of criteria, number of samples, expert opinions, distribution type
    - Output: list of valid matrices, count of valid matrices
    - For each sample:
        - Create a matrix with ones
        - For each pair of criteria, generate a random sample based on the distribution type
        - Update the matrix with the sample and its reciprocal
        - Check if the matrix is consistent, add to list if valid

4. Calculate weights using AHP:
    - Input: matrix
    - Output: weights, consistency index
    - Calculate principal eigenvector and maximum eigenvalue
    - Normalize the principal eigenvector to get weights

5. Check consistency ratio:
    - Input: matrix
    - Output: whether the ratio is satisfied, CRI value
    - Calculate weights and consistency index
    - Calculate CRI and check if it is satisfied

6. Plot distributions:
    - Input: distribution parameters
    - Output: none
    - Plot the probability density function for normal, triangular, and lognormal distributions

7. Main function:
    - Get user inputs: number of criteria, number of experts, number of samples, distribution type
    - Get expert opinions
    - Generate comparison matrices
    - For each valid matrix, print it, check consistency, and calculate weights if consistent
    - Plot histograms of weights for each criterion
    - Calculate and print mean and standard deviation of weights
    - Plot distributions for each pair of criteria
    - Plot final weights of criteria in a bar chart

8. Run main function if the script is executed directly
```

Figure 4.2. Pseudocode for MC- AHP Steps

4.2.4.1 Criteria for Selection the Best Subcontractor

Firstly, Figure 4.3 illustrates the three pairwise comparison matrices provided by three experts.

	PEC	STC	CFC	QC	RC	SCC	HSC	LC
PEC	1	2	2	3	4	4	1/3	3
STC	1/2	1	2	1/3	5	4	1/2	3
CFC	1/2	1/2	1	1/3	3	3	1/2	2
QC	1/3	3	3	1	4	4	1/2	3
RC	1/4	1/5	1/3	1/4	1	1	1/3	2
SCC	1/4	1/4	1/3	1/4	1	1	1/3	2
HSC	3	2	2	2	3	3	1	3
LC	1/3	1/3	1/2	1/3	1/2	1/2	1/3	1

Figure 4.3.1 Expert 01

	PEC	STC	CFC	QC	RC	SCC	HSC	LC
PEC	1	2	2	2	2	2	1/3	2
STC	1/2	1	2	1/5	4	4	1/4	3
CFC	1/2	1/2	1	1/3	2	2	1/4	2
QC	1/2	5	3	1	4	3	1/4	3
RC	1/2	1/4	1/2	1/4	1	1	1/4	2
SCC	1/2	1/4	1/2	1/3	1	1	1/4	2
HSC	3	4	4	4	4	4	1	2
LC	1/2	1/3	1/2	1/3	1/2	1/2	1/2	1

Figure 4.3.2 Expert 02

	PEC	STC	CFC	QC	RC	SCC	HSC	LC
PEC	1	4	7	2	2	3	1	7
STC	1/4	1	5	1/4	1/4	1/4	1/7	4
CFC	1/7	1/5	1	1/7	1/7	1/6	1/6	2
QC	1/2	4	7	1	6	1/2	1/6	4
RC	1/2	4	7	1/6	1	1/6	1/3	2
SCC	1/3	4	6	2	6	1	1/3	2
HSC	1	7	6	6	3	3	1	2
LC	1/7	1/4	1/2	1/4	1/2	1/2	1/2	1

Figure 4.3.3 Expert 03

Figure 4.3. Pairwise Comparison Matrices

Next, three types of distributions-Normal (ND), Triangular (TD), and Lognormal (LD) are employed. Figure 4.4, Figure 4.5., and Figure 4.6 show examples for ND, TD, and LD, respectively.

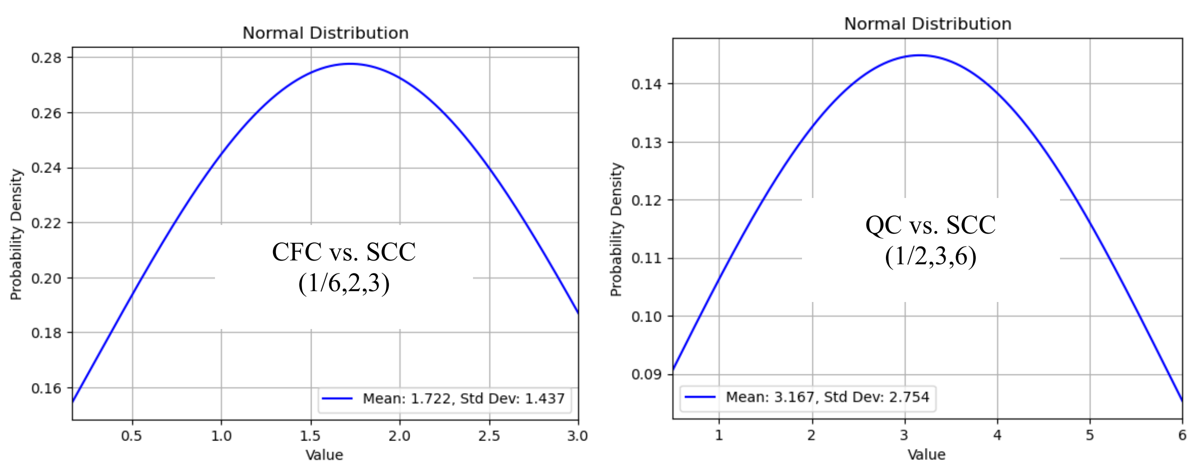


Figure 4.4. Normal Distribution (ND) for Three Experts

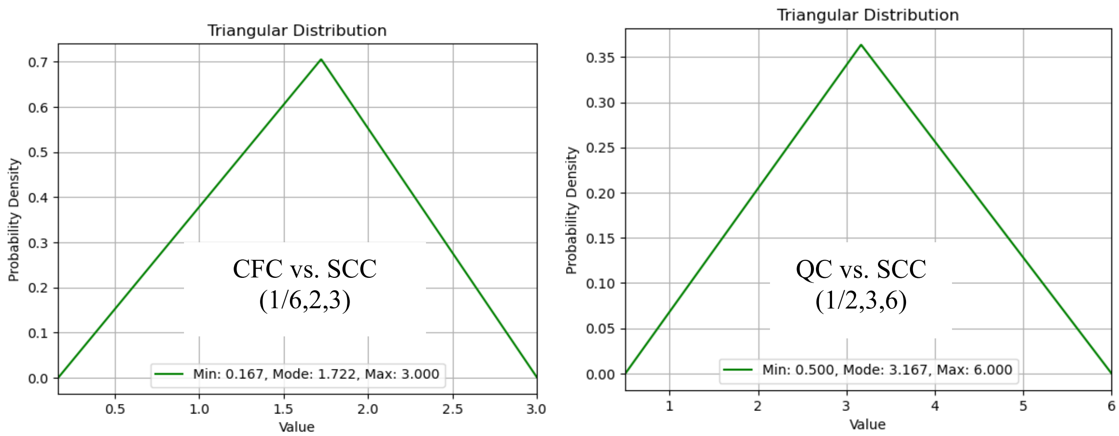


Figure 4.5.Triangular Distribution (TD) for Three Experts

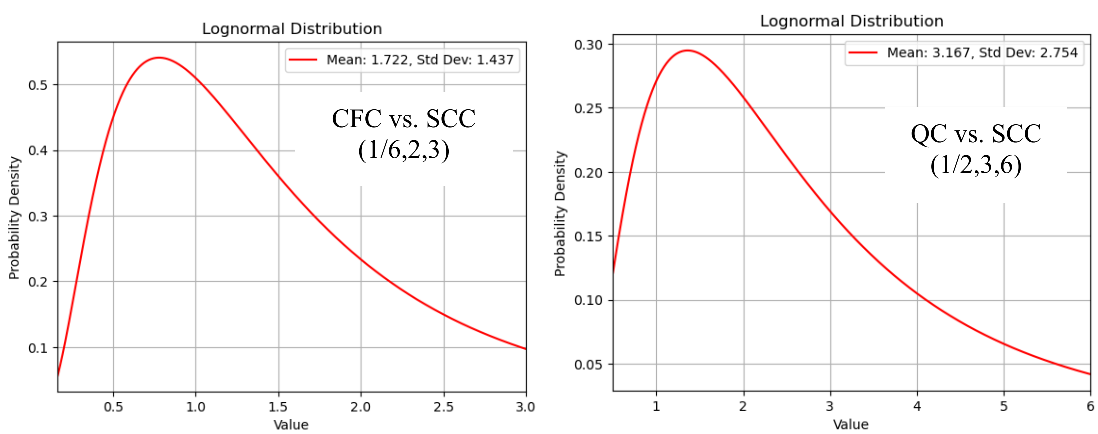


Figure 4.6. Lognormal Distribution (LD) for Three Experts

Next, 100,000 random samples for each value have been generated using ND, TD, and LD. The number of accepted pairwise comparison matrices (CRI < 0.1) is 7,406 out of 100,000 from ND, 74,743 out of 100,000 from TD, and 23,046 out of 100,000 from LD. Figure 4.7 illustrates the last accepted matrix for ND, TD, and LD.

```
Pairwise comparison matrix for Sample 7406:
[[1.         2.         3.25049107 2.92265841 3.20488553 3.07723777
  0.83614457 5.84112443]
 [0.5        1.         3.11837408 0.25425593 1.06232855 0.83533758
  0.36350208 3.29227053]
 [0.30764582 0.32067994 1.         0.14285714 0.40995706 1.98797551
  0.31374354 2.78254187]
 [0.34215425 3.93304496 7.         1.         4.35595912 3.54125702
  0.32040389 3.22873529]
```

```
 [0.31202362 0.94132837 2.43927988 0.22957057 1.         0.7452148
  0.33333333 3.2230872 ]
 [0.32496676 1.19712081 0.50302431 0.2823856  1.34189498 1.
  0.28833505 2.        ]
 [1.19596543 2.75101589 3.18731661 3.12106069 3.         3.46818743
  1.         2.        ]
 [0.17119991 0.30374175 0.35938363 0.30971879 0.31026154 0.5
  0.5        1.        ]]
CRI Satisfied: True, CRI: 0.0988+0.0000j, RI: 1.41, Consistency Index: 0.1
393+0.0000j
Weights for the matrix: 0.2311, 0.0888, 0.0598, 0.2026, 0.0760, 0.0652, 0.
2357, 0.0407

Pairwise comparison matrix for Sample 74743:
[[1.         2.60056704 3.23444691 2.29155315 3.26828853 3.15069359
  0.95849656 3.42843073]
 [0.38453152 1.         2.92559911 0.27717129 4.76541908 1.93073523
  0.28510744 3.12834489]
 [0.30917187 0.34181033 1.         0.28305838 1.03808579 0.80927838
  0.3349755  2.3503462
 [0.43638525 3.60787733 3.53284009 1.         4.2873742  1.306153
  0.39449635 3.4369148 ]
 [0.30597054 0.20984513 0.96331152 0.233243   1.         0.93307936
  0.28196991 2.55417065]
 [0.31739043 0.51793741 1.23566874 0.76560709 1.0717202  1.
  0.30234338 2.35119015]
 [1.04330056 3.50744969 2.98529292 2.53487771 3.54647767 3.3074976
  1.         2.11239914]
 [0.29167864 0.31965785 0.42546922 0.29095862 0.39151652 0.42531651
  0.47339538 1.        ]]
CRI Satisfied: True, CRI: 0.0723+0.0000j, RI: 1.41, Consistency Index: 0.0
91020+0.0000j
Weights for the matrix: PEC(0.2241),STC (0.1224),CFC (0.0607),QC (0.1752),
RC(0.0580),SCC (0.0758), HSC(0.2386),LC (0.0453)

Pairwise comparison matrix for Sample 23046:
[[1.         2.61045392 7.         2.67177306 2.79863516 2.80587409
  0.37435329 5.64493306]
 [0.38307514 1.         3.14566981 0.26178945 2.06443576 0.82797447
  0.16906331 3.01968994]
 [0.14285714 0.31789732 1.         0.33333333 2.15194143 1.12726084
  0.24311087 2.        ]
 [0.37428329 3.81986361 3.         1.         4.67435721 1.93909645
  0.25817727 3.55483438]
 [0.35731703 0.48439386 0.46469666 0.21393316 1.         0.6899989
  0.33333333 2.16336377]
   [0.17715002 0.33115983 0.5        0.28130706 0.46224311 0.46927228
  0.36429756 1.        ]]
CRI Satisfied: True, CRI: 0.0831+0.0000j, RI: 1.41, Consistency Index: 0.1
172+0.0000j
Weights for the matrix: 0.2229, 0.0841, 0.0593, 0.1534, 0.0540, 0.0726, 0.
3136, 0.0401
```

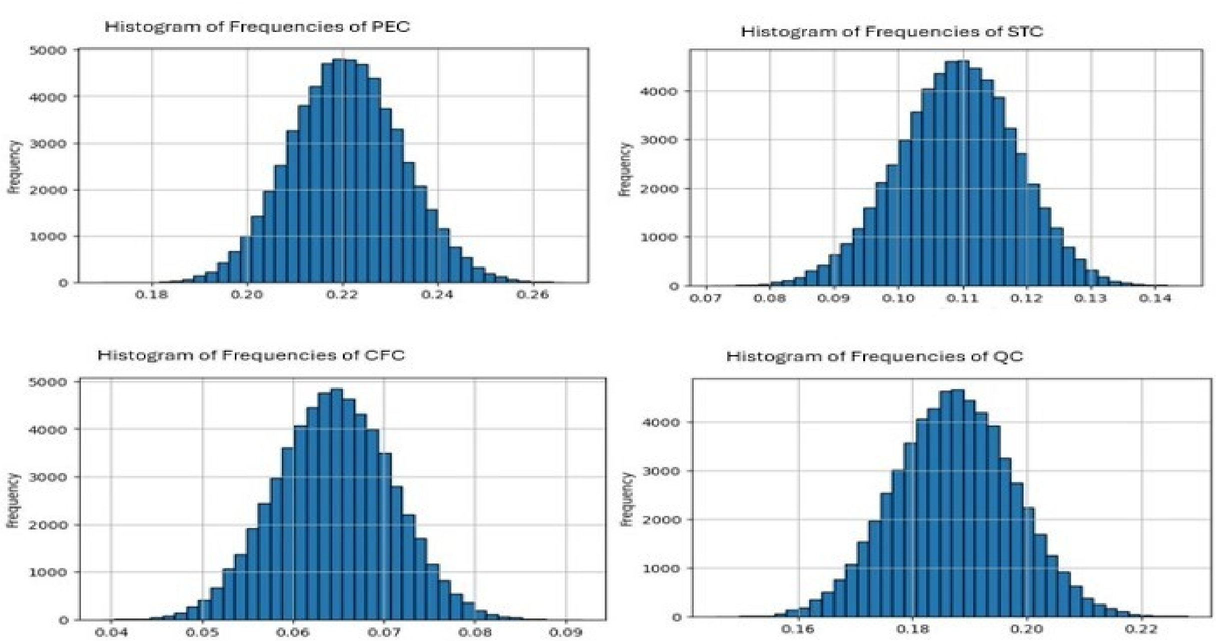
Figure 4.7. Last Pairwise Comparison Matrix for ND, TD, and LD

Lastly, the final weights have been calculated by taking the average of weights derived from the accepted matrices, as shown in Table 4.4.

Table 4.4. Weights of Criteria for Selecting SC

Criteria	MC-AHP						AHP			
	ND		TD		LD		Expert1	Expert2	Expert3	Average
	Weight	Std Dev	Weight	Std Dev	Weight	Std Dev	Weight	Weight	Weight	Weight
PEC	0.215	(±0.012)	0.220	(±0.006)	0.203	(±0.020)	0.197	0.138	0.223	0.186
STC	0.109	(±0.016)	0.109	(±0.005)	0.102	(±0.014)	0.141	0.124	0.062	0.109
CFC	0.068	(±0.011)	0.064	(±0.004)	0.064	(±0.010)	0.098	0.084	0.029	0.070
QC	0.189	(±0.018)	0.187	(±0.006)	0.184	(±0.018)	0.181	0.175	0.142	0.166
RC	0.057	(±0.008)	0.064	(±0.002)	0.059	(±0.008)	0.051	0.067	0.091	0.070
SCC	0.065	(±0.014)	0.056	(±0.002)	0.072	(±0.012)	0.052	0.062	0.147	0.087
HSC	0.252	(±0.027)	0.256	(±0.008)	0.271	(±0.028)	0.231	0.296	0.258	0.262
LC	0.041	(±0.003)	0.040	(±0.001)	0.043	(±0.003)	0.045	0.050	0.043	0.046
Total	1.000		1.000		1.000		1.000	1.000	1.000	1.000

To show the distribution of weights for each criterion and to analyze and interpret the behavior of each criterion, histograms of frequencies for ND, TD, and LD have been plotted, as illustrated in Figure 4.8.



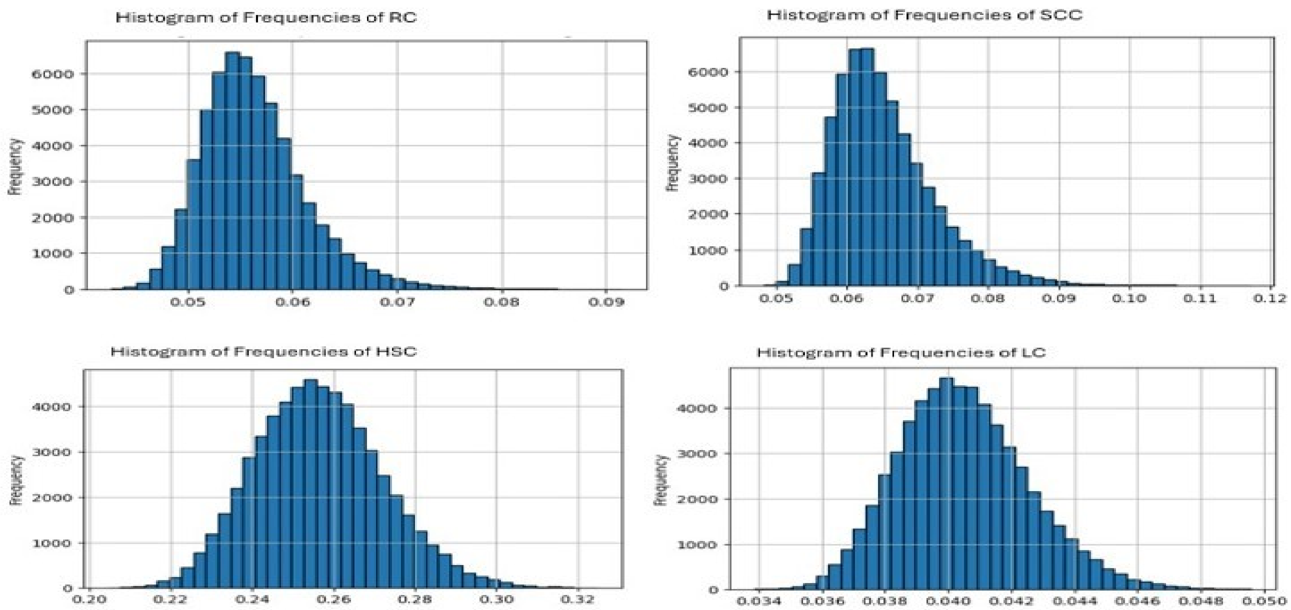


Figure 4.8. Histogram of Frequencies for Each Criterion - ND

Based on the results, Figure 4.9 and Figure 4.10, and Table 4.5 illustrate the compression between weights and ranking of criteria.

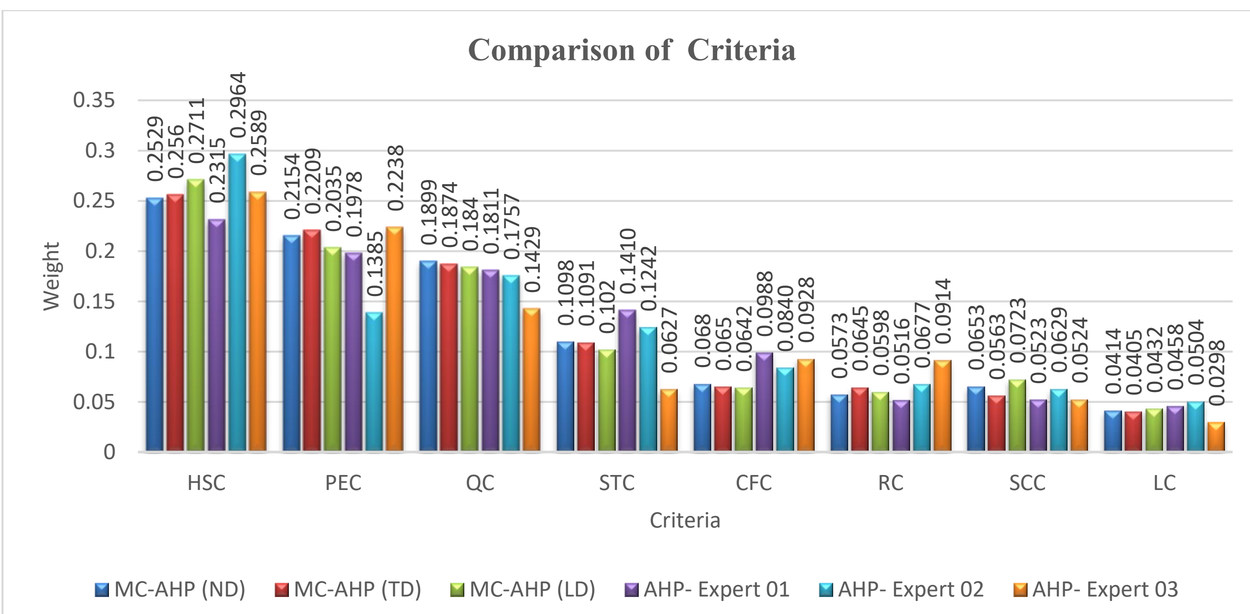


Figure 4.9. Comparison Criteria

Table 4.5. Ranking of Criteria

Criteria	MC-AHP	Expert1	Expert2	Expert3	Average AHP
	Rank	Rank	Rank	Rank	Rank
HSC	1	1	1	1	1
PEC	2	2	3	2	2
QC	3	3	2	4	3
STC	4	4	4	6	4
CFC	5	5	5	8	6
RC	6	7	6	5	7
SCC	7	6	7	3	5
LC	8	8	8	7	8

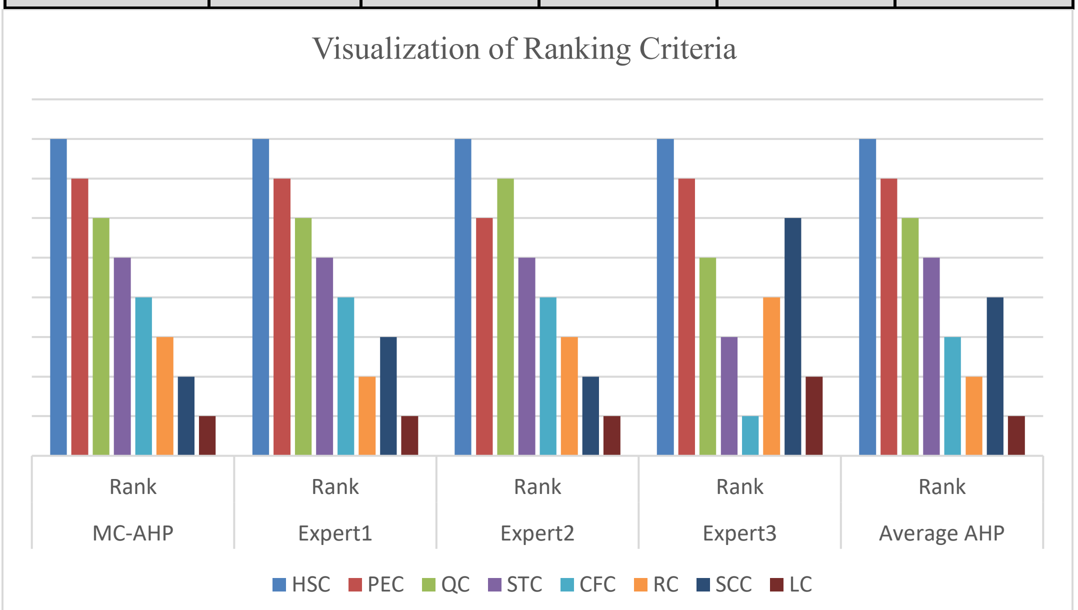


Figure 4.10. Visualization of Ranking Criteria

4.4.2 Indices for Evaluating the Performance of SC

The steps have been repeated to obtain the weights, with 100,000 random samples generated for each value using ND, TD, and LD. The number of accepted pairwise comparison matrices is 4,852 out of 100,000 for ND, 37,012 out of 100,000 for TD, and 13,863 out of 100,000 for LD.

Figure 4.11 shows histogram of frequencies for ND, TD, and LD for one index. The weights have been calculated as shown in Table 4.6.

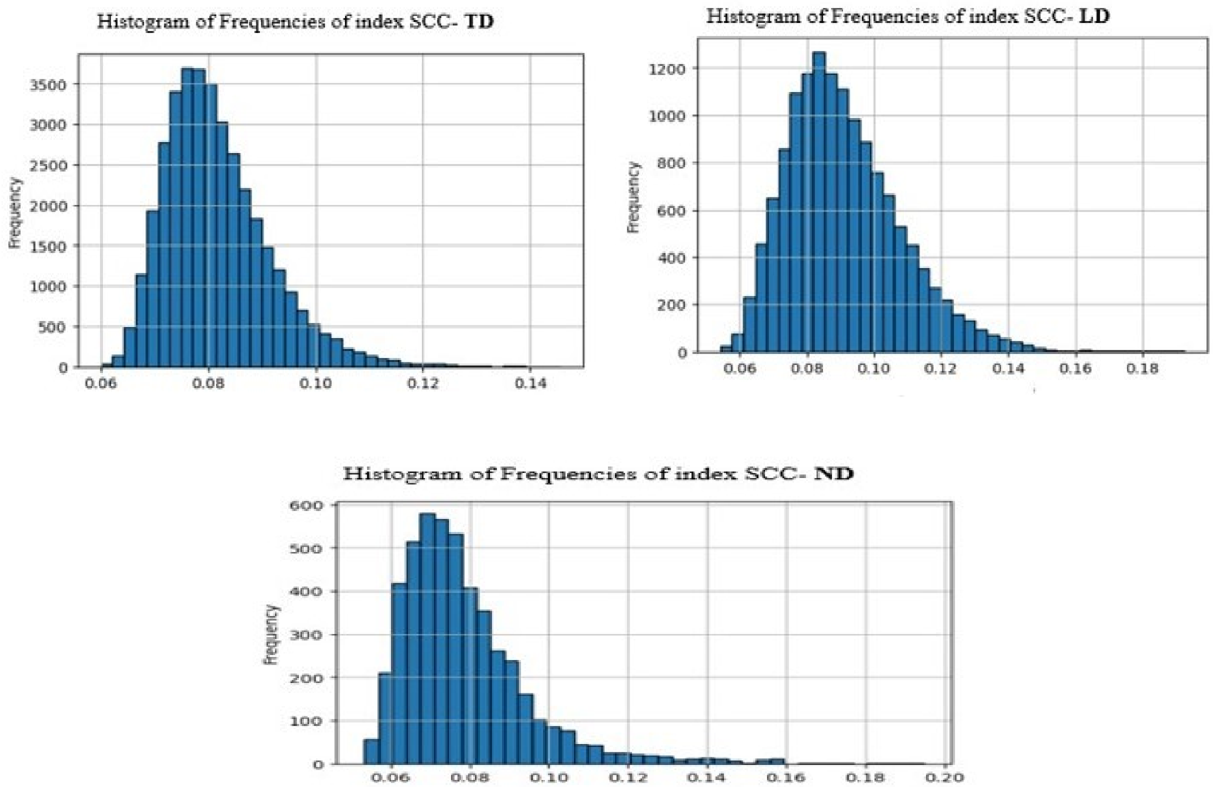


Figure 4.11. Histogram of Frequencies - Index SCC

Based on the results, Figure 4.12, Figure 4.13, and Table 4.6 illustrate the comparison between weights and ranking of criteria.

Table 4.6. Weights of Indices for Evaluating SC

Criteria	ND Weight	TD Weight	LD Weight	Expert2 Weight	Expert2 Weight	Expert2 Weight	Average Weight
STC	0.148	0.144	0.132	0.176	0.148	0.083	0.1359
CFC	0.087	0.083	0.079	0.120	0.097	0.039	0.0857
QC	0.267	0.261	0.255	0.240	0.218	0.180	0.2131
RC	0.067	0.068	0.072	0.065	0.075	0.110	0.0831
SCC	0.078	0.081	0.090	0.065	0.069	0.195	0.1101
HSC	0.298	0.311	0.316	0.279	0.336	0.331	0.3159
LC	0.051	0.050	0.052	0.053	0.054	0.060	0.0561
Total	1.000	1.000	1.000	1.000	1.000	1.000	1.000

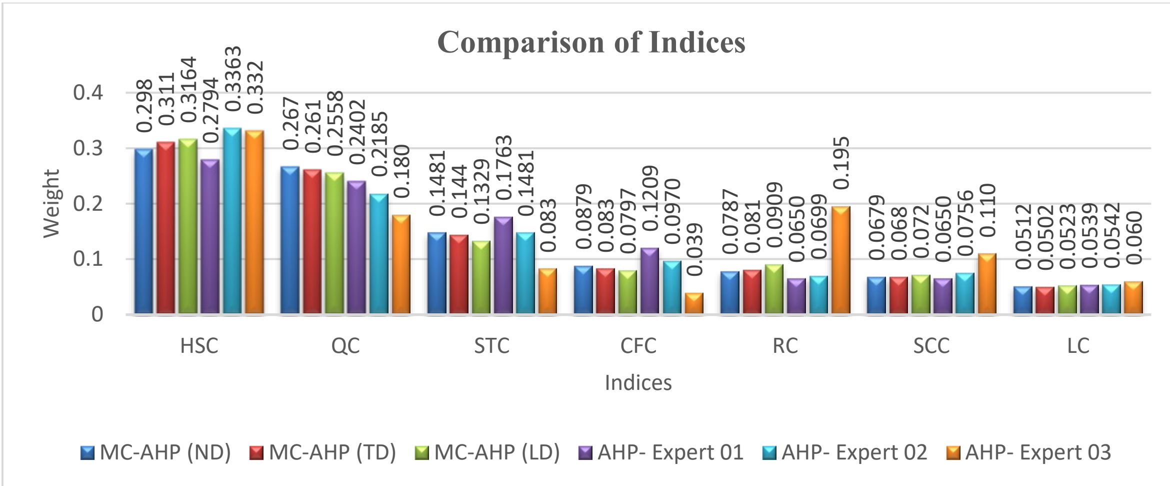


Figure 4.12. Comparison of Indices

Table 4.7. Ranking Indices

Criteria	**MC-AHP**	**Expert1**	**Expert2**	**Expert3**	**Average AHP**
	Rank	Rank	Rank	Rank	Rank
HSC	1	1	1	1	1
QC	2	2	2	3	2
STC	3	3	3	5	3
CFC	4	4	4	7	5
SCC	5	6	6	2	4
RC	6	5	5	4	6
LC	7	7	7	6	7

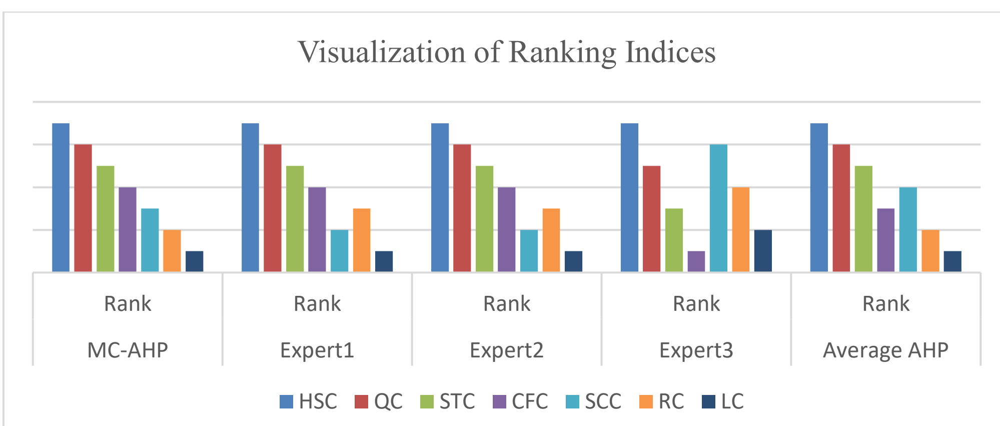


Figure 4.13. Visualization of Ranking Indices

4.2.4.3 Weights of Sub-Criteria for the Evaluation and Selection Process

Each criterion consists of sub-criteria, as shown in Table 3.9. The weighting steps have been implemented for each criterion that has at least three sub-criteria, which include PEC, CFC, QC, SCC, and LC. In other words, fewer than three sub-criteria obtain their weights directly without the weighting process. The weighting steps were performed with 10,000 random samples generated for each value using ND, TD, and LD. Table 4.8 illustrates weights of sub criteria.

Table 4.8.Weights of Sub- Criteria

Ceriterion - PEC						
Sub Criteria	MC-AHP (ND)		MC-AHP (TD)		MC-AHP (LD)	
	Weight	Std Dev	Weight	Std Dev	Weight	Std Dev
PEC1	0. 469	(±0.030)	0.452	(±0.015)	0. 465	(±0.030)
PEC2	0. 282	(±0.031)	0.295	(±0.017)	0. 280	(±0.029)
PEC3	0. 156	(±0.019)	0.155	(±0.009)	0. 160	(±0.018)
PEC4	0. 090	(±0.014)	0.097	(±0.006)	0. 093	(±0.014)
Total	1.000		1.000		1.000	

Ceriterion - CFC						
Sub Criteria	MC-AHP (ND)		MC-AHP (TD)		MC-AHP (LD)	
	Weight	Std Dev	Weight	Std Dev	Weight	Std Dev
CFC1	0.506	(±0.050)	0.515	(±0.026)	0.465	(±0.030)
CFC2	0.216	(±0.041)	0.223	(±0.021)	0.280	(±0.029)
CFC3	0.176	(±0.031)	0.161	(±0.015)	0.160	(±0.018)
CFC4	0.101	(±0.020)	0.098	(±0.010)	0.093	(±0.014)
Total	1.000		1.000		1.000	

Ceriterion - SCC						
Sub Criteria	MC-AHP (ND)		MC-AHP (TD)		MC-AHP (LD)	
	Weight	Std Dev	Weight	Std Dev	Weight	Std Dev
SCC1	0.498	(±0.082)	0.512	(±0.041)	0.481	(±0.076)
SCC2	0.309	(±0.065)	0.304	(±0.034)	0.313	(±0.060)
SCC3	0.192	(±0.054)	0.182	(±0.025)	0.205	(±0.052)
Total	1.000		1.000		1.000	

Ceriterion - QC						
Sub Criteria	MC-AHP (ND)		MC-AHP (TD)		MC-AHP (LD)	
	Weight	Std Dev	Weight	Std Dev	Weight	Std Dev
QC1	0.499	(±0.081)	0.510	(±0.041)	0.480	(±0.077)
QC2	0.165	(±0.034)	0.166	(±0.017)	0.172	(±0.034)
QC3	0.335	(±0.058)	0.323	(±0.030)	0.346	(±0.053)
Total	1.000		1.000		1.000	

Ceriterion - LC						
Sub Criteria	MC-AHP (ND)		MC-AHP (TD)		MC-AHP (LD)	
	Weight	Std Dev	Weight	Std Dev	Weight	Std Dev
LC1	0.491	(±0.061)	0.508	(±0.031)	0.479	(±0.055)
LC2	0.324	(±0.066)	0.312	(±0.033)	0.3316	(±0.060)
LC3	0.184	(±0.030)	0.178	(±0.016)	0.1886	(±0.028)
Total	1.000		1.000		1.000	

4.2.4.4 Determine the final Criteria Based on Results

4.2.4.4.1 Selection Criteria:

Regarding Table 4.4 and Table 4.8, the ranking of criteria remains consistent when utilizing MC-AHP with ND, TD, or LD, despite differences in the values of weights. However, the ranking of criteria differs when implementing traditional AHP using pairwise comparisons from expert 01, 02, and 03, as well as when using the average of their weights. It is important to note that only the rank of HSC is the same for all methods.

In this study, MC-AHP is chosen as the method for the reasons outlined in Chapter 2. Consequently, the final weight values are derived from MC-AHP (ND), MC-AHP (TD), or MC-AHP (LD). Two factors are crucial in determining the most accurate values.

Firstly, the volume of accepted matrices (CRI < 0.1) plays a significant role. An increasing number of accepted matrices helps obtain more reliable weight values, which contribute to calculating the mean and also indicate that the probability distribution used is the best fit for the actual data (expert opinions).

Secondly, the standard deviation (Std Dev) values are considered. The standard deviation measures how accurately the mean represents the data (Lee et al., 2015). In other words, a lower standard deviation signifies that the values are close to the mean, reflecting greater consistency in the results, while a higher standard deviation indicates that the values are spread out over a larger range.

Table 4.9 illustrates the final weight values derived from MC-AHP (TD) after considering two factors. The box plots, shown in Figure 4.14, provide a visual representation of the weight values with their standard deviations for each criterion across the ND, TD, and LD methods.

Table 4.9. The final Weights of Selection Criteria

	MC-AHP (ND)		MC-AHP (TD)		MC-AHP (LD)		Lower Std Dev (Method)
Criteria	Weight	Std Dev	Weight	Std Dev	Weight	Std Dev	
PEC	0.215	(±0.012)	0.220	(±0.006)	0.203	(±0.020)	MC-AHP (TD)
STC	0.109	(±0.016)	0.109	(±0.005)	0.102	(±0.014)	MC-AHP (TD)
CFC	0.068	(±0.011)	0.064	(±0.004)	0.064	(±0.010)	MC-AHP (TD)
QC	0.189	(±0.018)	0.187	(±0.006)	0.184	(±0.018)	MC-AHP (TD)
RC	0.057	(±0.008)	0.064	(±0.002)	0.059	(±0.008)	MC-AHP (TD)
SCC	0.065	(±0.014)	0.056	(±0.002)	0.072	(±0.012)	MC-AHP (TD)
HSC	0.252	(±0.027)	0.256	(±0.008)	0.271	(±0.028)	MC-AHP (TD)
LC	0.041	(±0.003)	0.040	(±0.001)	0.043	(±0.003)	MC-AHP (TD)
Accepted Matrices	7,406		74,743		23,046		MC-AHP (TD)

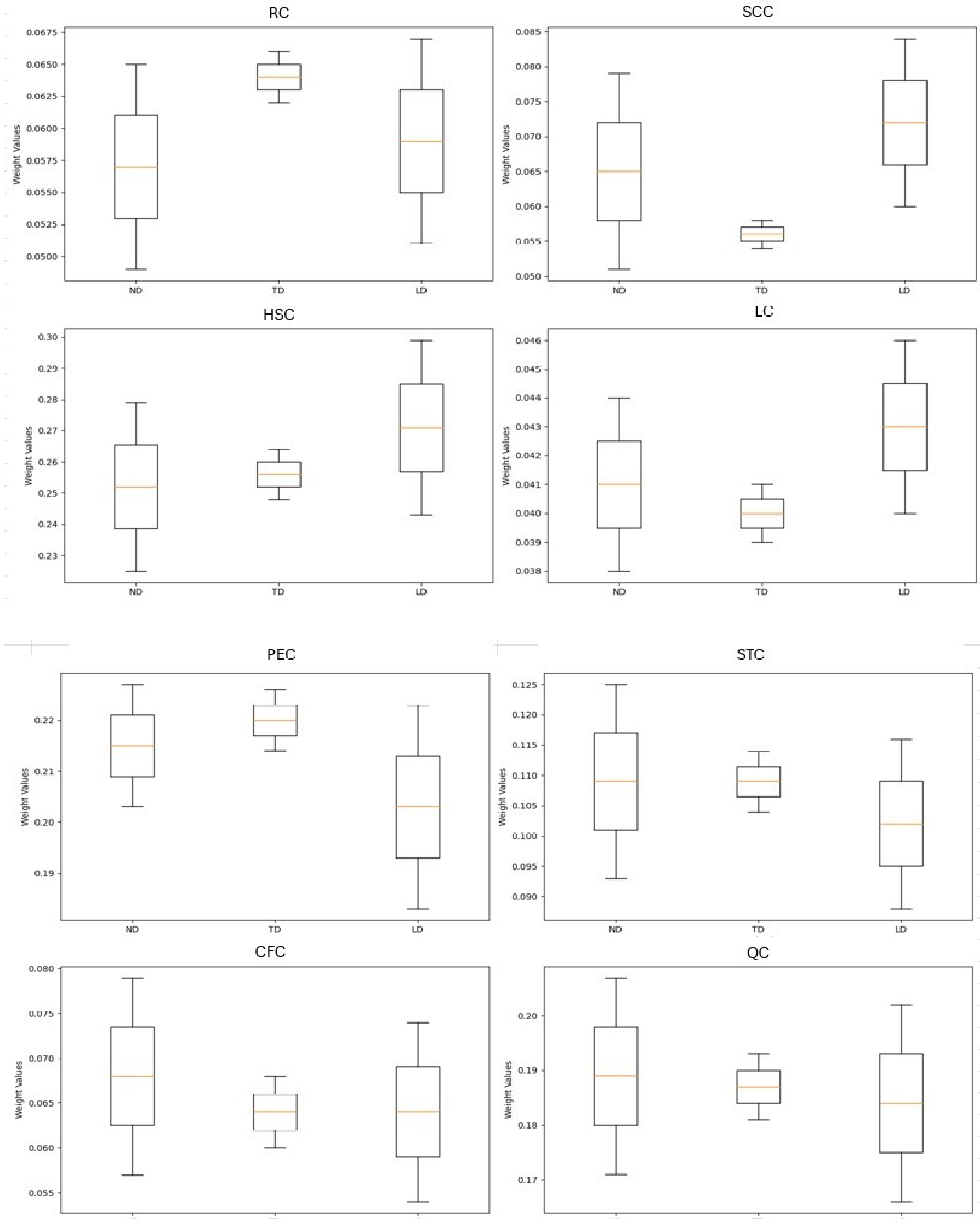


Figure 4.14. Box- Plot for Each Criterion

4.2.4.4.2 Evaluation Indices:

In reference to Table 4.6 and Table 4.8, the ranking of criteria remains consistent when using MC-AHP with ND, TD, or LD, despite variations in the weight values.

Table 4.10 illustrates the final weight values derived from MC-AHP (TD) after considering two factors (accepted matrices and standard deviation).

Table 4.10. The Final Weight Values of Evaluation Indices

	MC-AHP (ND)		MC-AHP (TD)		MC-AHP (LD)		Lower Std Dev (Method)
Criteria	Weight	Std Dev	Weight	Std Dev	Weight	Std Dev	
STC	0.148	(±0.020)	0.144	(±0.012)	0.132	(±0.02)	MC-AHP (TD)
CFC	0.087	(±0.014)	0.083	(±0.008)	0.079	(±0.013)	MC-AHP (TD)
QC	0.267	(±0.022)	0.261	(±0.014)	0.255	(±0.024)	MC-AHP (TD)
RC	0.067	(±0.010)	0.068	(±0.006)	0.072	(±0.010)	MC-AHP (TD)
SCC	0.078	(±0.016)	0.081	(±0.009)	0.090	(±0.016)	MC-AHP (TD)
HSC	0.298	(±0.025)	0.311	(±0.016)	0.316	(±0.029)	MC-AHP (TD)
LC	0.051	(±0.003)	0.050	(±0.001)	0.052	(±0.003)	MC-AHP (TD)
Accepted Matrices	4,852		37,012		13,863		MC-AHP (TD)

4.2.4.4.3 Weights of Sub-Criteria

Regarding Table 4.8 and considering two factors, the final weight values of sub-criteria as shown in Table 4.11.

Table 4.11. The Final Weight Values of Sub- Criteria

Sub-Criteria	MC-AHP (TD)		Sub-Criteria	MC-AHP (TD)	
PEC	Weight	Std Dev	CFC	Weight	Std Dev
PEC1	0.452	(±0.015)	CFC1	0.515	(±0.026)
PEC2	0.295	(±0.017)	CFC2	0.223	(±0.021)
PEC3	0.155	(±0.009)	CFC3	0.161	(±0.015)
PEC4	0.097	(±0.006)	CFC4	0.098	(±0.010)
Accepted Matrices	5,637			9,363	

Sub-Criteria	MC-AHP (TD)		Fewer than three sub-criteria	
LC	Weight	Std Dev	Sub-Criteria	Weight
LC1	0.508	(±0.031)	HSC1	0.8
LC2	0.312	(±0.033)	HSC2	0.2
LC3	0.178	(±0.016)	RC1	0.5
Accepted Matrices	9,875		RC2	0.5

Sub-Criteria	MC-AHP (TD)		Sub-Criteria	MC-AHP (TD)	
QC	Weight	Std Dev	SCC	Weight	Std Dev
QC1	0.510	(±0.041)	SCC1	0.512	(±0.041)
QC2	0.166	(±0.017)	SCC2	0.304	(±0.034)
QC3	0.323	(±0.030)	SCC3	0.182	(±0.025)
Accepted Matrices	8,388			9,069	

4.2.4.4.3 Summary:

Table 4.12 and Table 4.13, along with Figure 4.15 and Figure 4.16, represent the integration of main criteria with sub-criteria for use in evaluation and selection processes.

Table 4.12. Integration of Criteria and Sub-Criteria

Sr.N	Criteria	Weight	Sub- Criteria	Weight
1	PEC	0.22	PEC1	0.452
			PEC2	0.295
			PEC3	0.155
			PEC4	0.097
2	STC	0.109	STC	0.109
3	CFC	0.064	CFC1	0.515
			CFC2	0.223
			CFC3	0.161
			CFC4	0.098
4	QC	0.187	QC1	0.51
			QC2	0.166
			QC3	0.323
5	RC	0.064	RC1	0.5
			RC2	0.5
6	HSC	0.256	HSC1	0.8
			HSC2	0.2
7	SCC	0.056	SCC1	0.512
			SCC2	0.304
			SCC3	0.182
8	LC	0.04	LC1	0.508
			LC2	0.312
			LC3	0.178

Sub- Criteria	Weight
PEC1	0.0994
PEC2	0.0649
PEC3	0.0341
PEC4	0.0213
STC	0.1090
CFC1	0.0330
CFC2	0.0143
CFC3	0.0103
CFC4	0.0063
QC1	0.0954
QC2	0.0310
QC3	0.0604
RC1	0.0320
RC2	0.0320
HSC1	0.2048
HSC2	0.0512
SCC1	0.0287
SCC2	0.0170
SCC3	0.0102
LC1	0.0203
LC2	0.0125
LC3	0.0071

$\sum$	= 1.000

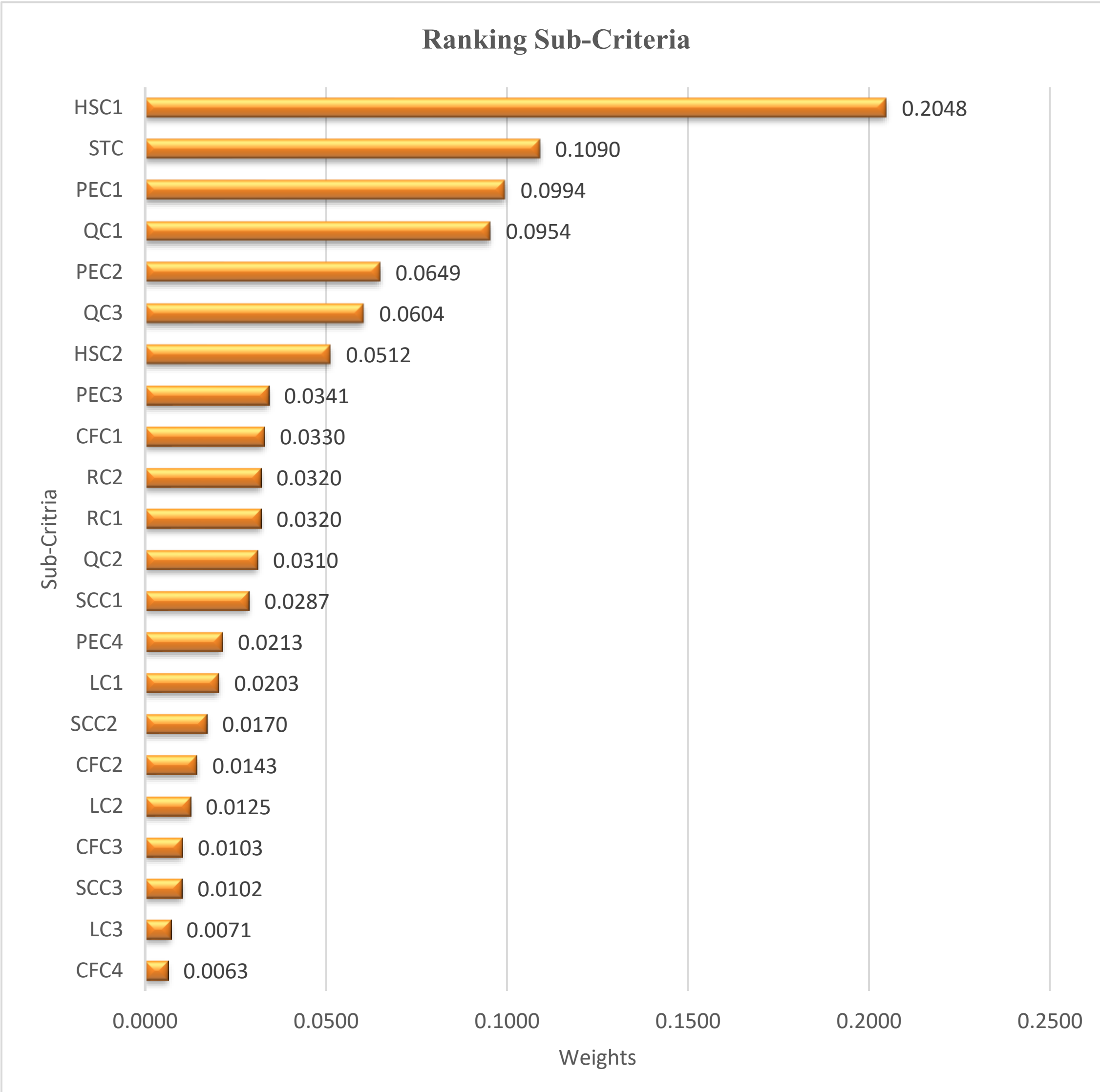


Figure 4.15. Ranking of Sub-Criteria with the Final Weights

Table 4.13. Integration of Indices and Sub- Indices

Sr.N	Indices	Weight	Sub-Indices	Weight
1	STC	0.148	STC	0.148
2	CFC	0.087	CFC1	0.515
			CFC2	0.223
			CFC3	0.161
			CFC4	0.098
3	QC	0.267	QC1	0.51
			QC2	0.166
			QC3	0.323
4	RC	0.067	RC1	0.5
			RC2	0.5
5	HSC	0.298	HSC1	0.8
			HSC2	0.2
6	SCC	0.078	SCC1	0.512
			SCC2	0.304
			SCC3	0.182
7	LC	0.051	LC1	0.508
			LC2	0.312
			LC3	0.178

Sub-Indices	Weight
STC	0.148
CFC1	0.045
CFC2	0.019
CFC3	0.014
CFC4	0.009
QC1	0.136
QC2	0.044
QC3	0.086
RC1	0.034
RC2	0.034
HSC1	0.249
HSC2	0.062
SCC1	0.041
SCC2	0.025
SCC3	0.015
LC1	0.026
LC2	0.016
LC3	0.009

$\sum$	= 1.000

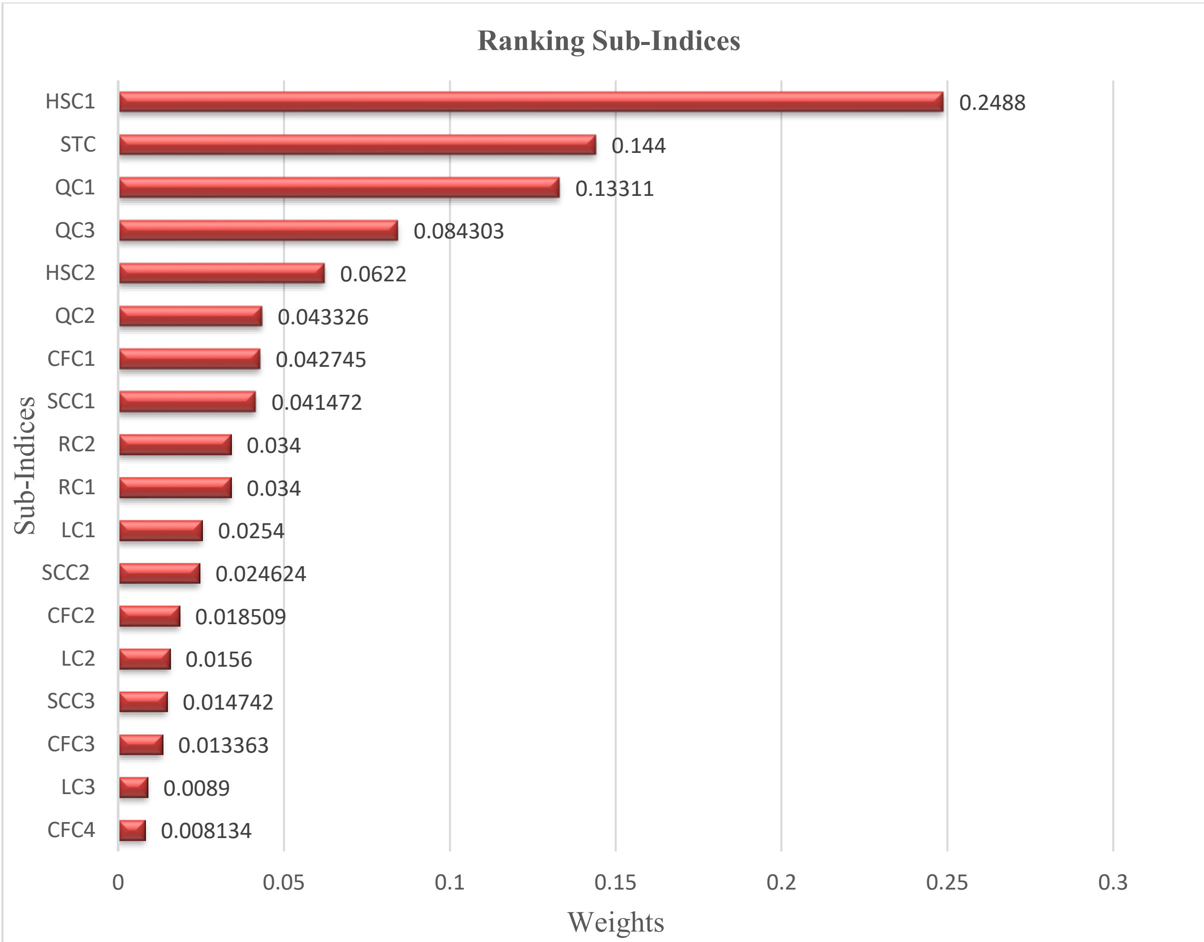


Figure 4.16. Ranking of Sub-Indices with the Final Weights

4.3 Developing an Integrated Model for Evaluating the Performance of SC

4.3.1 Introduction

In the construction sector, GCs are crucial in ensuring projects are completed successfully. A key component of this role is the systematic assessment of subcontractor performance after the project's conclusion. Subcontractors, who carry out specialized tasks, have a substantial influence on the overall quality, cost, safety, and schedule compliance of construction projects. Thus, a thorough and meticulous evaluation of their performance is essential to guarantee project success and promote ongoing improvements.

Furthermore, the analysis of the outcomes of evaluation facilitates the identification of best practices and the revelation of inefficiencies or challenges that impede project success.

Consequently, the insights gained from one project can be applied to subsequent projects, thereby refining and enhancing the overall project management methodology.

Traditional methods of evaluating subcontractor performance often rely on manual assessments and subjective judgments, which can be time-consuming and prone to bias. To address these challenges, there is a growing need to develop an integrated system that automates and standardizes the evaluation process. Such a system would not only increase efficiency but also provide a more objective and comprehensive assessment of subcontractor performance.

An integrated model for evaluating subcontractor performance calculates the subcontractor performance index (PI) utilizing a linear additive utility model (LAUM) that considers multiple criteria, including cost, quality, safety, time, resource adequacy, general contractor satisfaction, and leadership, as shown in Figure 4.17.

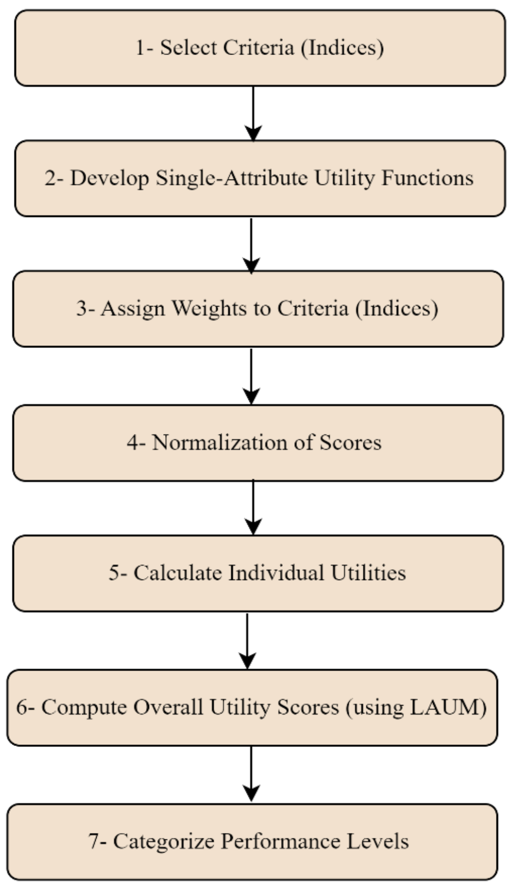


Figure 4.17. Steps for Calculating PI

Steps 01 and 02 have been covered in Chapter 3, and the weights of the indices have been assigned using MCAHP in relation to Step 3.

4.3.2 Normalization of the SC Performance Indices

Normalization of SC performance indices is essential for ensuring a fair, accurate, and objective evaluation process. It eliminates issues related to scale and unit differences, allows for proper weighting, and enhances the overall decision-making process. By adopting appropriate normalization techniques, GCs can ensure that their performance assessments are robust, consistent, and reflective of true performance (Kroonenberg, 2008).

Nassar (2005) noted that the complexity of performance measurement arises from several factors. These include the dynamic nature of project objectives, which change over time, and the involvement of numerous project participants who represent various interests in defining and prioritizing these objectives.

Additionally, some desirable objectives are subjective in nature. Nassar (2005) also clarified that because construction projects are unique, performance-normalization tables must reflect project-specific conditions and the project's control philosophy. Therefore, the normalization of the SC performance indices varies based on each project. In this study, the normalization process proposes three types of normalization based on the level of tolerance values of indices: high, medium, and low.

For demonstration purposes only, the following outlines the normalization of seven identified indices based on a medium level of tolerance:

4.3.2.1 Normalization of Time Index (STC)

STC measures by using Equations in Table 3.9 . To normalize the obtained index, the STC rating scale is proposed in Table 4.14. This proposed scale is for illustration only and needs to be modified to reflect the specific conditions of the project and GC’s policy.

Table 4.14.Time Rating Table

STC			
Condition	Rating	Index Range	STC Range
A	Outstanding Performance	I > 1.15	STC > 1.15
B	Exceeds Target	1.05 < I <= 1.15	1.05 < STC <= 1.15
C	Within Target	0.95 < I <= 1.05	0.95 < STC <= 1.05
D	Below Target	0.85 < I <= 0.95	0.85 < STC <= 0.95
F	Poor Performance	I <= 0.85	STC <= 0.85

4.3.2.2 Normalization of Cost and Finance Index (CFC)

CFC is divided into four indices: CFC1, CFC2, CFC3, and CFC4. CFC1 and CFC3 are measured using Equations in Table 3.9. Table 4.15 illustrates the normalization of the CFC rating scale. This rating scale is for demonstration purposes only.

Table 4.15. Cost and Finance Rating Table

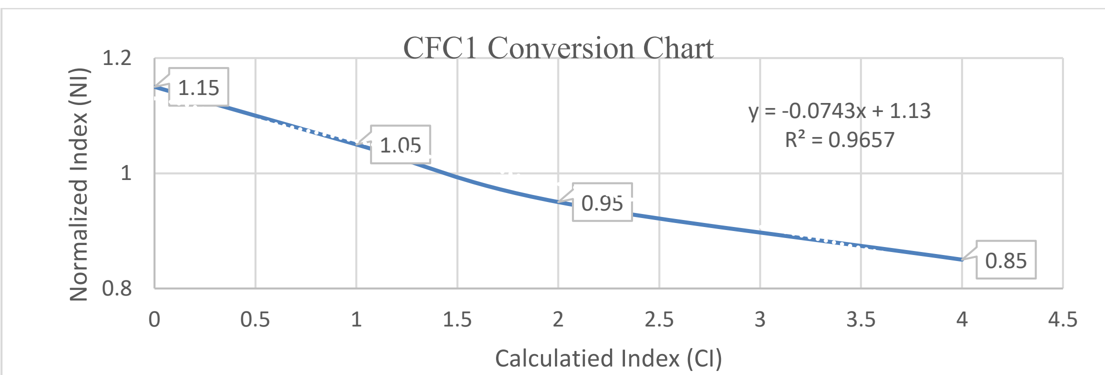
CFC1			
Condition	Rating	Index Range	CFC1 Range
A	Outstanding Performance	I > 1.15	CFC1= 0
B	Exceeds Target	1.05 < I <= 1.15	0 < CFC1<=0.1
C	Within Target	0.95 < I <= 1.05	0.1 < CFC1<=0.2
D	Below Target	0.85 < I <= 0.95	0.2 < CFC1<=0.5
F	Poor Performance	I <= 0.85	0.5 < CFC1

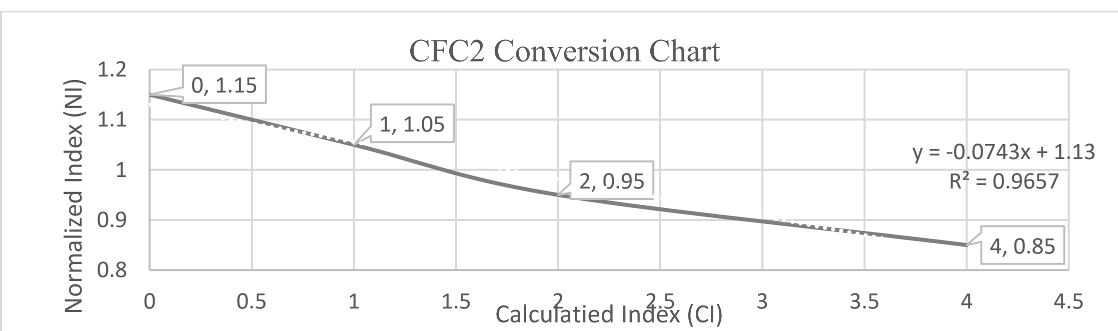
CFC2			
Condition	Rating	Index Range	CFC2 Range
A	Outstanding Performance	I > 1.15	CFC2= 0
B	Exceeds Target	1.05 < I <= 1.15	0 < CFC2<=1
C	Within Target	0.95 < I <= 1.05	1 < CFC2<=2
D	Below Target	0.85 < I <= 0.95	2 < CFC2<=4
F	Poor Performance	I <= 0.85	4 < CFC2

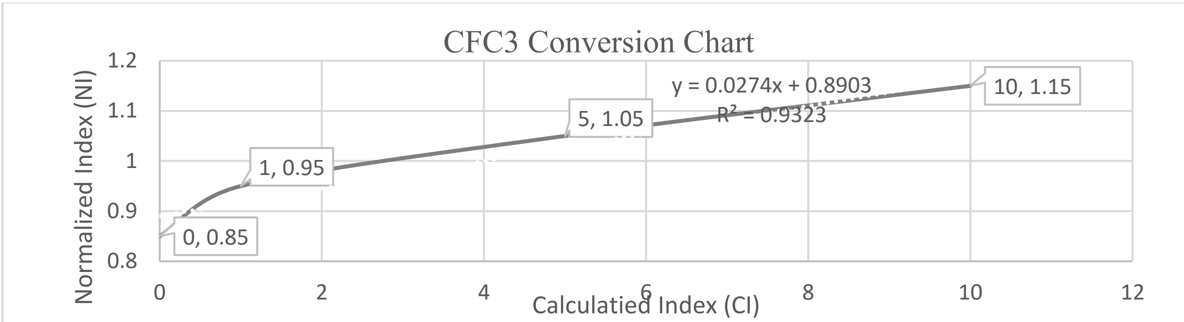
CFC3			
Condition	Rating	Index Range	CFC3 Range
A	Outstanding Performance	I > 1.15	CFC3> 10
B	Exceeds Target	1.05 < I <= 1.15	5 < CFC3<=10
C	Within Target	0.95 < I <= 1.05	1 < CFC3<=5
D	Below Target	0.85 < I <= 0.95	0 < CFC3<=1
F	Poor Performance	I <= 0.85	0 = CFC2

CFC4			
Condition	Rating	Index Range	CFC4 Range
A	Outstanding Performance	I > 1.15	CFC2= 0
B	Exceeds Target	1.05 < I <= 1.15	0 < CFC2<=1
C	Within Target	0.95 < I <= 1.05	1 < CFC2<=2
D	Below Target	0.85 < I <= 0.95	2 < CFC2<=4
F	Poor Performance	I <= 0.85	4 < CFC2

The calculated CFC (Cl) value can be converted into the normalized CFC (NI) value using Figure 4.18. where NI = f (Cl).







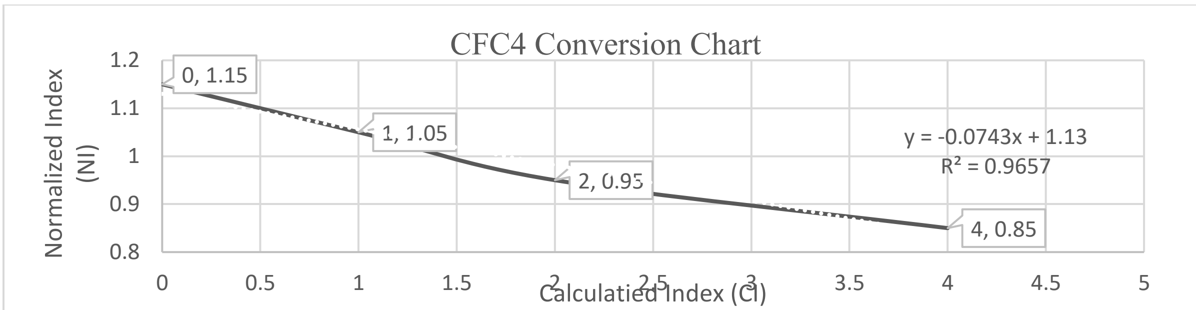


Figure 4.18. Linear Transformation between Normalized and Calculated CFC Index

4.3.2.3 Normalization of Quality Index (QC)

QC is divided into three indices: QC1, QC2, and QC3. To normalize the resulting index, the QC rating scale is suggested in Table 4.16. This scale is intended for illustrative purposes only.

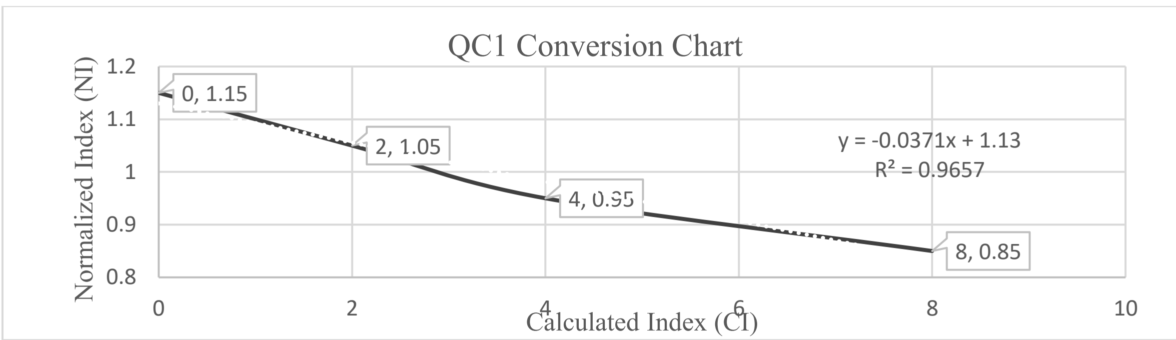
Table 4.16. Quality Rating Table

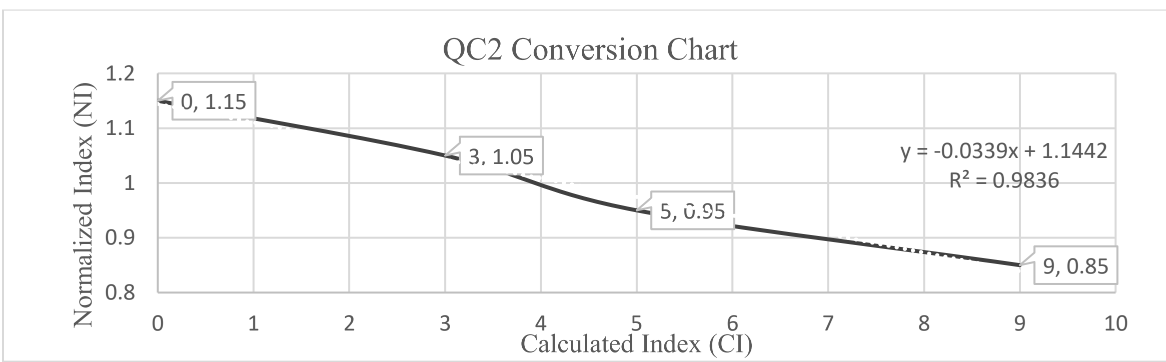
QC1			
Condition	Rating	Index Range	QC1 Range
A	Outstanding Performance	I > 1.15	QC1= 0
B	Exceeds Target	1.05 < I <= 1.15	0 < QC1 <=2
C	Within Target	0.95 < I <= 1.05	2 < QC1 <=4
D	Below Target	0.85 < I <= 0.95	4 < QC1 <=8
F	Poor Performance	I <= 0.85	8 < QC1

QC2			
Condition	Rating	Index Range	QC2 Range
A	Outstanding Performance	I > 1.15	QC2= 0
B	Exceeds Target	1.05 < I <= 1.15	0 < QC2 <=3
C	Within Target	0.95 < I <= 1.05	3 < QC2 <=5
D	Below Target	0.85 < I <= 0.95	5 < QC2 <=7
F	Poor Performance	I <= 0.85	7 < QC2

QC3			
Condition	Rating	Index Range	QC3 Range
A	Outstanding Performance	I > 1.15	QC3= 0
B	Exceeds Target	1.05 < I <= 1.15	0 < QC3 <=1
C	Within Target	0.95 < I <= 1.05	1 < QC3 <=3
D	Below Target	0.85 < I <= 0.95	3 < QC3 <=6
F	Poor Performance	I <= 0.85	6 < QC3

The calculated QC (Cl) value can be transformed into a normalized QC (NI) value using the function NI = f(Cl) as shown in Figure 4.19.





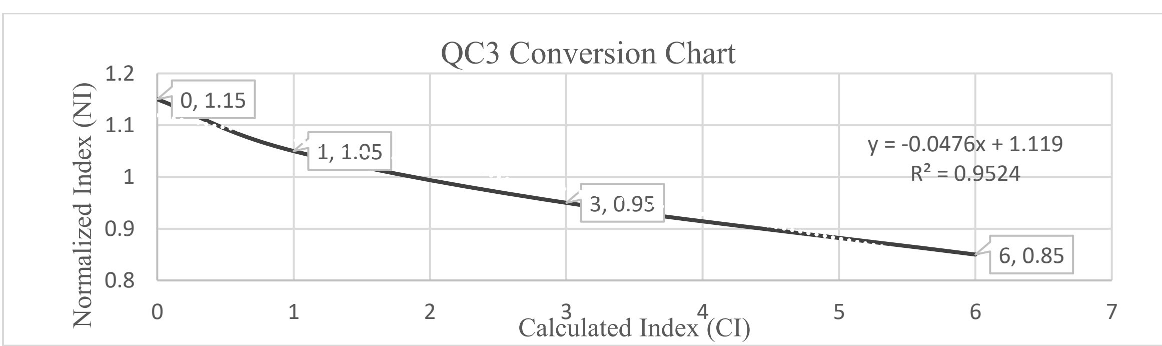


Figure 4.19. Linear Transformation between Normalized and Calculated QC Index

4.3.2.4 Normalization of Resource Adequacy Index (RC)

RC consists of RC1 and RC2. RC1 is measured using Equations in Table 3.9. Table 4.17 illustrates the normalization of the RC rating scale. This rating scale is for demonstration purposes only.

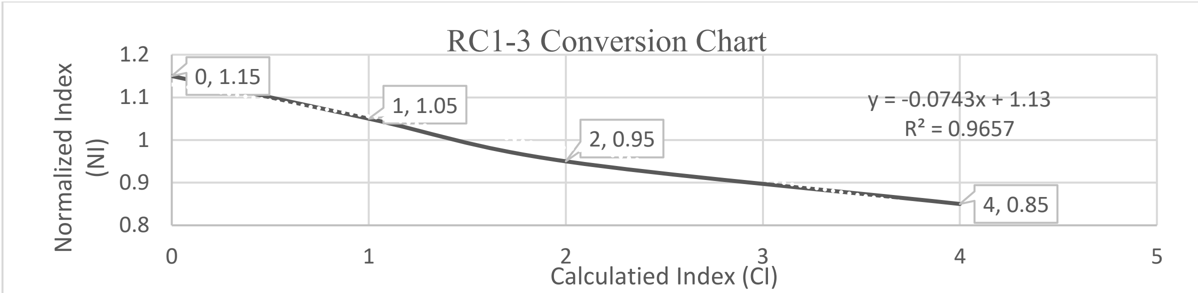
Table 4.17. Resource Adequacy Rating Table

RC1-1 and RC1-2		
Condition	Rating	Index Range
A	Outstanding Performance	I > 1.15
B	Exceeds Target	1.05 < I <= 1.15
C	Within Target	0.95 < I <= 1.05
D	Below Target	0.85 < I <= 0.95
F	Poor Performance	I <= 0.85

RC1-3			
Condition	Rating	Index Range	RC1-3 Range
A	Outstanding Performance	I > 1.15	RC1-3= 0
B	Exceeds Target	1.05 < I <= 1.15	0 < RC1-3 <=1
C	Within Target	0.95 < I <= 1.05	1< RC1-3 <=2
D	Below Target	0.85 < I <= 0.95	2 < RC1-3 <=4
F	Poor Performance	I <= 0.85	4 < RC1-3

RC2			
Condition	Rating	Index Range	RC2 Range
A	Outstanding Performance	I > 1.15	RC2= 0
B	Exceeds Target	1.05 < I <= 1.15	0 < RC2 <=1%
C	Within Target	0.95 < I <= 1.05	1 < RC2 <=2%
D	Below Target	0.85 < I <= 0.95	2 < RC2 <=4%
F	Poor Performance	I <= 0.85	4%< RC2

The calculated RC (Cl) value can be converted into the normalized RC (NI) value using Figure 4.20. where NI = f (Cl).



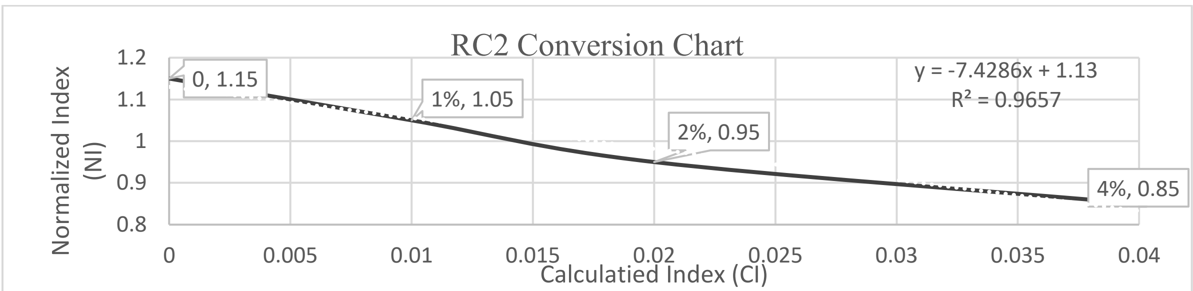


Figure 4.20. Linear Transformation between Normalized and Calculated RC Index

4.3.2.5 Normalization of Occupational Health and Safety and Environmental Protection Index (HSC)

HSC is divided into two indices: HSC1 and HSC2. To normalize the resulting index, the HSC rating scale is proposed in Table 4.18. This scale is intended for illustrative purposes only.

Table 4.18. Occupational Health and Safety and Environmental Protection Rating Table

HSC1-1			
Condition	Rating	Index Range	HSC1 Range
A	Outstanding Performance	I > 1.15	HSC1-1= 0
B	Exceeds Target	1.05 < I <= 1.15	0 <HSC1-1 <=1
C	Within Target	0.95 < I <= 1.05	1 <HSC1-1 <=2
D	Below Target	0.85 < I <= 0.95	2 <HSC1-1 <=3
F	Poor Performance	I <= 0.85	3< HSC1-1

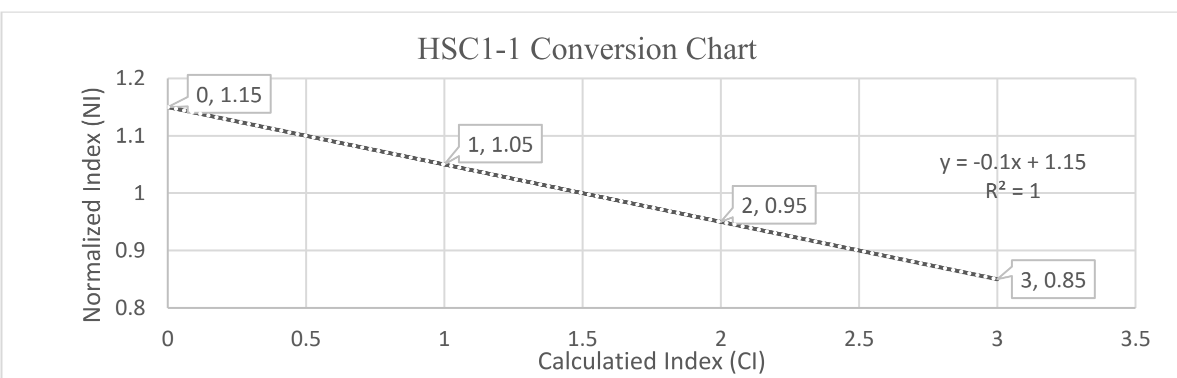
HSC1-2			
Condition	Rating	Index Range	HSC1 Range
C	Outstanding Performance	I > 1.15	HSC1-2= 0
F	Poor Performance	I <= 0.85	1<= HSC1-2

HSC1-3			
A	Outstanding Performance	I > 1.15	HSC1-1= 0
B	Exceeds Target	1.05 < I <= 1.15	0 <HSC1-1 <=1
C	Within Target	0.95 < I <= 1.05	1 <HSC1-1 <=2
D	Below Target	0.85 < I <= 0.95	2 <HSC1-1 <=3
F	Poor Performance	I <= 0.85	3< HSC1-1

HSC1-4			
Condition	Rating	Index Range	HSC1-4 Range
A	Outstanding Performance	I > 1.15	HSC1-1= 0
B	Exceeds Target	1.05 < I <= 1.15	0 <HSC1-1 <=1
C	Within Target	0.95 < I <= 1.05	1 <HSC1-1 <=2
D	Below Target	0.85 < I <= 0.95	2 <HSC1-1 <=3
F	Poor Performance	I <= 0.85	3< HSC1-1

HSC2			
Condition	Rating	Index Range	HSC2 Range
A	Outstanding Performance	I > 1.15	HSC1-1= 0
B	Exceeds Target	1.05 < I <= 1.15	0 <HSC1-1 <=1
C	Within Target	0.95 < I <= 1.05	1 <HSC1-1 <=3
D	Below Target	0.85 < I <= 0.95	2 <HSC1-1 <=4
F	Poor Performance	I <= 0.85	4< HSC1-1

The calculated HSC (Cl) value can be transformed into a normalized HSC (NI) value using the function NI = f(Cl) as shown in Figure 4.21.



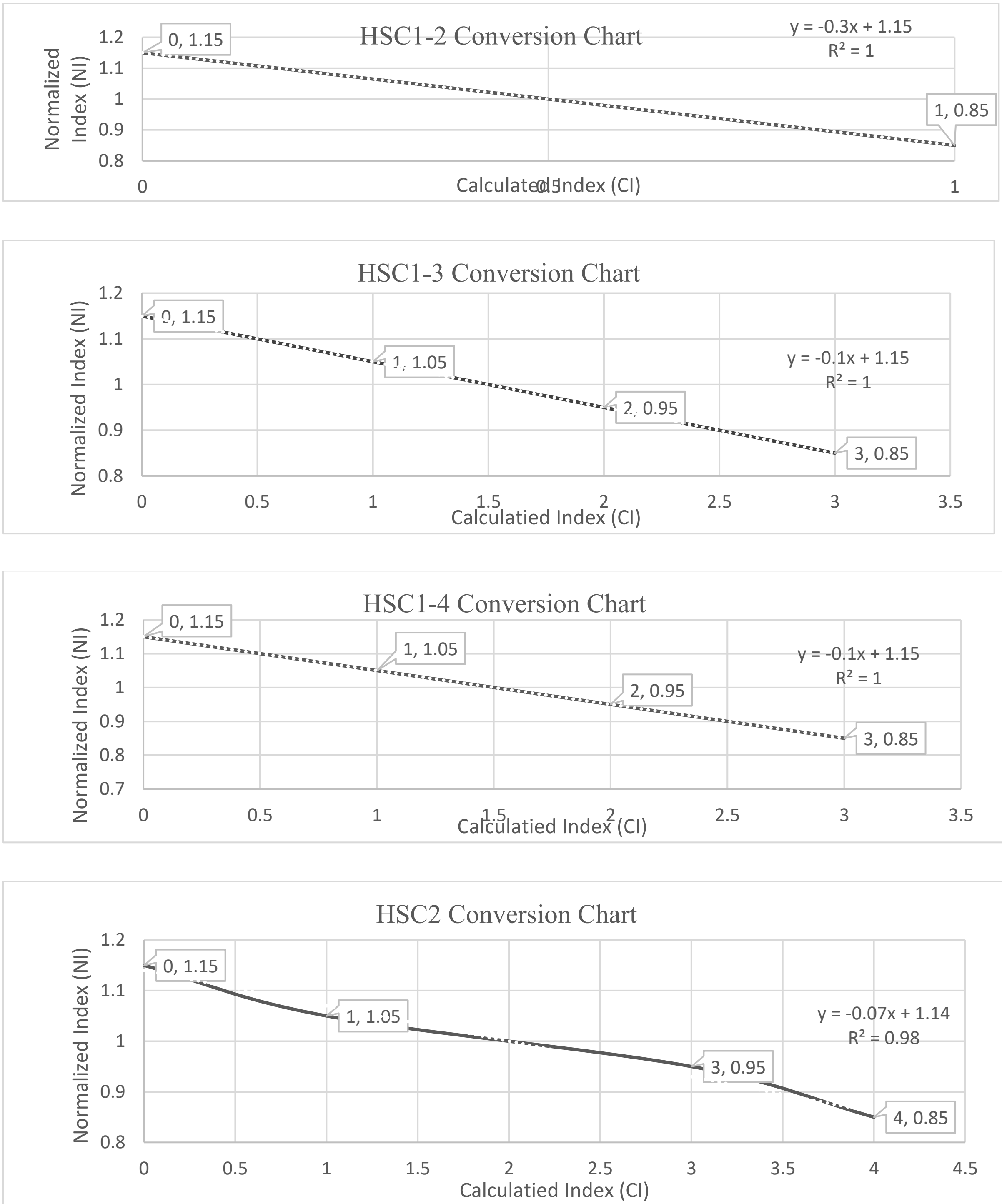


Figure 4.21. Linear Transformation between Normalized and Calculated HSC Index

4.3.2.6 Normalization of General Contractor Satisfaction Index (SCC)

SCC consists of SCC1, SCC2, and SCC3. SCC1 is measured using Equations (3.11), (3.12), and (3.13), while SCC2 utilizes Equation (3.15). Table 4.19 illustrates the normalization of the SCC rating scale. This rating scale is for demonstration purposes only.

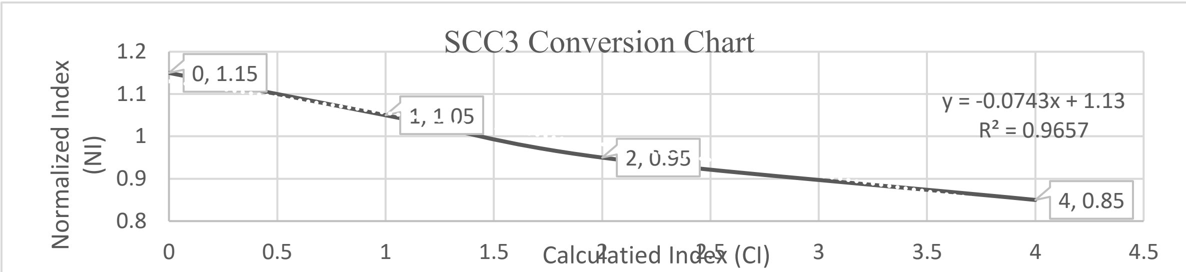
Table 4.19 General Contractor Satisfaction Rating and Normalization Table

SCC1-1, SCC1-2, and SCC1-3			
Condition	Rating	Index Range	SCC1 Range
A	Outstanding Performance	I > 1.15	SCC1 > 1.15
B	Exceeds Target	1.05 < I <= 1.15	1.05 < SCC1 <= 1.15
C	Within Target	0.95 < I <= 1.05	0.95 < SCC1 <= 1.05
D	Below Target	0.85 < I <= 0.95	0.85 < SCC1 <= 0.95
F	Poor Performance	I <= 0.85	SCC1 <= 0.85

SCC2			
Condition	Rating	Index Range	SCC2 Range
A	Outstanding Performance	I > 1.15	SCC2= 100%
B	Exceeds Target	1.05 < I <= 1.15	100% > SCC2 >=90%
C	Within Target	0.95 < I <= 1.05	90% > SCC2 >=80%
D	Below Target	0.85 < I <= 0.95	80% > SCC2 >=75%
F	Poor Performance	I <= 0.85	75% > SCC2

SCC3			
Condition	Rating	Index Range	SCC3 Range
A	Outstanding Performance	I > 1.15	SCC3= 0
B	Exceeds Target	1.05 < I <= 1.15	0 < SCC3 <=1
C	Within Target	0.95 < I <= 1.05	1 < SCC3 <=2
D	Below Target	0.85 < I <= 0.95	2 < SCC3 <=4

The calculated SCC2 (Cl) and SCC3 (Cl) value can be converted into the normalized SCC2 (NI) and SCC3 (NI) value respectively using the function NI = f(Cl) as shown in Figure 4.22.



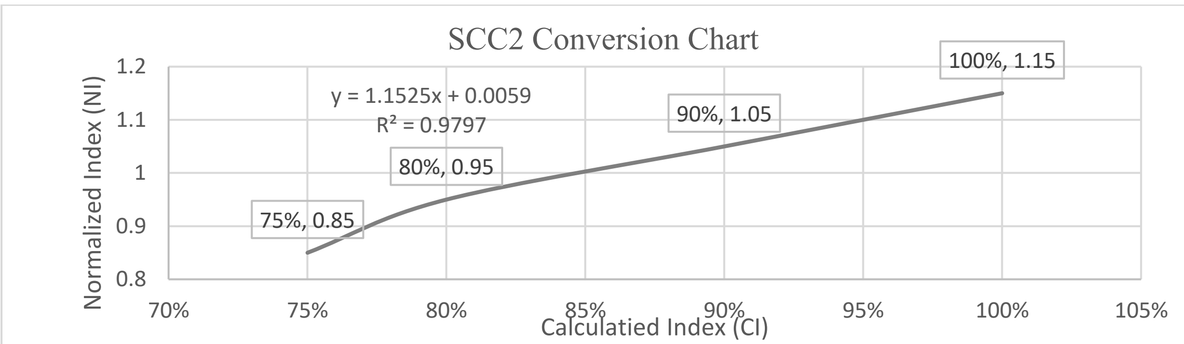


Figure 4.22. Linear Transformation between Normalized and Calculated SCC2 and SCC3 Index

4.3.2.7 Normalization of Leadership Index (LC)

LC is divided into two indices: LC1 and LC2. LC is measured by implementing the rating scale and weighted average with the GC team calibration method to obtain the final aggregated value. The LC value ranges between 1 and 10. The LC rating scale is proposed in Table 4.20, intended for illustrative purposes only.

Table 4.20. Leadership Rating and Normalization Table

LC1, LC2, LC3			
Condition	Rating	Index Range	LC1 Range
A	Outstanding Performance	I > 1.15	LC1 > 9.5
B	Exceeds Target	1.05 < I <= 1.15	9.0 < LC1<= 9.5
C	Within Target	0.95 < I <= 1.05	8.0 < LC1<= 9.0
D	Below Target	0.85 < I <= 0.95	6.0 < LC1<= 8.0
F	Poor Performance	I <= 0.85	LC1<= 6

The calculated LC (Cl) value can be transformed into a normalized LC (NI) value using the function NI = f(Cl) as shown in Figure 4.23.

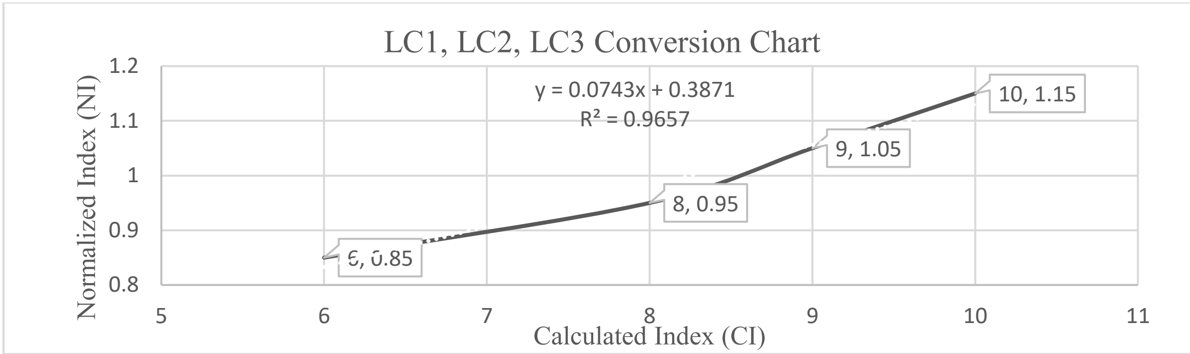


Figure 4.23. Linear Transformation between Normalized and Calculated SCC3 Index

4.3.3 SC Performance Index (PI): A Linear Additive Utility Model (LAUM)

4.3.3.1 Background

The Linear Additive Utility Model (LAUM) is a widely used approach in multi-criteria decision analysis (MCDA) for evaluating and ranking alternatives based on multiple criteria with significant advantages in terms of simplicity and transparency (Figueira et al., 2005) . This model is particularly advantageous in scenarios where decision-making involves balancing various, often conflicting, criteria. It provides a structured and quantifiable method to aggregate different performance metrics into a single composite score, facilitating a more comprehensive evaluation of alternatives (Figueira et al., 2005; Belton & Stewart, 2002).

4.3.3.2 Implement A Linear Additive Utility Model (LAUM)

The condition for implementing LAUM to calculate PI is that the various indices considered in evaluating the performance of SC are mutually preferentially independent (Nassar, 2005) . In other words, it ensures that the preferences for any subset of criteria are independent of the levels of other criteria, allowing for a straightforward additive representation of the utility function. For example, an attribute A is said to be preferentially independent of B if preferences for specific values of A do not depend on B (Nassar, 2005).

Nassar (2005) asserts that the condition of mutual preferential independence can be satisfied in order to decompose the joint utility function into a sum of individual single-attribute utility functions when the utilities are represented by numerical values. In this study, the condition is met because all criteria are quantitative.

Performance index (PI) can be formulated as a linear additive utility model using Equation 4.8.

$$PI = \sum_{i=1}^{n} Wi \times Ii \tag{4.8}$$

Where:

- W_i = utility weight or the relative importance of the performance index (Ii) with respect to the subcontractor performance (PI) upon completion of the project.
- n: the number of indices.

4.3.3 Categorize Performance Levels

Categorizing performance levels using normalization involves converting raw performance scores into a standardized range and then assigning these normalized scores to specific performance categories. Table 4.21 illustrates the normalization of the performance levels. This scale is for demonstration purposes only.

Table 4.21. Normalization of Performance Level Table

PI		
Condition	Rating	Index Range
A	Outstanding Performance	PI > 1.15
B	Exceeds Target	1.05 < PI <= 1.15
C	Within Target	0.95 < PI <= 1.05
D	Below Target	0.85 < PI <= 0.95
F	Poor Performance	PI <= 0.85

4.4 Developing a Comprehensive Decision Support System (DSS) for Selecting the Best SC

4.4.1 Introduction

A decision support system (DSS) is a computerized information system intended to aid decision-makers by incorporating domain-specific knowledge and analytical decision models. It presents relevant information and offers interpretations of various alternatives (Radermacher, 1994) .

In the construction industry, the selection of the best SCs is a critical decision that significantly impacts the overall success of a project. GC must consider a multitude of factors, including bid price, quality, and SC's past performance. The complexity of this decision-making process necessitates the development of a robust and comprehensive decision support system (Clemen & Decisions, 2001).

A comprehensive DSS for subcontractor selection integrates various quantitative and qualitative criteria, ensuring a holistic evaluation of potential subcontractors. DSS leverages multi-criteria decision-making (MCDM) techniques to objectively assess and rank SCs.

Implementing a comprehensive DSS not only streamlines the selection process but also enhances decision accuracy, reduces biases, and fosters continuous improvement. It enables GCs to make informed decisions based on systematic and objective evaluations, ultimately contributing to the successful completion of construction projects. It is crucial to collect all necessary data about potential SCs from the first day of the pre-construction phase, especially for those with whom the general contractor (GC) does not have historical information.

4.4.2 Decision Support System (DSS) Process

Figure 4.24. outlines the steps undertaken to establish a robust decision support system for selecting the best subcontractor for awarding a new project.

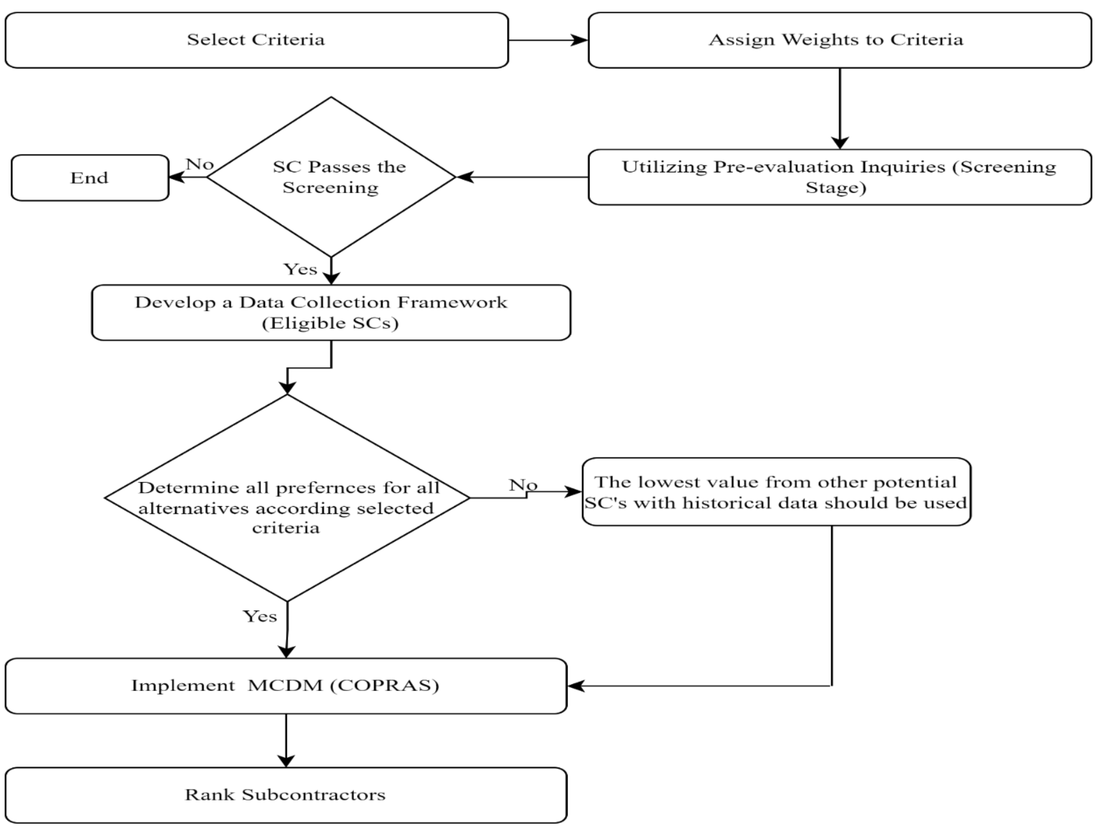


Figure 4.24. Steps of DSS for Selection the Best SC

4.4.2.1 Step 01 and Step 02 (select and weigh criteria):

Regarding the first and second steps, including selecting criteria (eight criteria) and assigning weights to them, these are accomplished in Chapter 3 (refer to Table 3.9). The remaining steps are explained next.

4.4.2.2 Step 03 (Screening Stage):

Implementation of pre-evaluation is considered crucial contractually. A construction contract delineates general and specific conditions according to a project regarding SCs. In other words, each SC must meet these conditions to be included in the list of eligible subcontractors. For instance, one condition may require a subcontractor to have an active professional license in a certain province or a minimum level of experience in specific types of work. If some subcontractors do not meet these conditions, they will not be included in the list of eligible SCs.

4.4.2.3 Step 04. Develop a Data Collection Framework (Eligible SCs):

The acquisition of data related to selected criteria on eligible SCs is a foundational step in creating a reliable and effective DSS for subcontractor selection. It ensures that the data used for evaluation is relevant, accurate, and consistent, thereby supporting comprehensive and objective decision-making. A robust data collection framework enhances the reliability, validity, and transparency of the subcontractor selection process, ultimately contributing to better project outcomes and stakeholder satisfaction.

In the procurement stage and the study of subcontractor prequalification, not all SCs included in the list of eligible SCs are actually known to the GC or have previous experience with them. In this context, this study discusses the two scenarios that the GC may encounter when collecting data on eligible SCs.

4.4.2.3.1 Scenario 01:

In this scenario, all SCs listed as eligible have prior working experience with the GC. Data on these SCs is retrieved from a data repository established through performance assessments conducted upon the completion of previous projects between the same GC and SC. These data include seven criteria as illustrated in Figure 3.9 while eighth criteria (PEC) is related new project by analysis results from utilizing Equations in Table 3.9. The data are highly robust, accurate, and transparent, effectively minimizing bias, as they are derived from quantitative inputs provided by the GC's staff.

In cases where the SC has worked with the GC on multiple projects, the GC implements the application to assess SC performance multiple times, resulting in more values for each criterion. When the GC retrieves data from the data repository, the final value for each criterion is calculated using Equation 4.9, considering the volume of the project, usually represented by the revised value of the contract for each project. It is necessary to indicate that the type, condition, and situation of each project are considered when implementing Equation 4.9. For example, some projects may have a higher percentage of the contract value allocated to equipment, which should be noted accordingly.

$$FV = \frac{\sum_{i=1}^{n} Vi \times RVi}{\sum_{i=1}^{n} RVi} \tag{4.9}$$

Where:

- FV = final value of certain criterion
- V_i= value of certain criterion of each project
- RV_i = revised value of the contract for each project
- n = number of projects

For more clarification, if subcontractor A has worked with general contractor B on three previous projects, it means that the value retrieved for the non-conformance report (NCR) to measure the QC1 sub-criterion for A is calculated using Equation 4.9 as follows:

$$NCR = \frac{NCR1 \times RV1 + NCR2 \times RV2 + NCR2 \times RV2}{RV1 + RV2 + RV3}$$

4.4.2.3.2 Scenario 02:

In this scenario, not all subcontractors (SCs) listed as eligible have prior working experience with the general contractor (GC). This means that the GC does not have data regarding seven criteria for one or more SCs. In this case, the GC should collect data by analyzing SC qualifications, communicating with reference GCs, and using any possible means to obtain data regarding the seven criteria.

To ensure the DSS process is fair, it is necessary to compare all potential subcontractors using the same criteria. Therefore, if any value is unavailable, the lowest value from other potential subcontractors with historical data should be used. It is important to note that Equation 5.9 should be used when there are multiple values for a single criterion.

4.4.2.4 Step 04. Implement Multi Criteria Decision Making Method - COPRAS:

4.4.2.4.1 Introduction

In 1996, the researchers of Vilnius Gediminas Technical University created a method of complex proportional evaluation COPRAS (Complex Proportional Assessment). It is used for multicriteria evaluation of both maximizing and minimizing criteria values (Podvezko, 2011).

This method evaluates both the maximizing and minimizing index values, considering the impact of these attributes separately on the overall assessment results (Alinezhad & Khalili, 2019).

COPRAS is particularly useful for decision-making scenarios where both beneficial (positive impact) and non-beneficial (negative impact) criteria must be considered (Podvezko, 2011; Alinezhad & Khalili, 2019).

4.4.2.4.2 Steps of COPRAS

Method of the COPRAS includes several steps:

- **Step 1**: Construction of Decision Matrix: As in all multiple criteria decision-making problems, the first step is to form a decision matrix. The decision matrix is as follows:

$$\mathbf{X} = \begin{bmatrix} x_{11} & \cdots & x_{1j} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix}_{m \times n} \quad i = 1, \ldots, m, \; j = 1, \ldots, n \quad (4.10)$$

In Equation 4.10, x_{ij} is the i-th alternative assessment value with respect to the j- th criterion, m is the number of alternatives and n is the number of criteria.

➢ **Step 2**: Normalization of decision matrix using the equation 4.11:

$$R= [r_{ij}]= \frac{Xij}{\sum_{i=1}^{m} Xij} \tag{4.11}$$

➢ **Step 3**: Determination of the weighted normalized decision matrix, D, by using the equation 4.12:

$$D= [yij]_{m\times n}= rij\times Wij \tag{4.12}$$

Where r_{ij} is the normalized performance value of i-th alternative on j-th criterion and w_j is the weight of j-th criterion.

➢ **Step 4**: In this step the sums of weighted normalized values are calculated for both the beneficial and nonbeneficial criteria by using the equation 4.13:

$$S(+i) = \sum_{j=1}^{n} y(+ij) \quad , \quad S(-i) = \sum_{j=1}^{n} y(-ij) \tag{4.13}$$

Where $y(+ij)$ and $y(-ij)$ are the weighted nominalized values for the beneficial and non-beneficial criteria, respectively.

➢ **Step 5**: Determination the relative significances of the alternatives, Q_i, by using the equation 4.14:

$$Qi= S(+i) + \frac{\min S(-i) \sum_{i=1}^{m} S(-i)}{S(-i) \sum_{i=1}^{m} \left(\frac{\min\ S(-i)}{S(-i)}\right)} \tag{4.14}$$

➢ **Step 6**: Calculation of the quantitative utility, U_i, for i-th alternative by using the equation 4.15:

$$Ui = \frac{Qi}{Q_{max}} \times 100\% \tag{4.15}$$

Where Q_{max} is the maximum relative significance value. The degree of utility of the alternative is determined by comparing the analyzed alternatives with the most efficient alternative. All the benefits of the degree of benefit related to the analyzed alternatives will range from 0% to 100%.

4.4.2.5 Step 05. Ranking Alternatives:

In this step, the results of the COPRAS method are used to determine the best alternative. The alternatives are ranked based on their quantitative utility (Ui) in descending order. The alternative with the highest quantitative utility is considered the best choice.

Chapter 5: Application of An integrated Model for Evaluation of Performance and the Developed Decision Support System

5.1 Introduction

Chapter 4 outlines the detailed steps of implementing an integrated model for calculating the performance index (PI) of subcontractors (SC) and a decision support system (DSS) for selecting the best SC. In this chapter, a hypothetical example will be provided to demonstrate the application. Firstly, the PI for each SC will be calculated, determining whether each SC is within the target, above, or below expectations upon completing their projects, and storing the historical data. Secondly, the DSS will be applied to select one of the SCs for a new project by retrieving data from the GC's data repository.

5.2 Hypothetical example

5.2.1 Assumption:

The general contractor (GC) X has managed many projects, including three nearly completed ones (P1, P2, and P3). GC X contracted three subcontractors (SC1, SC2, and SC3) for the structural timber work on projects P1, P2, and P3, respectively. GC X intends to evaluate the performance of each SC involved in these projects to analyze lessons learned and improve managerial practices within the organization. After six months, GC (X) needs to decide which subcontractor, among SC1, SC2, and SC3, should be awarded the structural timber works for the new project (P4).

5.2.2 Inputs:

The data input into the model is categorized into two types. Firstly, there is the contractual data, which is agreed upon by the GC and the SC. Secondly, there is the data collected during the execution stage, which pertains to the SC's work performance.

5.2 Application of an integrated Model for Evaluation of Performance (SC1,SC2, and SC3)

Based on steps for calculating performance index (PI) (refer to Figure 4.17) and the utilization of results from MC-AHP (refer to Table 4.13). Figure 5.1 shows the interface of application, and The presented example assumes the data illustrated in Table 5.1 and Table 5.2.

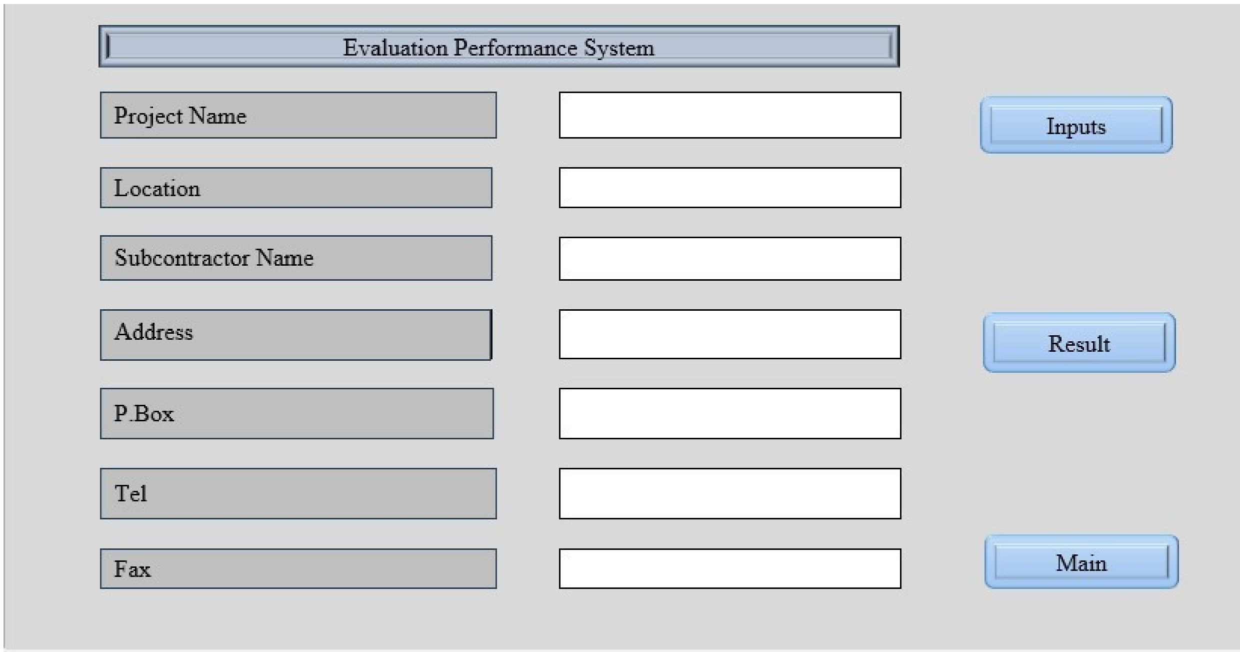


Figure 5.1. Interface of performance System

Table 5.1. Contractual Data of Projects

Projects of GC (X)			
Items	**Project-P1**	**Project-P2**	**Project-P3**
Contract period - days	302	186	109
Contract Value – C$	518,000.00	313,017.00	276,511.00
Commencement date	2022-03-20	2022-08-12	2022-10-18
Number of required technicians according to contract	2	4	1
Number of required professional certificate according to contract	1	1	1
Number of specialized equipment according to contract	1	2	1
Number of meetings that subcontractor should be attended as contract	10	6	8
Number of documents as contract for closing project	12	6	5

Table 5.2. Data Collected Upon Completion of the Project

Sr.N	Data	SC1(P1)	SC2(P2)	SC3(P3)
01	**Time and Schedule**			
	Revised contract period (RC) - days	302	186	109
	Finished date	2023-02-19	2023-02-14	2023-02-02
	Construction Time (CT)	336	186	107
02	**Cost and Finance**			
	Revised contract value (RV)	C$505,820.00	C$307,667.00	C$276,511.00

	Financial claims (FC)	0	C$7,325.00	0
	Frequency of subcontractor submissions of invoices to the GC **X** prior to the contractual dates	2	1	2
	Cost Saving (Tasks)			
	Cost (Task-01)	C$18,000.00	C$23,400.00	-
	Modified cost (Task-01)	C$13,000.00	C$18,050.00	-
	Cost (Task-02)	C$42,082.00	-	-
	Modified cost (Task-02)	C$34,902.00	-	-
	Assessing the frequency of delayed payments (workers and material suppliers) throughout the project.	1	1	0
03	**Quality**			
	Number of non-conformance reports (NCRs) regarding materials	6	2	0
	Number of non-conformance reports (NCRs) related to work requiring rework.	2	3	3
	Number of non-conformance reports (NCRs) related to finished production	3	1	2
04	**Resource Adequacy**			
	Number of technicians and professional certificates (Subcontractor)	1	5	1
	Number of specialized equipment	0	1	0
	Number of software issues	0	2	1
	Total of days of delay in the delivery of materials – days	23	11	5
05	**Occupational Health and Safety and Environmental Protection**			
	Number of incidents of damaging utilities, works or materials by subcontractor workers during project	4	1	0
	Number of fatal incidents by subcontractor workers during project	0	0	0
	Number of reportable safety violation and injuries during project.	3	2	4
	Number of prosecutions made by Labor Department or Union during project	3	0	1
	Number of warnings issued by GC (**X**) regarding subcontractor include the following: Subcontractor kept a dirty workplace on two occasions, improperly stored hazardous materials once, and disposed of construction waste in a manner not compliant with waste management regulations.	5	3	0
06	**GC (X) - Satisfaction**			

	Number of requests for information by subcontractor	4	0	1
	Official letters (sent and responded) from subcontractor	27	13	7
	Official letters (sent and responded) from GC	30	19	10
	Number of attendance meeting by subcontractor	9	5	6
	Number of submitting documents by subcontractor for closing project	12	6	5
	Number of changes required by GC (X)	4	3	1
	Number of accepted changes by subcontractor	3	3	1
	Number of incidents, complaints, or conflicts with other subcontractors reported by GC (**X**) engineers	2	4	0
07	**Leadership**			
	Collaborative Leadership (from three of GC team)	(6,6,9)	(4,5,4)	(4,5,7)
	Dedication (from three of GC team)	(3,5,4)	(5,7,9)	(6,6,8)
	Effective leadership (from three of GC team)	(9,8,9)	(8,8,7)	(4,6,7)

After collecting the required data, the calculation of individual utilities will be completed according to the equations (refer to Table 3.9) and normalized them, as shown in Table 5.3 and Figure 5.2 and Figure 5.3.

Table 5.3. Calculation of Individual Utilities

Table 5.3.1 Calculation of Individual Utilities for Each Project

Sr.N	Indices	Sub-indices	SC1-(P1)	SC2-(P2)	SC3-(P3)
01	STC	STC1	RC/ CT = 0.9	1.00	1.02
02	CFC	CFC1	0	2%	0
		CFC2	2	1	2
		CFC3	20.27	22.86	0
		CFC4	1	1	0
03	QC	QC1	6	2	0
		QC2	2	3	3
		QC3	3	1	2
04	RC	RC1	0.85*	0.93	0.9

		RC2	7.6	5.9	4.6
05	HSC	HSC1	0.93**	1.08	1.125
		HSC2	5	3	0
06	SCC	SCC1	0.96***	0.91	0.89
		SCC2	75%	100%	100%
		SCC3	2	4	0
07	LC	LC1	7.3****	4.3	5.8
		LC2	4.1	7.6	7
		LC3	8.6	6.7	6.1

Table 5.3.2 Detailed Calculation of HSC1 for SC1- (P1)

Calculation of HSC1			
HSC1	Value	Normalization	Refer to
HSC1-1	4	0.85	Table 3.9
HSC2-1	0	1.15	
HSC3-1	3	0.85	
HSC4-1	3	0.85	
HSC1		0.93**	

Table 5.3.3 Detailed Calculation of SCC1 for SC1- (P1)

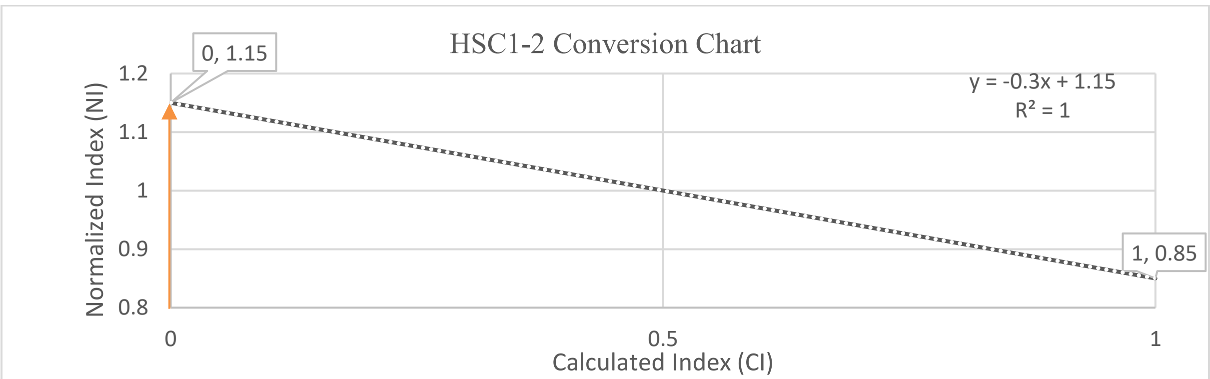
Calculation of SCC1			
SCC1	Value	Normalization	Refer to
SCC1-1	1.03	1.03	Table 4.19
SCC1-2	0.9	0.9	
SCC1-3	1	1	
SCC 1		0.96***	Table 3.9

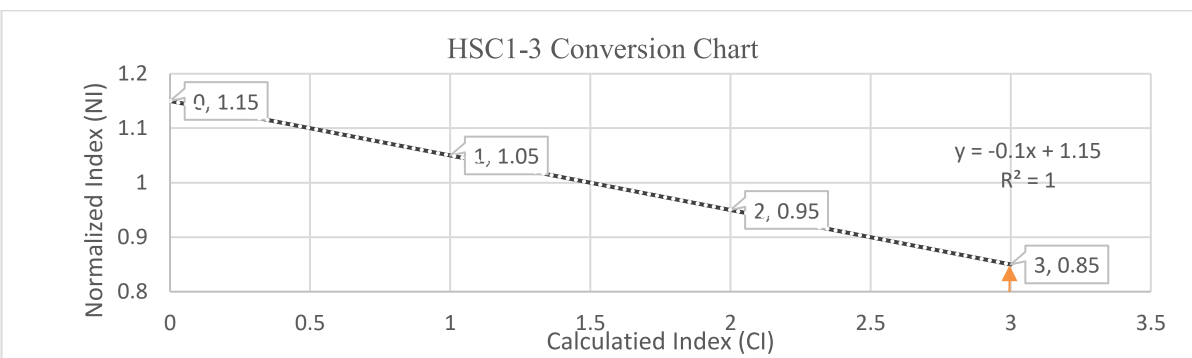
Table 5.3.4 Detailed Calculation of RC1 for SC1- (P1)

Calculation of RC1			
RC1	Value	Normalization	Refer to
RC1-1	0.33	0.85	Table 4.17
RC1-2	0	0.85	
RC 1		0.85*	Table 3.9

Table 5.3.5 Detailed Calculation of LC for SC1- (P1)

Calculation of LC							
GC Team	Weight of GC Team	LC	Value - Team	Final Value	Refer to	Normalization	Refer to
Project Manager	3	LC1	(6,6,9)	7.3****	Table 3.9	0.93	Table 4.20
Site Eng	5	LC2	(3,5,4)	4.1		0.69	
Superintendent	6	LC3	(9,8,9)	8.6		1.03	





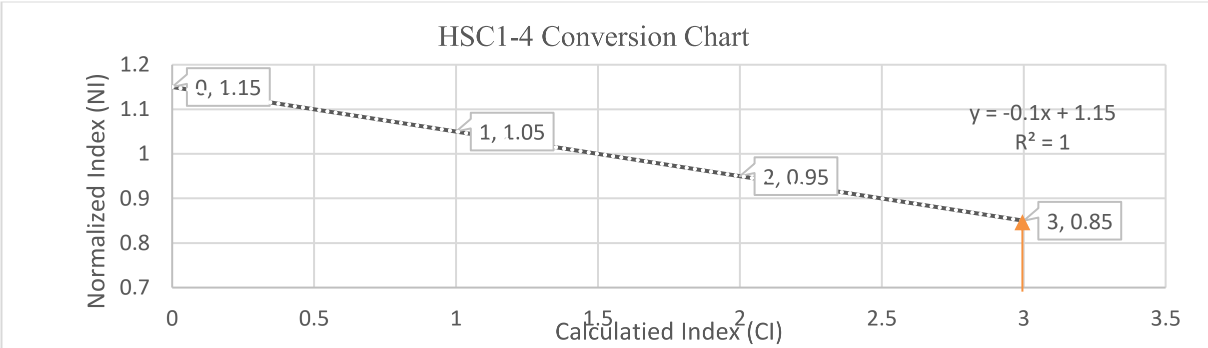


Figure 5.2.Normalization of HSC1 for SC1- (P1)

Table 5.4. Normalization of Individual Utilities

Sub-Indices	**SC1-(P1)**		**SC2-(P2)**		**SC3-(P3)**	
	Value	Normalization	Value	Normalization	Value	Normalization
STC1	0.90	0.90	1.00	1.00	1.02	1.02
CFC1	0	1.15	2%	0.85	0	1.15
CFC2	2	1.03	1	1.05	2	0.95
CFC3	20.27	1.15	22.86	1.15	0	0.85
CFC4	1	1.12	1	1.05	0	1.15
QC1	6	0.95	2	1.05	0	1.15
QC2	2	1.09	3	1.05	3	1.05
QC3	3	0.92	1	1.05	2	1.02
RC1	0.85	0.85	0.93	0.93	0.9	0.85
RC2	7.62	0.85	5.9	0.85	4.6	0.85
HSC1	0.93	1.01	1.08	1.08	1.125	1.13
HSC2	5	0.91	3	0.95	0	1.15
SCC1	0.97	0.99	0.91	0.91	0.89	0.89
SCC2	75%	0.97	100%	1.15	100%	1.15
SCC3	2	1.05	4	0.85	0	1.15
LC1	7.30	1.00	4.3	0.85	5.8	0.85
LC2	4.14	0.85	7.6	0.95	7	0.85
LC3	8.64	1.09	6.7	0.88	6.1	0.85

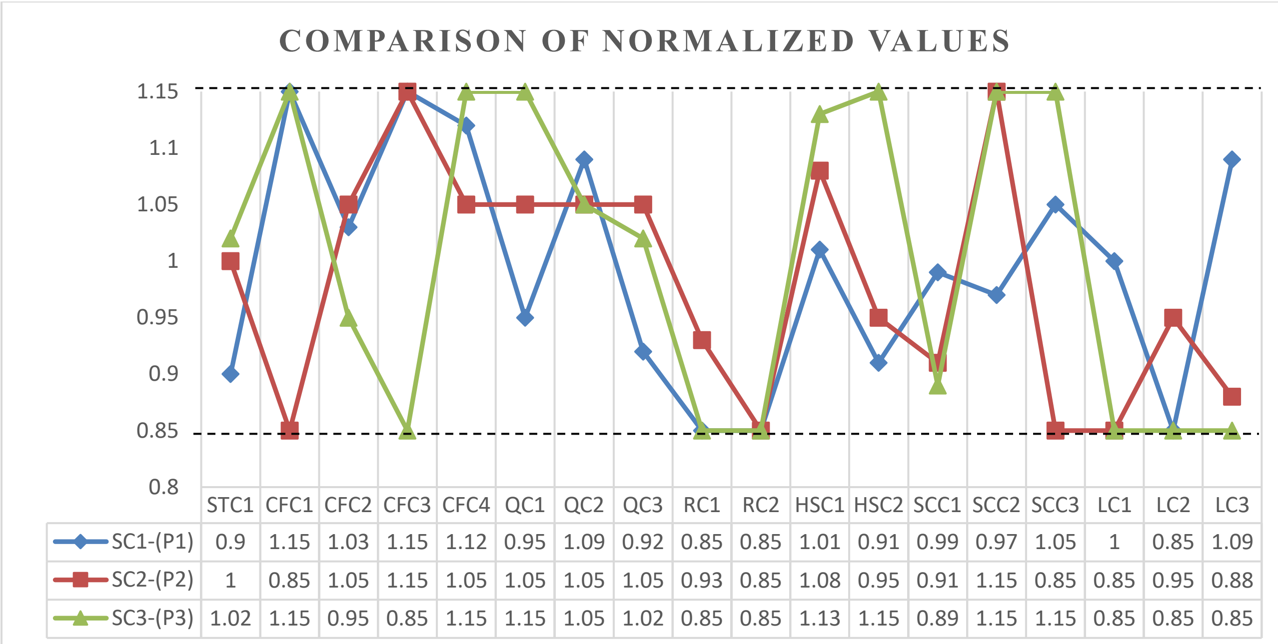


Figure 5.3. Comparison of Normalized Values

Lastly, the performance index (PI) will be calculated and the final weights (refer to Table 4.13). The performance levels will be categorized according to Table 4.21 for each SC, as shown in Table 5.5 and Table 5.6.

Table 5.5. Calculation of PI for Each SC

Sub-Indices		**SC1-(P1)**	**SC2-(P2)**	**SC3-(P3)**	**PI**		
	Weight **(W)**	Normalization **(N_1)**	Normalization **(N_2)**	Normalization **(N_3)**	**W×N_1**	**W×N_2**	**W×N_3**
STC1	0.148	0.90	1.00	1.02	0.13	0.15	0.15
CFC1	0.045	1.15	0.85	1.15	0.05	0.04	0.05
CFC2	0.019	1.03	1.05	0.95	0.02	0.02	0.02
CFC3	0.014	1.15	1.15	0.85	0.02	0.02	0.01
CFC4	0.009	1.12	1.05	1.15	0.01	0.01	0.01
QC1	0.136	0.95	1.05	1.15	0.13	0.14	0.16
QC2	0.044	1.09	1.05	1.05	0.05	0.05	0.05
QC3	0.086	0.92	1.05	1.02	0.08	0.09	0.09
RC1	0.034	0.85	0.93	0.85	0.03	0.03	0.03

RC2	0.034	0.85	0.85	0.85	0.03	0.03	0.03
HSC1	0.249	1.01	1.08	1.13	0.25	0.27	0.28
HSC2	0.062	0.91	0.95	1.15	0.06	0.06	0.07
SCC1	0.041	0.99	0.91	0.89	0.04	0.04	0.04
SCC2	0.025	0.97	1.15	1.15	0.02	0.03	0.03
SCC3	0.015	1.05	0.85	1.15	0.02	0.01	0.02
LC1	0.026	1.00	0.85	0.85	0.03	0.02	0.02
LC2	0.016	0.85	0.95	0.85	0.01	0.02	0.01
LC3	0.009	1.09	0.88	0.85	0.01	0.01	0.01
PI= $\sum$ W × N					**0.99**	**1.02**	**1.07**

Table 5.6. Categorization of Level of Each SC

	SC1-(P1)	**SC2-(P2)**	**SC3-(P3)**
PI	0.99	1.02	1.07
Level of Tolerance	Hight Tolerance	Medium Tolerance	Medium Tolerance
Level of Performance	Within Target	Within Target	Exceeds Target

Based on th results (refer to Table 5.6), the performance of SC3 in the third project (P3) exceeds the target, while SC1 in the first project (P1) and SC2 are within target. This is corroborated by the comparison of normalized values across various indices. SC3 consistently outperforms the other SCs in most indices, demonstrating fewer issues with safety and quality and completing the project ahead of schedule.

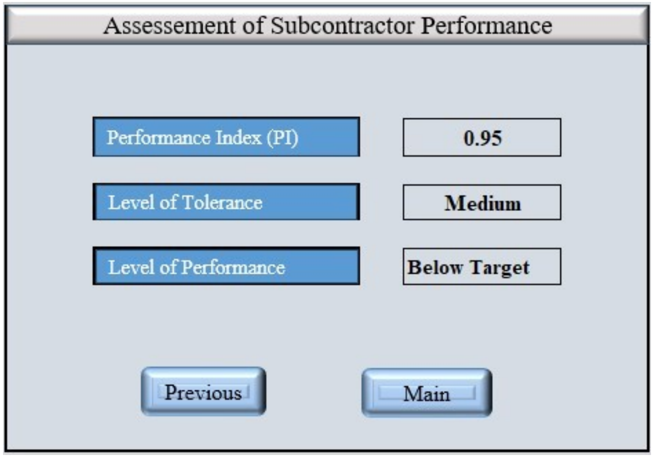


Figure 5.4. Assessment of SC1 Performance (Medium of Tolerance)

5.2 Application of the Developed Decision Support System to Select the Best SC

After six months, GC (X) needs to decide which subcontractor, among SC1, SC2, SC3, and SC4, should be awarded the structural timber works for the new project (P4). The contractual conditions for awarding SC in project (P4) are that the candidate SC must have at least 6 years of experience in the construction industry and a commercial license in the same province as the project and minimum number of specialized equipment. Figure 5.5 shows the interface of application, and the presented example assumes the data illustrated in Table 5.7.

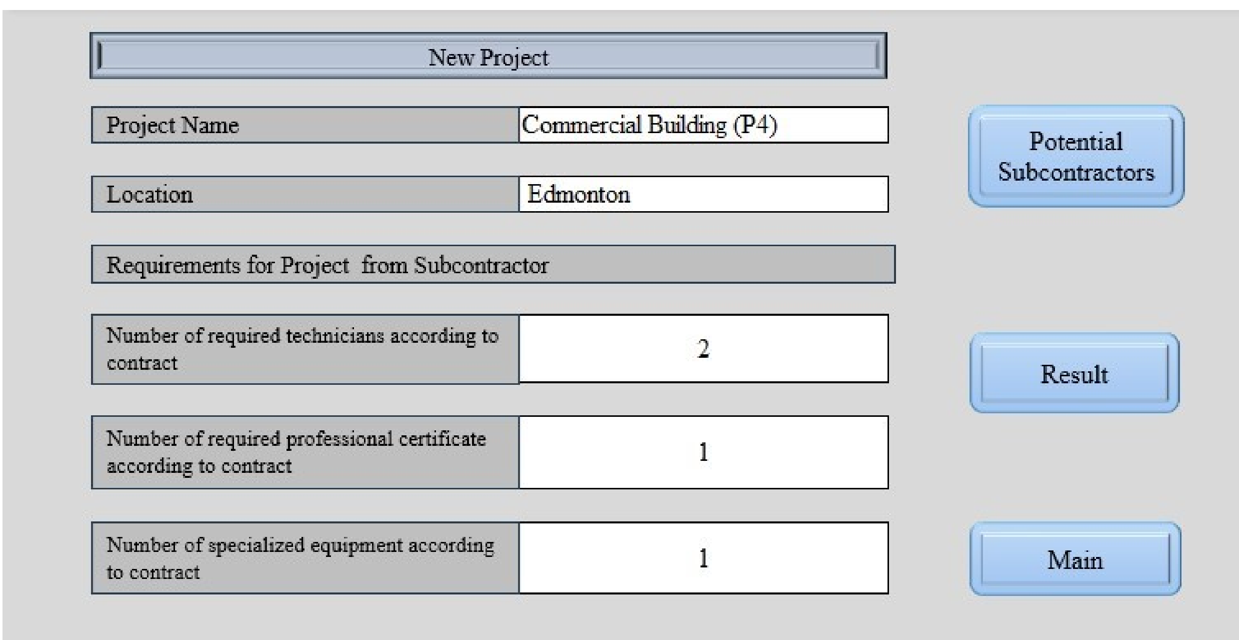


Figure 5.5. Interface of DSS

Table 5.7. Data of SCs Regarding Financial Capacity and Experience

Item	SC1	SC2	SC3	SC4
Bid offer	217,296.00	203,200.00	228,100.00	196,820.00
Profitability (PI)	4.4%	4%	2%	6%
Growth (GI)	2.9%	2.3%	1.1%	3.2%
Activeness (AI)	1.05%	0.9%	1.01%	1.4%
/3/ year average annual revenue	346,050	212,819	312,000	308,006
Credit rating score	22	16	20	20
Experience of similar works	11	9	6	4
Experience in the construction industry	14	9	10	4

Application of DSS requires the steps described in Figure 4.24. Firstly, using the screening stage according to the conditions, it was determined that SC4 did not meet the requirements. Therefore, the shortlist of SCs includes SC1, SC2, and SC3.

Secondly, referring to Table 3.9, data collection and determination of all preferences for the accepted alternatives (SC1, SC2, and SC3) are accomplished by retrieving information from a data repository established after the completion of projects P1, P2, and P3. Table 5.8 shows all preferences that will be used in DSS.

Table 5.8. Preferences of SCs

Sr.N	Criteria	Sub-Criteria	SC1	SC2	SC3
1	PEC	PEC1	217,296.00	203,200.00	228,100.00
		PEC2	69,214.42[#]	42,567.01	62,404.01
		PEC3	11	9	6
		PEC4	14	9	10
2	STC	STC1	0.9	1	1.02
3	CFC	CFC1	0	0.02	0
		CFC2	2	1	2
		CFC3	20.27	22.86	0
		CFC4	1	1	0
4	QC	QC1	6	2	0
		QC2	2	3	3
		QC3	3	1	2
5	RC	RC1	0.17	0.67	0.17
		RC2	0.08	0.06	0.05
6	HSC	HSC1	2.5	0.75	1.25
		HSC2	5	3	0

7	SCC	SCC1	0.97	0.83	0.84
		SCC2	75%	100%	100%
		SCC3	2	4	0
8	LC	LC1	7.3	4.3	5.8
		LC2	4.1	7.6	7
		LC3	8.6	6.7	6.1

Table 5.9. Detailed Calculation of PEC2 for SC1

Calculation of PEC2 for SC1		
Item	Value	Refer to
PI	4.4%	Table 3.9
GI	2.9%	
AI	1.05%	
SI-1	346,050	
SI-2	22	
PEC2	69,214.42#	

Next, MCDM (COPRAS) is implemented by utilizing data from Table 5.10 created from Table 5.8. All steps of COPRAS are coded in Python to automate the entire process. After inputting the number of alternatives, the number of criteria, the weights of the criteria, and the influence of each criterion, the final outputs include the quantitative utility (UI) and a chart ranking the alternatives as shown Figure 5.6 and Figure 5.7.

Table 5.10. Sub-Criteria and weights

Sub-Criteria	**SC1**	**SC2**	**SC3**	**Weights**	**Influence**
PEC1	217,296.00	203,200.00	228,100.00	0.0994	Cost Criterion
PEC2	69,214.42	42,567.01	62,404.01	0.0649	Beneficial Criterion
PEC3	11	9	6	0.0341	Beneficial Criterion
PEC4	14	9	10	0.0213	Beneficial Criterion
STC1	0.9	1	1.02	0.1090	Beneficial Criterion
CFC1	0	2%	0	0.0330	Cost Criterion
CFC2	2	1	2	0.0143	Cost Criterion
CFC3	20.27	22.86	0	0.0103	Beneficial Criterion
CFC4	1	1	0	0.0063	Cost Criterion
QC1	6	2	0	0.0954	Cost Criterion

QC2	2	3	3	0.0310	Cost Criterion
QC3	3	1	2	0.0604	Cost Criterion
RC1	0.17	0.75	0.25	0.0320	Beneficial Criterion
RC2	0.08	0.06	0.05	0.0320	Cost Criterion
HSC1	2.5	0.75	1.25	0.2048	Cost Criterion
HSC2	5	3	0	0.0512	Cost Criterion
SCC1	0.96	0.91	0.89	0.0287	Beneficial Criterion
SCC2	75%	100%	100%	0.0170	Beneficial Criterion
SCC3	2	4	0	0.0102	Cost Criterion
LC1	7.3	4.3	5.8	0.0203	Beneficial Criterion
LC2	4.1	7.6	7	0.0125	Beneficial Criterion
LC3	8.6	6.7	6.1	0.0071	Beneficial Criterion

```
In [ ]: COPRAS Steps:

import numpy as np
from pymcdm.methods import copras
from pymcdm.helpers import rrankdata
import matplotlib.pyplot as plt
import pandas as pd

# Step 1: Input Initialization
INPUT num_criteria
INPUT criteria_labels FOR num_criteria
INPUT num_alternatives
INPUT alternative_labels FOR num_alternatives
INPUT weights AND types FOR num_criteria
INPUT decision_matrix FOR num_alternatives AND num_criteria

# Print the Decision Matrix
CONVERT decision_matrix TO DataFrame df_decision_matrix
PRINT df_decision_matrix

# Step 2: Method Object Creation
CREATE method AS new copras.COPRAS()

# Step 3: Quantitative Utility and Ranking Calculation
COMPUTE Ui USING method(decision_matrix, weights, types)
COMPUTE ranking USING rrankdata(Ui)

# Step 4: Sort Alternatives and Utilities
SORT Ui IN descending order TO GET sorted_indices
MAP sorted_indices TO sorted_alternatives AND sorted_utilities

# Step 5: Plotting
CREATE bar chart OF sorted_alternatives AND sorted_utilities * 100
LABEL plot AND axes
SHOW plot

# Step 6: Create a new ranking based on utility values
COMPUTE utility_ranking USING np.argsort(sorted_utilities)[::-1] + 1

# Step 7: Print Ranking based on utility
CREATE DataFrame df_results WITH sorted_alternatives, utility_ranking, AND sorted_utilities * 100
PRINT df_results
```

Figure 5.6. pseudocode for COPRAS steps

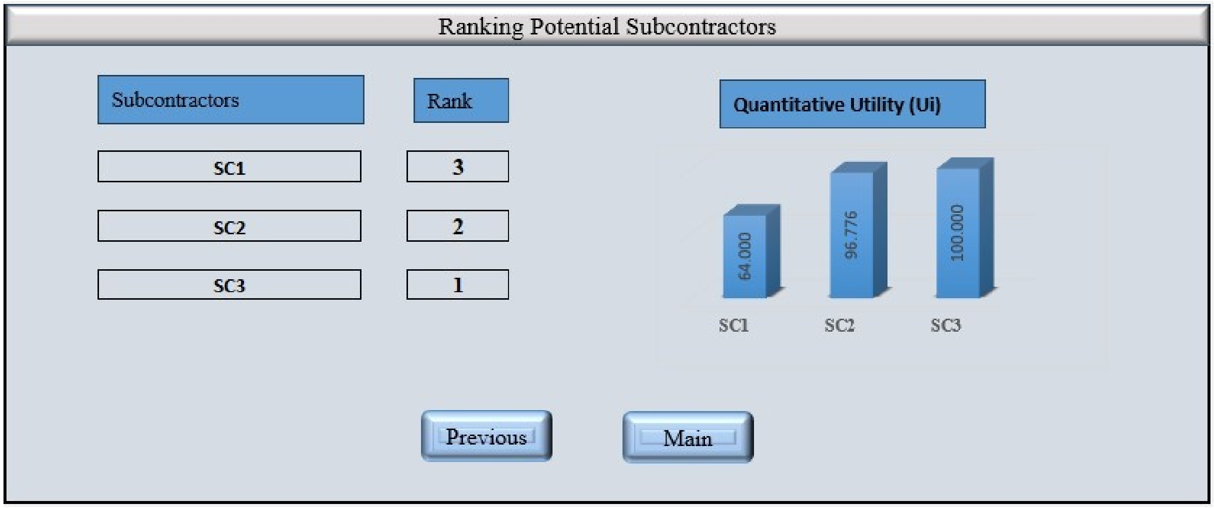


Figure 5.7. Rank Alternatives

Chapter 6: Verification and Validation

6.1 Introduction

This chapter explored the methods used for verifying and validating calculations, as well as for developing the performance evaluation model and decision support system (DSS). Input and output validation was conducted through expert feedback and comments, while verification of the calculations, performance evaluation model, and DSS was performed using sensitivity analysis.

6.2 Sensitivity Analysis

Sensitivity analysis is an invaluable tool for understanding the behavior of complex models and making informed decisions based on model outputs . By systematically varying input variables and analyzing the resulting changes in output, sensitivity analysis helps identify key drivers, validate models, manage risks, and optimize performance across various fields (Helton et al., 2003; Saltelli et al., 2004). Researchers used different techniques like Monte Carlo Simulations and Regression Analysis (Helton et al., 2003).

6.2.1 Normalization Sensitivity for evaluation PI

The sensitivity of value normalization is examined according to three levels of tolerance to calculate the Performance Index (PI). These levels include high-level tolerance (HLT), medium-level tolerance (MLT), and low-level tolerance (LLT). Table 6.1 and Figure 6.1 illustrate three scenarios for calculating the PI based on these levels of tolerance. Scenario 01 implements the model for three projects with low-level tolerance, Scenario 02 implements the model for three projects with medium-level tolerance, and Scenario 03 implements the model for three projects with high-level tolerance.

Table 6.1. Calculation of PI According to Scenarios

Scenarios	SC	Project	Contract ID	Level of Tolerance	PI	Categorize level of performance
Scenario 01	SC1	P1	P11	High	0.991	Within Target
	SC2	P2	P22	High	1.046	Within Target
	SC3	P3	P33	High	1.097	Exceed Target
Scenario 02	SC1	P1	P11	Medium	0.935	Below Target
	SC2	P2	P22	Medium	1.006	Within Target
	SC3	P3	P33	Medium	1.078	Exceed Target
Scenario 03	SC1	P1	P11	Low	0.908	Below Target
	SC2	P2	P22	Low	0.981	Within Target
	SC3	P3	P33	Low	1.074	Exceed Target

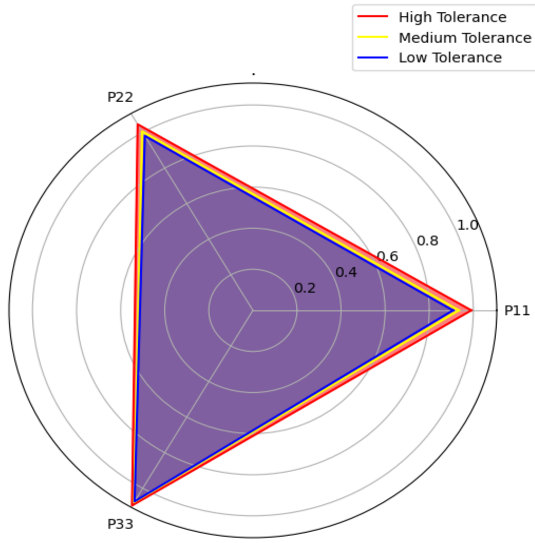


Figure 6.1. Rader Chart - The Sensitivity of The Model for Tolerance Level

6.2.1.1 Interpretation of Sensitivity Results:

1. Consistency Across Projects:
    - P33 consistently performs well across all tolerance levels, always falling into the "Exceed Target" category. This suggests that P33 is robust and performs well under varying conditions.
    - P22 remains within the target range for both High and Medium tolerance levels and slightly below target for Low tolerance. This indicates good performance but suggests potential areas for improvement under stricter conditions.
    - P11 struggles more with lower tolerance levels, dropping below the target. This points to potential vulnerabilities that need to be addressed for P11 to improve its performance under stricter criteria.
2. Impact of Tolerance Levels:
    - As tolerance levels decrease from High to Low, there is a noticeable drop in the Performance Index for all SC. This is expected, as stricter criteria typically expose more weaknesses and reduce overall performance metrics.
    - The variance in performance indices between tolerance levels is more pronounced for P11, indicating it is more sensitive to changes in criteria stringency compared to P22 and P33.

6.2.2 Criteria Weightage Sensitivity for DSS

The sensitivity of the criteria weights was analyzed through the creation of four different scenarios. The first scenario involved testing the sensitivity of the criterion with the highest weight (HSC1) by increasing and decreasing its value by a percentage and adjusting the other weights proportionally to maintain a total weight sum of 1.

The second scenario followed a similar approach, focusing on the criterion with the second-highest weight (STC). The third scenario encompassed adjustments by increasing and decreasing the weights of the beneficial criteria while proportionally adjusting the cost weights to keep the total weight sum equal to 1. The final scenario included increasing and decreasing the weights of the cost criteria and adjusting the beneficial weights proportionally. These scenarios were then tested to observe their influence on the UI values of the developed DSS, which express the ranking of alternatives.

6.2.2.1 Sensitivity Results:

6.2.2.1.1 Scenario 01

The sensitivity analysis for criterion HSC1 reveals that changes in its weight significantly influence the rankings of alternatives SC1, SC2, and SC3 as shown in Figure 6.2. When the weight for HSC1 decreases by 5% to 50%, the ranking consistently places SC3 first, SC2 second, and SC1 third. Conversely, increasing the weight of HSC1 by 30% to 50% consistently results in SC2 achieving the highest rank, followed by SC3 in second place and SC1 in third. This demonstrates that criterion HSC1 has a critical impact on the alternative rankings, with higher weights favoring SC2 and lower weights maintaining SC3 at the top .

6.2.2.1.2 Scenario 02

The sensitivity analysis for criterion STC reveals that changes in its weight primarily influence the UI values of alternative SC1, while the UI values for SC2 and SC3 remain stable as illustrated Figure 6.2. Reductions in STC weight lead to a gradual decrease in SC1's UI value, from 63.60 to 62.49, with SC2's UI value consistently around 96.61 and SC3 maintaining a perfect score of 100. Conversely, increases in STC weight result in a steady rise in SC1's UI value, from 64.70 to 65.81, while SC2's UI value slightly increases to 96.75, and SC3 continues to score 100. Despite these variations, the overall ranking of alternatives remains unchanged across all weight adjustments.

6.2.2.1.3 Scenario 03

The sensitivity analysis for the beneficial weights criterion reveals that varying its weight affects the rankings of alternatives SC1, SC2, and SC3 as shown in Figure 6.2. For decreases and moderate increases in weight, SC3 consistently holds the top position, followed by SC2 in second and SC1 in third. However, with higher weight increases (45% and 50%), SC2 advances to first place, SC3 falls to second, and SC1 remains third. This suggests that increasing the weight of the Beneficial Weights criterion benefits SC2's position relative to SC3, while SC1 consistently remains in the third position across all weight adjustments.

6.2.2.1.4 Scenario 04

The sensitivity analysis for the Cost Weights criterion reveals that changes in weight affect the rankings of the alternatives SC1, SC2, and SC3 as illustrated in Figure 6.2. When the weight is reduced by 10% to 20%, SC3 consistently ranks first, SC2 second, and SC1 third. However, as the weight decreases further, by 25% to 50%, SC2 overtakes SC3, becoming the highest-ranked alternative, with SC3 dropping to second place, and SC1 remaining in third. On the other hand, when the weight is increased by 25% to 50%, the rankings revert to SC3 in first place, SC2 in second, and SC1 in third. This analysis demonstrates that while SC3 generally maintains the top position, a significant decrease in the cost weights criterion allows SC2 to surpass it, altering the relative rankings.

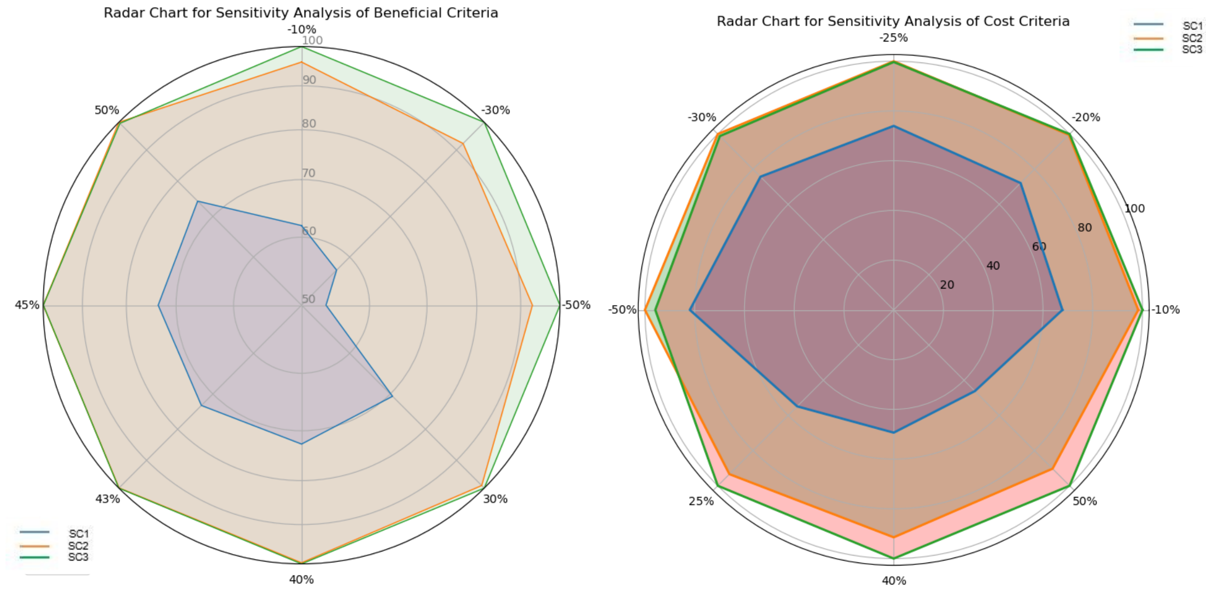


Figure 6.2. Radar Charts for Four Different Scenarios

6.3 Experts Validation

During the meeting held with industry experts to validate the model for assessing subcontractor performance and the decision support system for selecting the best subcontractor, the experts provided feedback and comments.

6.3.1 Evaluation System

The expert referred that evaluation system is robust because it depend on objective evaluations except leadership that rely on work team and data required to conduct process of evaluation are available through the documents of project or reports of safety offices or procurement departments or daily and weekly reports from site GC team.

The experts highlighted that considering the number of software issues as part of measuring resource adequacy is unnecessary, as subcontractors either do not need to use software or complex software, or they are already familiar with the required software from the outset.

The experts emphasized that the contract value, used to calculate certain indices, must be determined accurately, as the contract value in some projects awarded to subcontractors does not represent the true volume of work. For instance, in projects where the scope includes both the supply and installation of medical equipment, the actual work may represent only 30%–40% of the contract value. Therefore, considering the real volume of work is crucial to ensuring an accurate assessment of subcontractor performance.

The experts noted that the application provides three assumptions for normalizing indices to scale them within certain ranges based on the level of tolerance. While one expert agreed with this approach, another remarked that each contract between the project and the subcontractor involves specific circumstances and conditions. Therefore, it would be more reasonable for the general contractor's management to determine the normalization ranges in accordance with regulations and organizational objectives, particularly for distinct project contracts or sensitive work.

6.3.2 Decision Support System

The developed decision support system was implemented to select the best subcontractor for a new project. The experts agreed on the comprehensive criteria used for comparison and recognized that utilizing qualitative inputs rather than quantitative ones is beneficial and reduces bias in decision-making.

One expert emphasized that the criterion related to financial capacity does not provide a comprehensive assessment of a subcontractor's financial capability. This expert argued that financial capacity alone might be insufficient for capturing the full scope of a subcontractor's financial health and stability. Therefore, the expert suggested incorporating additional financial indicators or metrics to create a more holistic evaluation of a subcontractor's financial capability.

The experts questioned whether some data might be missing when the required information was collected from historical records (where the subcontractor had previously worked with the general contractor), by directly asking the subcontractor, or by consulting another general contractor with experience with the subcontractor (in cases where there is no historical data available with the current general contractor). They inquired about the process for addressing this issue.

The application addresses missing data by utilizing lower values (if the criterion is beneficial) or higher values (if the criterion relates to cost) from other subcontractors participating in the comparison process who have previously worked with the general contractor, while maintaining all criteria and their weights. Some experts support this approach as a means to resolve the issue, while others suggest excluding the weight of criteria associated with missing values and proportionally adjusting the weights of the remaining criteria to ensure that the total weight sums to 1, with the goal of achieving a fairer decision-making process.

6.3.3 Steps Taken to Address Experts' Feedback and Comments

In the development and refinement of both the evaluation system and the decision support system, incorporating expert feedback is crucial for enhancing the system's effectiveness and reliability. This section details the actions taken to address the feedback and comments provided by experts throughout the evaluation process. By systematically integrating expert insights, the study aims to improve the system's methodology, accuracy, and practical applicability. The goal is to align the system more closely with user needs and expectations through the incorporation of expert recommendations. This process involves assessing the validity of the feedback, implementing necessary adjustments, and documenting the modifications to accurately reflect the expert input.

- Regarding the number of software issues, it has been excluded from the criteria for measuring resource adequacy in the evaluation system, as it is deemed unnecessary.
- A note has been added to the end-user interface of the application to exclude values that do not accurately reflect the true volume of work (such as equipment) if these values increase by 10% or more compared to the contract value. This adjustment in contract value is intended to ensure a more accurate performance evaluation within the system.
- In response to comments regarding the criterion related to financial capacity, a discussion was held with experts. It was determined that a comprehensive financial assessment of potential subcontractors is conducted by a specialized department within the general contractor's organization. This assessment forms part of a focused study to evaluate this criterion more thoroughly.
- Regarding the approach to address missing information, the system employs a method that maintains all criteria and their respective weights while utilizing values from other subcontractors involved in the comparison process who have previously worked with the general contractor. This approach is designed to ensure fairness to subcontractors with known performance histories.

Chapter 7: Conclusions and Recommendations

7.1 Study Overview

The development of a performance assessment model for subcontractors upon the completion of projects and decision support system to select the best subcontractor for new project are a significant advancement for the construction industry. Traditional subcontractor evaluation methods often focus narrowly on the bidding process or the execution phase, with insufficient emphasis on comprehensive performance assessments at project completion. This narrow focus can result in incomplete evaluations and hinder accurate subcontractor selection for future projects. By creating a detailed performance assessment model based on specific indices, construction firms can systematically evaluate subcontractors across a range of critical criteria, including time, cost, quality, safety, and leadership.

This models provide a structured approach to quantifying subcontractor performance through objective metrics, which enhances decision-making accuracy and reduces the risk of bias inherent in subjective evaluations. Implementing quantitative scales and objective measurements ensures a higher degree of transparency and consistency in the evaluation process. Additionally, incorporating practices regarding in waste management and cleaning workplace into the performance assessment framework aligns with the growing emphasis on environmental responsibility in construction projects.

Furthermore, linking the performance assessments of subcontractors upon completed projects with the selection process for new projects offers a comprehensive framework for subcontractor selection. This integration ensures that past performance is systematically considered when choosing subcontractors for future projects, leading to more informed and effective decision-making. The use of a multi-criteria decision-making (MCDM) method within this framework allows for the balancing of various evaluation criteria, providing a holistic view of subcontractor capabilities and performance. Ultimately, this approach improves project outcomes by optimizing subcontractor selection, enhancing resource allocation, and increasing client satisfaction, thereby addressing existing gaps in subcontractor evaluation practices and contributing to overall project success.

7.2 Conclusions

To determine the research objectives, a literature review of relevant studies and journal papers was conducted, and meetings were held with experts from the Canadian construction industry. Subsequently, the research gaps were identified, and the objectives were established. Additionally, the review included an examination of methods and tools used by researchers in multi-criteria decision-making (MCDM) to select the best subcontractors and methods for weighing criteria.

One of the critical challenges is identifying the indices used to assess the performance of subcontractors, the criteria used in decision support systems, and the relationships between indices and criteria. To address this challenge, thirty-six studies (thirteen focusing on performance evaluation and twenty-three on the selection process) were analyzed. Two methods were employed to analyze and identify the most important criteria mentioned in these studies.

Firstly, the Relative Usage Index (RUI) method calculates the frequency of each sub-criterion by summing the values in each row of a matrix. These frequency values are then used to compute the RUI values via a specified equation, which helps in identifying the most and least frequently mentioned criteria. Secondly, social network analysis (SNA) treats each criterion as a node within a network. Relationships (edges) between nodes are inferred if the criteria are co-mentioned within the same source.

The analysis reveals that the indices include time, cost and finance, quality, resource adequacy, occupational health and safety, general contractor satisfaction, and leadership. The criteria encompass these indices along with the additional factors of pricing and experience. Additionally, the analysis identifies which criteria are beneficial (positive) and which are cost-related (negative).

Another objective is to weigh the identified indices and criteria while minimizing bias. To achieve this, a hybrid approach combining Monte Carlo simulation with AHP is employed. This approach provides statistical significance to the results and helps mitigate judgment uncertainty. The process begins with preparing a pairwise comparison matrix between criteria based on expert opinions. Next, three probability distribution functions (normal, triangular, and lognormal) are defined for each deterministic variable. Pairwise matrices are then created using random values (100,000 simulations), followed by a consistency ratio check (CR < 0.1). Finally, the weights for each index and criterion are determined.

The results indicate that the safety criterion has the highest weight, followed by time and quality, while the remaining criteria are closely aligned.

To achieve the objective of making the performance assessment and selection process more accurate and transparent, it is essential to use objective measurements rather than subjective ones. Therefore, the identified criteria are formulated based on previous studies or expert experience. All criteria are measured using quantitative inputs, with the exception of the leadership criterion. The formulas for these measurements have been discussed and agreed upon by academic and industry experts.

After identifying and weighing the important indices and criteria and formulating them, an integrated model for subcontractor assessment is developed. To conduct a performance assessment, issues related to scale and unit differences must be addressed. Therefore, a normalization approach is implemented, with three categories of normalization based on the level of tolerance. The final step involves calculating the Performance Index (PI) using a Linear Additive Utility Model (LAUM) and categorizing performance levels into outstanding performance, exceeding target, within target, below target, and poor performance.

Finally, a decision support system (DSS) is developed to select the best subcontractor for awarding a new project. The process begins with conducting a screening procedure to determine a list of eligible subcontractors, followed by the collection of data that should be relevant, accurate, and transparent. To achieve this, data is retrieved from a data repository established through performance assessments conducted upon the completion of previous projects between the same general contractor (GC) and subcontractor (SC). Additionally, data is collected by analyzing SC qualifications, communicating with reference GCs, and using any available means to obtain information regarding the criteria. To complete the DSS process, the best subcontractor is determined by implementing the Complex Proportional Assessment (COPRAS) method, which is a multi-criteria decision-making (MCDM) technique used to evaluate and rank alternatives based on multiple criteria, considering whether each criterion is beneficial or cost related.

7.3 Limitations

This research employs a hybrid method combining Monte Carlo simulation with AHP to weigh indices and criteria. This approach requires data, specifically expert opinions, to create probability distributions. Accurately assigning the type of distribution depends on the volume of data available. In this study, opinions from three experts were used to create three probability distributions (normal, triangular, and lognormal). A larger number of experts would provide a more comprehensive basis for determining the type of distribution.

Additionally, the number of industry experts who participated in the model validation process is limited and primarily from general contractors (GCs). This may be considered a limitation, as more experts from different perspectives would be beneficial to form a more diverse and representative panel.

Furthermore, the Linear Additive Utility Model (LAUM) was employed in this research with three levels of normalization (low, medium, and high). Formulas were generated based on these normalization levels and applied accordingly. Modifying the normalization levels for any given scenario requires re-coding new formulas based on the updated levels. This is considered a limitation of the application.

7.4 Recommendations for Future Work

This research focuses on the assessment of subcontractors upon project completion. Future researchers can focus on the objective assessment of subcontractors periodically during the project's progress. Additionally, The application is considered a generic at first and second and third level (Criteria and Sub-criteria and measurements). Therefore, researchers can explore cross-industry applications by investigating the applicability of the hybrid approach in other industries at third level where subcontractor assessment and selection are critical, such as manufacturing, oil and gas, or IT services, to identify potential cross-industry benefits and insights.

Bibliography:

Abbasianjahromi, H., Rajaie, H., & Shakeri, E. (2013). A framework for subcontractor selection in the construction industry. Journal of Civil Engineering and Management, 19(2), 158-168. https://doi.org/10.3846/13923730.2012.743922

Abbasianjahromi, H., Sepehri, M., & Abbasi, O. (2018). A decision-making framework for subcontractor selection in construction projects. Engineering Management Journal, 30(2), 141-152. https://doi.org/10.1080/10429247.2018.1448967

Abdull Rahman, S. H., Mat Isa, C. M., Kamaruding, M., & Nusa, F. N. M. (2024). Performance Measurement Criteria. In Green Infrastructure: Materials and Sustainable Management. Singapore: Springer Nature Singapore. http://dx.doi.org/10.1007/978-981-99-7003-2_3

Afshar, M. R., Shahhosseini, V., & Sebt, M. H. (2022). Optimal sub-contractor selection and allocation in a multiple construction project: Project portfolio planning in practice. Journal of the Operational Research Society, 73(2), 351-364. https://doi.org/10.1080/01605682.2020.1835450

Akintoye, A., & Skitmore, M. (1991). Profitability of UK construction contractors. Construction Management and Economics, 9(4), 311-325. https://doi.org/10.1080/01446199100000025

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. https://doi.org/10.1023/b:jims.0000034112.00652.4c

Ali-Mohammad, A., Mahdi, B., & Zahra, A. (2010, February). The critical path definition with fuzzy multi criteria decision making. https://doi.org/10.1109/iccae.2010.5451469

Alinezhad, A., & Khalili, J. (2019). New methods and applications in multiple attribute decision making (MADM) (Vol. 277, pp. 199-203). Cham: Springer. https://doi.org/10.1007/978-3-030-15009-9_26

Arditi, D., & Chotibhongs, R. (2005). Issues in subcontracting practice. Journal of construction engineering and management, 131(8), 866-876. https://doi.org/10.1061/(asce)0733-9364(2005)131:8(866)

Arroyo, P., Tommelein, I., & Ballard, G. (2012, July). Deciding a sustainable alternative by 'choosing by advantages' in the AEC industry. https://doi.org/10.1061/9780784412688.104

Arslan, G., Kivrak, S., Birgonul, M. T., & Dikmen, I. (2008). Improving sub-contractor selection process in construction projects: Web-based sub-contractor evaluation system (WEBSES). Automation in Construction, 17(4), 480-488. https://doi.org/10.1016/j.autcon.2007.08.004

Ataei, M., Shahsavany, H., & Mikaeil, R. (2013). Monte Carlo Analytic Hierarchy Process (MAHP) approach to selection of optimum mining method. International Journal of Mining Science and Technology, 23(4), 573-578. https://doi.org/10.1016/j.ijmst.2013.07.017

Banzon, M. J. R., Bacudio, L. R., & Promentilla, M. A. B. (2016, March). Application of Monte Carlo analytic hierarchical process (MCAHP) in the prioritization of theme park service quality elements. In Proceedings of the 2016 International Conference on Industrial Engineering and Operations Management. https://ieomsociety.org/ieom_2016/pdfs/339.pdf

Başaran, Y., Aladağ, H., & Işık, Z. (2023). Pythagorean Fuzzy AHP Based Dynamic Subcontractor Management Framework. Buildings, 13(5), 1351. https://doi.org/10.3390/buildings13051351

Bastian, M., Heymann, S., & Jacomy, M. (2009, March). Gephi: an open source software for exploring and manipulating networks. In Proceedings of the international AAAI conference on web and social media. https://doi.org/10.1609/icwsm.v3i1.13937

Belton, V., & Stewart, T. (2002). Multiple criteria decision analysis: an integrated approach. Springer Science & Business Media. https://doi.org/10.1007/978-1-4615-1495-4_11

Biketi, F. Q., Kivaa, T., & Munala, G. (2017). Factors for Efficient Relationship between Contractors and Subcontractors in Project Implementation in Nairobi Kenya. http://repository.mut.ac.ke:8080/xmlui/handle/123456789/2854

Brans, J. P., & Mareschal, B. (1995). The PROMETHEE VI procedure: how to differentiate hard from soft multicriteria problems. Journal of Decision Systems, 4(3), 213-223. https://doi.org/10.1080/12460125.1995.10511652

Brans, J. P., & Vincke, P. (1985). Note—A Preference Ranking Organisation Method: (The PROMETHEE Method for Multiple Criteria Decision-Making). Management science, 31(6), 647-656. https://doi.org/10.1287/mnsc.31.6.647

Brans, J. P., Vincke, P., & Mareschal, B. (1986). How to select and how to rank projects: The PROMETHEE method. European journal of operational research, 24(2), 228-238. https://doi.org/10.1016/0377-2217(86)90044-5

Bubshait, A. A., & Almohawis, S. A. (1994). Evaluating the general conditions of a construction contract. International Journal of Project Management, 12(3), 133-136. https://doi.org/10.1016/0263-7863(94)90027-2

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(3), 3000-3011. https://doi.org/10.1016/j.eswa.2011.08.162

Cha, H. S., & Kim, C. K. (2011). Quantitative approach for project performance measurement on building construction in South Korea. KSCE Journal of Civil Engineering, 15, 1319-1328. https://doi.org/10.1007/s12205-011-1323-5

Chan, A. P., & Chan, A. P. (2004). Key performance indicators for measuring construction success. Benchmarking: an international journal, 11(2), 203-221. https://doi.org/10.1108/14635770410532624

Chen, L., & Pan, W. (2021). Review fuzzy multi-criteria decision-making in construction management using a network approach. Applied soft computing, 102, 107103. https://doi.org/10.1016/j.asoc.2021.107103

Chen, X., Ding, Y., Cory, C. A., Hu, Y., Wu, K. J., & Feng, X. (2021). A decision support model for subcontractor selection using a hybrid approach of QFD and AHP-improved grey correlation analysis. Engineering, Construction and Architectural Management, 28(6), 1780-1806. https://doi.org/10.1108/ecam-12-2019-0715

Cheng, M. Y., & Wu, Y. W. (2012). Improved construction subcontractor evaluation performance using ESIM. Applied Artificial Intelligence, 26(3), 261-273. https://doi.org/10.1080/08839514.2012.648403

Cheng, M. Y., Tsai, H. C., & Sudjono, E. (2011). Evaluating subcontractor performance using evolutionary fuzzy hybrid neural network. International Journal of Project Management, 29(3), 349-356. https://doi.org/10.1016/j.ijproman.2010.03.005

Cheung, S. O., & Li, K. (2019). Biases in construction project dispute resolution. Engineering, Construction and Architectural Management, 26(2), 321-348. https://doi.org/10.1108/ecam-03-2018-0109

Chou, J. S., Pham, A. D., & Wang, H. (2013). Bidding strategy to support decision-making by integrating fuzzy AHP and regression-based simulation. Automation in Construction, 35, 517-527. https://doi.org/10.1016/j.autcon.2013.06.007

Clemen, R. T., & Decisions, M. H. (2001). An introduction to decision analysis. R. Clemen, & T. Reilly, Making Hard Decisions with Decision Tools, 2. http://ndl.ethernet.edu.et/bitstream/123456789/40818/1/67.pdf

Cox, D. R., & Snell, E. J. (1968). A general definition of residuals. Journal of the Royal Statistical Society: Series B (Methodological), 30(2), 248-265. https://doi.org/10.1111/j.2517-6161.1968.tb00724.x

Dağdeviren, M., Yavuz, S., & Kılınç, N. (2009). Weapon selection using the AHP and TOPSIS methods under fuzzy environment. Expert systems with applications, 36(4), 8143-8151. https://doi.org/10.1016/j.eswa.2008.10.016

De Felice, F., & Petrillo, A. (2023). Analytic Hierarchy Process-Models, Methods, Concepts, and Applications. https://doi.org/10.5772/intechopen.1001519

Delazer, M., Zamarian, L., Bonatti, E., Walser, N., Kuchukhidze, G., Bodner, T., ... & Trinka, E. (2011). Decision making under ambiguity in temporal lobe epilepsy: does the location of the underlying structural abnormality matter?. Epilepsy & Behavior, 20(1), 34-37. https://doi.org/10.1016/j.yebeh.2010.11.006

Demirkesen, S., & Bayhan, H. G. (2019, February). Subcontractor selection with choosing-by-advantages (CBA) method. In IOP Conference Series: Materials Science and Engineering (Vol. 471, No. 2, p. 022020). IOP Publishing. https://doi.org/10.1088/1757-899x/471/2/022020

Deng, H., Yeh, C. H., & Willis, R. J. (2000). Inter-company comparison using modified TOPSIS with objective weights. Computers & Operations Research, 27(10), 963-973. https://doi.org/10.1016/s0305-0548(99)00069-6

Diwakar, R. (2019). An evaluation of normal versus lognormal distribution in data description and empirical analysis. Practical Assessment, Research, and Evaluation, 22(1), 13. https://doi.org/10.7275/zeyh-j468

Dulung, A. Z., & Pheng, L. S. (2005). Factors influencing the selection of subcontractors in refurbishment works. Architectural Science Review, 48(1), 93-103. https://doi.org/10.3763/asre.2005.4812

El-khalek, H. A., Aziz, R. F., & Morgan, E. S. (2019). Identification of construction subcontractor prequalification evaluation criteria and their impact on project success. Alexandria Engineering Journal, 58(1), 217-223. https://doi.org/10.1016/j.aej.2018.11.010

El-Mashaleh, M. S. (2009). A construction subcontractor selection model. Jordan journal of civil engineering, 3(4), 375-383. https://doi.org/10.1061/JCEMD4.COENG-14216

Eom, C. S., Yun, S. H., & Paek, J. H. (2008). Subcontractor evaluation and management framework for strategic partnering. Journal of Construction Engineering and Management, 134(11), 842-851. https://doi.org/10.1061/(asce)0733-9364(2008)134:11(842)

Ertuğrul, İ., & Karakaşoğlu, N. (2008). Comparison of fuzzy AHP and fuzzy TOPSIS methods for facility location selection. The International Journal of Advanced Manufacturing Technology, 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. In 29th Annual Conference of the

International Group for Lean Construction (IGLC29). Lima, Peru (pp. 870-879). https://doi.org/10.24928/2021/0209

Figueira, J., Greco, S., Ehrogott, M., & Dyer, J. S. (2005). MAUT—Mult attribute utility theory. Multiple criteria decision analysis: state of the art surveys, 265-292. https://doi.org/10.1007/0-387-23081-5_7

Firth, D. (1993). Bias reduction of maximum likelihood estimates. Biometrika, 80(1), 27-38. https://doi.org/10.1093/biomet/80.1.27

Forman, E. H., & Gass, S. I. (2001). The analytic hierarchy process—an exposition. Operations research, 49(4), 469-486. https://doi.org/10.1287/opre.49.4.469.11231

Gervásio, H., & Da Silva, L. S. (2012). A probabilistic decision-making approach for the sustainable assessment of infrastructures. Expert Systems with Applications, 39(8), 7121-7131. https://doi.org/10.1016/j.eswa.2012.01.032

Gharehbaghi, K., & McManus, K. (2003). Effective construction management. Leadership and Management in Engineering, 3(1), 54-55. https://doi.org/10.1061/(asce)1532-6748(2003)3:1(54)

Gorripati, R., Thakur, M., & Kolagani, N. (2022). A framework for optimal rank identification of resource management systems using probabilistic approaches in analytic hierarchy process. Water Policy, 24(6), 878-898. https://doi.org/10.2166/wp.2022.236

Guide, A. (2001). Project management body of knowledge (pmbok® guide). In Project Management Institute (Vol. 11, pp. 7-8). https://doi.org/10.1177/875697280103200310

Hanák, T., & Nekardová, I. (2020). Selecting and evaluating suppliers in the Czech construction sector. Periodica Polytechnica Social and Management Sciences, 28(2), 155-161. https://doi.org/10.3311/ppso.13328

Hanneman, R. A., & Riddle, M. (2005). Introduction to social network methods. https://wiki.gonzaga.edu/dpls707/images/6/6e/Introduction_to_Social_Network_Methods.pdf

Hansen, S., Fassa, F., & Michael, M. (2024). Selection Criteria for Named Subcontractors: Case Study of a Building Project. Jurnal Ilmiah Universitas Batanghari Jambi, 24(1), 583-587. https://doi.org/10.33087/jiubj.v24i1.4980

Helton, J. C., & Davis, F. J. (2003). Latin hypercube sampling and the propagation of uncertainty in analyses of complex systems. Reliability Engineering & System Safety, 81(1), 23-69. https://doi.org/10.1016/s0951-8320(03)00058-9

Hinze, J., & Tracey, A. (1994). The contractor-subcontractor relationship: the subcontractor's view. Journal of construction engineering and management, 120(2), 274-287. https://doi.org/10.1061/(asce)0733-9364(1994)120:2(274)

Hudson, M., Smart, A., & Bourne, M. (2001). Theory and practice in SME performance measurement systems. International journal of operations & production management, 21(8), 1096-1115. https://doi.org/10.1108/eum0000000005587

Husin, S. (2017). the subcontractor selection practice using ANN-multilayer. International Journal of Technology, 8(4). http://dx.doi.org/10.14716/ijtech.v8i4.9490

Hwang, C. L., Yoon, K., Hwang, C. L., & Yoon, K. (1981). Methods for multiple attribute decision making. Multiple attribute decision making: methods and applications a state-of-the-art survey, 58-191. V https://doi.org/10.2307/2581500

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

Javidmehr, M., & Ebrahimpour, M. (2015). Performance appraisal bias and errors: The influences and consequences. International Journal of Organizational Leadership, 4, 286-302. https://doi.org/10.33844/ijol.2015.60464

Jones, C. I. (2005). Growth and ideas. In Handbook of economic growth (Vol. 1, pp. 1063-1111). Elsevier. https://doi.org/10.1016/s1574-0684(05)01016-6

Kishk, M., & Al-Hajj, A. (1999, September). An integrated framework for life cycle costing in buildings. In Proceedings of the COBRA 1999 RICS construction and building research conference (Vol. 2, pp. 92-101). https://www.cs.auckland.ac.nz/w78/papers/W78-44.pdf

Kishore, R., Dehmourdi, S. A. M., Naik, M. G., & Hassanpour, M. (2020). Designing a framework for Subcontractor's selection in construction projects using MCDM model. Operational Research in Engineering Sciences: Theory and Applications, 3(3), 48-64. https://doi.org/10.31181/oresta20303048k

Koehler, D. J., & Harvey, N. (Eds.). (2008). Blackwell handbook of judgment and decision making. John Wiley & Sons. https://doi.org/10.1002/9780470752937

Koprivica, S. (2022). Evaluation of Subcontractor Selection Criteria and Comparison with Their Financial Performance Indicators. Operations Research and Engineering Letters, 1(1), 36-43. https://orel.unionnikolatesla.edu.rs/index.php/orel/article/view/16

Kotulski, Z. A., Szczepinski, W., Kotulski, Z., & Szczepiński, W. (2010). Probability Distributions and Their Characterizations. Error Analysis with Applications in Engineering, 49-90. https://doi.org/10.1007/978-90-481-3570-7_3

Krause, P. J. (1995). Fuzzy logic for the management of uncertainty edited by Lotfi Zadeh and Janusz Kacprzyk, John Wiley & Sons, New York, 1992, pp. 1–676, £ 47.50, ISBN 0-471-54799-9. The Knowledge Engineering Review, 10(1), 101-101. https://doi.org/10.1017/s0269888900007347

Kroonenberg, P. M. (2008). Applied multiway data analysis. John Wiley & Sons. https://doi.org/10.1002/9780470238004

Kumaraswamy, M. M., & Matthews, J. D. (2000). Improved subcontractor selection employing partnering principles. Journal of management in engineering, 16(3), 47-57. https://doi.org/10.1061/(asce)0742-597x(2000)16:3(47)

Kutsch, E., & Hall, M. (2005). Intervening conditions on the management of project risk: Dealing with uncertainty in information technology projects. International journal of project management, 23(8), 591-599. https://doi.org/10.1016/j.ijproman.2005.06.009

Kutsch, E., & Hall, M. (2010). Deliberate ignorance in project risk management. International journal of project management. https://doi.org/10.1016/j.ijproman.2009.05.003

Lee, D. K., In, J., & Lee, S. (2015). Standard deviation and standard error of the mean. Korean journal of anesthesiology, 68(3), 220-223. https://doi.org/10.4097/kjae.2015.68.3.220

Limsila, K., & Ogunlana, S. O. (2008). Performance and leadership outcome correlates of leadership styles and subordinate commitment. Engineering, construction, and architectural management, 15(2), 164-184. https://doi.org/10.1108/09699980810852682

Lin, Y. H., Lee, P. C., Chang, T. P., & Ting, H. I. (2008). Multi-attribute group decision making model under the condition of uncertain information. Automation in construction, 17(6), 792-797. https://doi.org/10.1016/j.autcon.2008.02.011

Liu, X., Chen, S., Ding, Z., & Xu, B. (2023). Bidding evaluation and contractor selection using balance index model and comprehensive input efficiency based on data envelopment analysis. Systems, 11(5), 245. https://doi.org/10.3390/systems11050245

Lopes, R. H., Reid, I. D., & Hobson, P. R. (2007). The two-dimensional Kolmogorov-Smirnov test. https://doi.org/10.1088/1742-6596/119/4/042019

Lumanauw, R. N., Ng, P. K., Saptari, A., Halim, I., Toha, M., & Ng, Y. J. (2023). No. 4. Performance Evaluation of Subcontractors Using Weighted Sum Method through KPI Measurement, Published: 15 March 2023, ORCiD: 0000-0001-7995-8251. Journal of Engineering Technology and Applied Physics, 5(1), 35-49. https://doi.org/10.33093/jetap.2023.5.1.4

Mahmoudi, A., & Javed, S. A. (2022). Performance Evaluation of Construction Sub-contractors using Ordinal Priority Approach. Evaluation and Program Planning, 91, 102022. https://doi.org/10.1016/j.evalprogplan.2021.102022

Martín-Martín, A., Thelwall, M., Orduna-Malea, E., & Delgado López-Cózar, E. (2021). Google Scholar, Microsoft Academic, Scopus, Dimensions, Web of Science, and OpenCitations' COCI: a multidisciplinary comparison of coverage via citations. Scientometrics, 126(1), 871-906. https://doi.org/10.1007/s11192-020-03690-4

Maturana, S., Alarcón, L. F., Gazmuri, P., & Vrsalovic, M. (2007). On-site subcontractor evaluation method based on lean principles and partnering practices. Journal of Management in Engineering, 23(2), 67-74. https://doi.org/10.1061/(asce)0742-597x(2007)23:2(67)

Mbachu, J. (2008). Conceptual framework for the assessment of subcontractors' eligibility and performance in the construction industry. Construction Management and Economics, 26(5), 471-484. https://doi.org/10.1080/01446190801918730

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(3), 706-717. https://doi.org/10.1016/j.jhazmat.2007.01.071

Moers, F. (2005). Discretion and bias in performance evaluation: the impact of diversity and subjectivity. Accounting, Organizations and Society, 30(1), 67-80. https://doi.org/10.1016/j.aos.2003.11.001

Momani, A. M., & Ahmed, A. A. (2011). Material handling equipment selection using hybrid Monte Carlo simulation and analytic hierarchy process. World Academy of Science, Engineering and Technology, 59(11), 953-958. https://doi.org/10.5281/zenodo.1085141

Nassar, N. K. (2005). An integrated framework for evaluation, forecasting and optimization of performance of construction projects. https://doi.org/10.4236/as.2022.135042

Nassar, N., & AbouRizk, S. (2014). Practical application for integrated performance measurement of construction projects. Journal of Management in Engineering, 30(6), 04014027. https://doi.org/10.1061/(asce)me.1943-5479.0000287

Ng, S. T., & Skitmore, M. (2014). Developing a framework for subcontractor appraisal using a balanced scorecard. Journal of Civil Engineering and Management, 20(2), 149-158. https://doi.org/10.3846/13923730.2013.802705

Ng, S. T., & Tang, Z. (2008). Delineating the predominant criteria for subcontractor appraisal and their latent relationships. Construction Management and Economics, 26(3), 249-259. https://doi.org/10.1080/01446190701874405

Ng, T. S. T. (2007). Using balanced scorecard for subcontractor performance appraisal. https://api.semanticscholar.org/CorpusID:168088823

Nieto-Morote, A., & Ruz-Vila, F. (2012). A fuzzy multi-criteria decision-making model for construction contractor prequalification. Automation in construction, 25, 8-19. https://doi.org/10.1016/j.autcon.2012.04.004

Okoroh, M. I., & Torrance, V. B. (1999). A model for subcontractor selection in refurbishment projects. Construction Management & Economics, 17(3), 315-327. https://doi.org/10.1080/014461999371529

Olea, R. A., & Pawlowsky-Glahn, V. (2009). Kolmogorov–Smirnov test for spatially correlated data. Stochastic Environmental Research and Risk Assessment, 23, 749-757. https://doi.org/10.1007/s00477-008-0255-1

Opricovic, S., & Tzeng, G. H. (2004). Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. European journal of operational research, 156(2), 445-455. https://doi.org/10.1016/s0377-2217(03)00020-1

Pallikkonda, K. D., Siriwardana, C. S. A., & Karunarathna, D. M. T. G. N. M. (2019). Developing a sub-contractor pre-assessment framework for Sri Lankan building construction industry. Kandy, Sri Lanka, 1, 15. https://www.kandyconference.org/wp-content/uploads/2023/08/The-13th-ICSBE-Volume-II.pdf

Parrish, K., & Tommelein, I. D. (2009, July). Making design decisions using choosing by advantages. In proc. 17th annual conference of the International Group for Lean Construction (IGLC 17) (pp. 15-17). https://iglc.net/Papers/Details/663

Peansupap, V., & Nov, P. (2022). Selection Model of Subcontractor Relationships by Using Discriminant Analysis. Engineering Journal, 26(7), 23-34. https://doi.org/10.4186/ej.2022.26.7.23

Pinto, J. K. (2013). Lies, damned lies, and project plans: Recurring human errors that can ruin the project planning process. Business Horizons, 56(5), 643-653. https://doi.org/10.1016/j.bushor.2013.05.006

Podvezko, V. (2011). The comparative analysis of MCDA methods SAW and COPRAS. Engineering Economics, 22(2), 134-146. https://doi.org/10.5755/j01.ee.22.2.310

Polat, G. (2016). Subcontractor selection using the integration of the AHP and PROMETHEE methods. Journal of Civil Engineering and Management, 22(8), 1042-1054. https://doi.org/10.3846/13923730.2014.948910

Putri, C. G., & Nusraningrum, D. (2022). Subcontractors Selection of Building Construction Project Using Analytical Hierarchy Process (AHP) and Technique for Others Reference by Similarity (TOPSIS) Methods. Jurnal Manajemen Teori dan Terapan, 15(2). https://doi.org/10.20473/jmtt.v15i2.35915

Radermacher, F. J. (1994). Decision support systems: Scope and potential. Decision Support Systems, 12(4-5), 257-265. https://doi.org/10.1016/0167-9236(94)90044-2

Rahman, M. M., & Kumaraswamy, M. M. (2005). Relational selection for collaborative working arrangements. Journal of Construction Engineering and Management, 131(10), 1087-1098. https://doi.org/10.1061/(asce)0733-9364(2005)131:10(1087)

Rana, S., & Bajpai, P. preparation of prequalification system for Indian road projects based on DEA. https://ijates.com/images/short_pdf/1466318672_341ijates.pdf

Saaty, T. L. (1987). Principles of the analytic hierarchy process. In Expert judgment and expert systems (pp. 27-73). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-86679-1_3

Saaty, T. L. (1990). How to make a decision: the analytic hierarchy process. European journal of operational research, 48(1), 9-26. https://doi.org/10.1016/0377-2217(90)90057-i

Saaty, T. L., & Vargas, L. G. (2012). Models, methods, concepts & applications of the analytic hierarchy process (Vol. 175). Springer Science & Business Media. https://doi.org/10.1007/978-1-4614-3597-6_18

Saaty, T. L., Vargas, L. G., Saaty, T. L., & Vargas, L. G. (2013). The analytic network process (pp. 1-40). Springer US. https://doi.org/10.1007/978-1-4614-7279-7_1

Saltelli, A., Tarantola, S., Campolongo, F., & Ratto, M. (2004). Sensitivity analysis in practice: a guide to assessing scientific models (Vol. 1). New York: Wiley. http://dx.doi.org/10.1002/0470870958

Schaefer, T., Udenio, M., Quinn, S., & Fransoo, J. C. (2019). Water risk assessment in supply chains. Journal of Cleaner Production, 208, 636-648. https://doi.org/10.1016/j.jclepro.2018.09.262

Scott, J., & Carrington, P. J. (2011). The SAGE handbook of social network analysis. SAGE publications. https://doi.org/10.4135/9781446294413

Shahar, D. J. (2017). Minimizing the variance of a weighted average. Open Journal of Statistics, 7(2), 216-224. https://doi.org/10.4236/ojs.2017.72017

Shahsavarani, A. M., & Azad Marz Abadi, E. (2015). The bases, principles, and methods of decision-making: a review of literature. International Journal of Medical Reviews, 2(1), 214-225. https://doi.org/10.14569/ijacsa.2015.060925

Shahvand, E., Sebt, M. H., & Banki, M. T. (2016). Developing fuzzy expert system for supplier and subcontractor evaluation in construction industry. Scientia Iranica. Transaction A, Civil Engineering, 23(3), 842. https://doi.org/10.24200/sci.2016.2163

Shen, L. Y., Bao, Q., & Yip, S. L. (2000, October). Implementing innovative functions in construction project management towards the mission of sustainable environment. In Proceedings of the Millennium Conference on Construction Project Management (pp. 77-84). https://doi.org/10.1016/S0263-7863(01)00054-0

Shiau, Y. C., Tsai, T., Wang, W., & Huang, M. (2003). Use questionnaire and AHP techniques to develop subcontractor selection system. Nist Special Publication Sp, 35-40. https://doi.org/10.22260/isarc2002/0006

Sims, B. L., & Anderson, W. (2003). Meeting customer expectations in the construction industry. Cost Engineering, 45(4), 30. https://doi.org/10.1061/(asce)1532-6748(2001)1:3(29)

Sipahi, S., & Timor, M. (2010). The analytic hierarchy process and analytic network process: an overview of applications. Management decision, 48(5), 775-808. https://doi.org/10.1108/00251741011043920

Stingl, V., & Geraldi, J. (2017). Errors, lies and misunderstandings: Systematic review on behavioural decision making in projects. International Journal of Project Management, 35(2), 121-135. https://doi.org/10.1016/j.ijproman.2016.10.009

Suhr, J. (1999). The choosing by advantages decision making system. Greenwood Publishing Group. https://doi.org/10.1108/al.1999.17308dad.004

Taherdoost, H., & Madanchian, M. (2023). Multi-criteria decision making (MCDM) methods and concepts. Encyclopedia, 3(1), 77-87. https://doi.org/10.3390/encyclopedia3010006

Thomopoulos, N. T. & Philipson. (2018). Probability Distributions. Springer. https://doi.org/10.1007/978-3-319-76042-1

Triantaphyllou, E., & Baig, K. (2005). The impact of aggregating benefit and cost criteria in four MCDA methods. IEEE transactions on engineering management, 52(2), 213-226. https://doi.org/10.1109/tem.2005.845221

Types of subcontractors in construction. (2022, Feb 18).. https://www.blackridgeresearch.com/blog/types-of-subcontractors-in-construction

Wang, L., Kunc, M., & Bai, S. J. (2017). Realizing value from project implementation under uncertainty: An exploratory study using system dynamics. International Journal of Project Management, 35(3), 341-352. https://doi.org/10.1016/j.ijproman.2017.01.009

Wang, Y. M., & Elhag, T. M. (2006). Fuzzy TOPSIS method based on alpha level sets with an application to bridge risk assessment. Expert systems with applications, 31(2), 309-319. https://doi.org/10.1016/j.eswa.2005.09.040

Wanke, P., Ewbank, H., Leiva, V., & Rojas, F. (2016). Inventory management for new products with triangularly distributed demand and lead-time. Computers & Operations Research, 69, 97-108. https://doi.org/10.1016/j.cor.2015.10.017

Wasserman, S., & Faust, K. (1994). Social network analysis: Methods and applications. https://doi.org/10.1017/cbo9780511815478

Wild, C. H. R. I. S. (2006). The concept of distribution. Statistics Education Research Journal, 5(2), 10-26. https://doi.org/10.52041/serj.v5i2.497

Yin, H., Wang, Z., Yu, J., Ji, Z., & Ni, H. (2009, May). Application of DEA cross-evaluation model in project dynamic alliance subcontractors selection. https://doi.org/10.1109/iwisa.2009.5072743

Yu, I., Kim, K., Jung, Y., & Chin, S. (2007). Comparable performance measurement system for construction companies. Journal of Management in Engineering, 23(3), 131-139. https://doi.org/10.1061/(asce)0742-597x(2007)23:3(131)

Zadeh, L. A. (1965). Fuzzy sets. Information and control, 8(3), 338-353. https://doi.org/10.1016/s0019-9958(65)90241-x

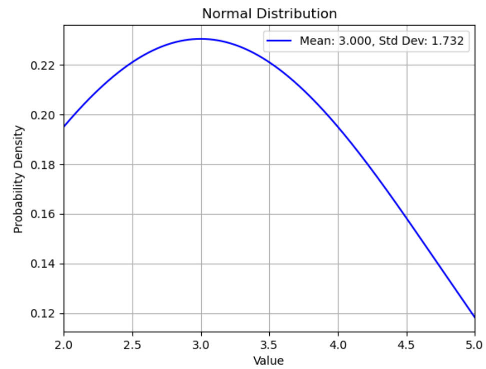
Zahedi, F. (1986). The analytic hierarchy process—a survey of the method and its applications. interfaces, 16(4), 96-108. https://doi.org/10.1287/inte.16.4.96

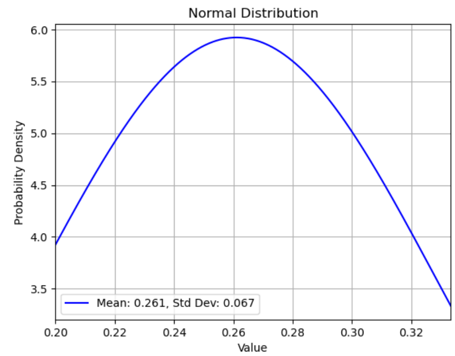
Zhang, X., Paul, S., & Wang, Y. G. (2021). Small sample bias correction or bias reduction? Communications in Statistics-Simulation and Computation, 50(4), 1165-1177. https://doi.org/10.1080/03610918.2019.1577976

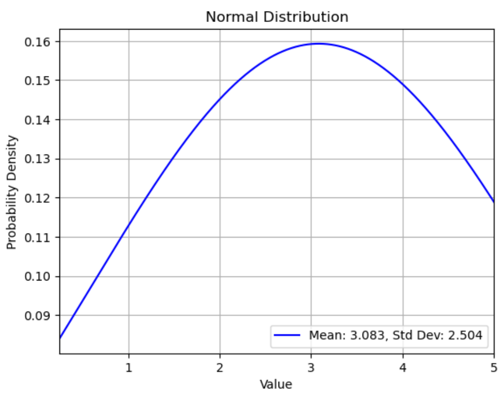
Zhong, S., & Elzarka, H. (2022). A hybrid grey system theory–based subcontractor selection model for high-stakes construction projects. Journal of Construction Engineering and Management, 148(6), 04022037. https://doi.org/10.1061/(asce)co.1943-7862.0002294

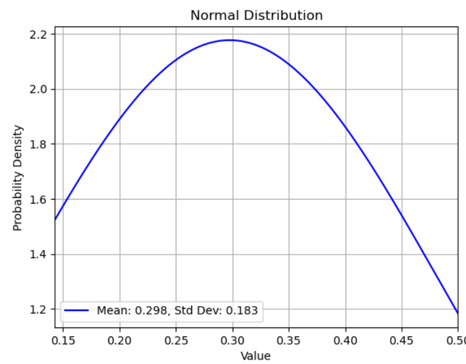
Appendix A: Examples of Distributions -MC-AHP

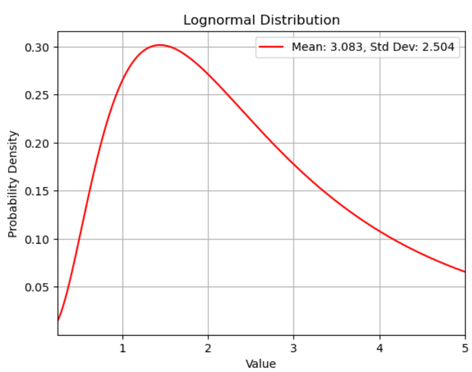
The following figures illustrate examples of normal, triangular, and lognormal distributions used in MC-AHP:

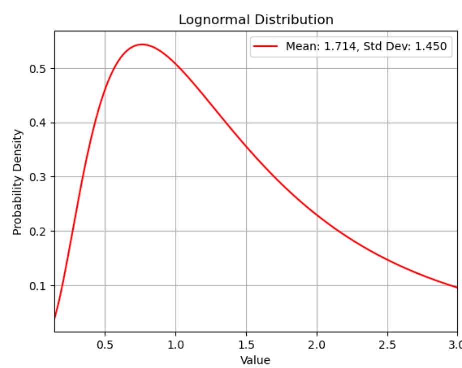


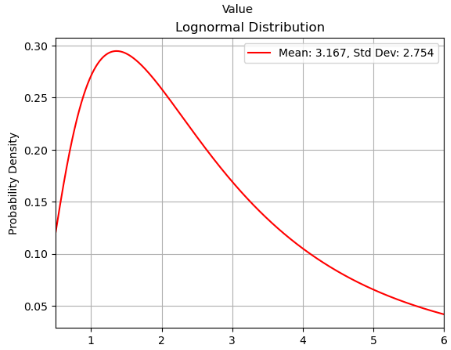


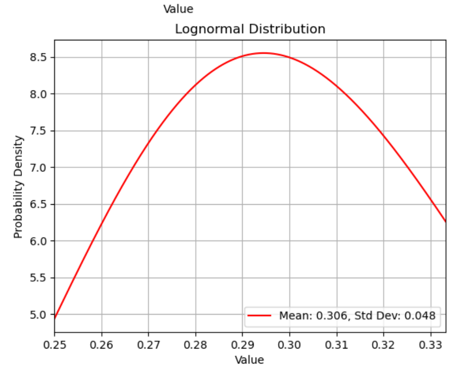


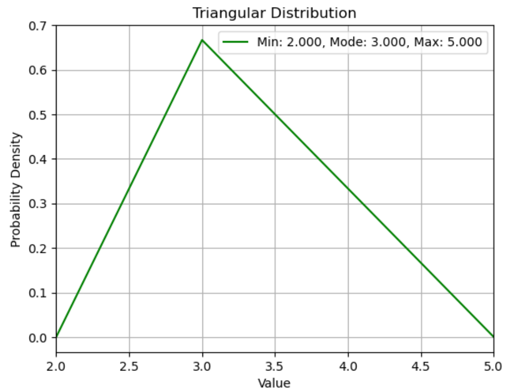


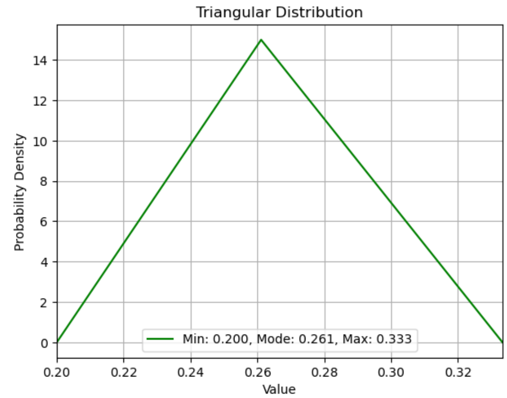


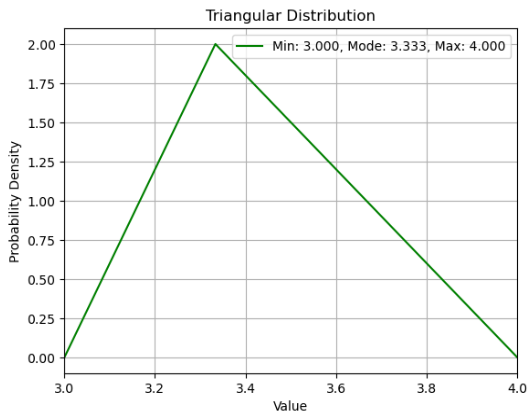


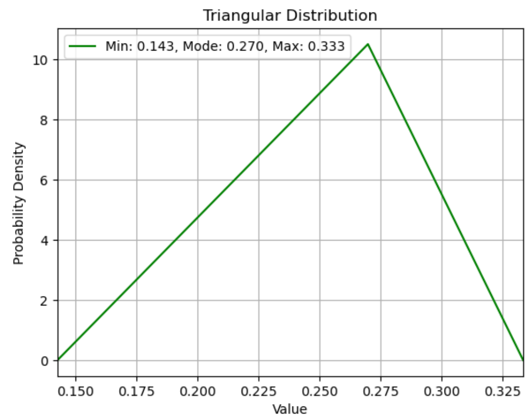






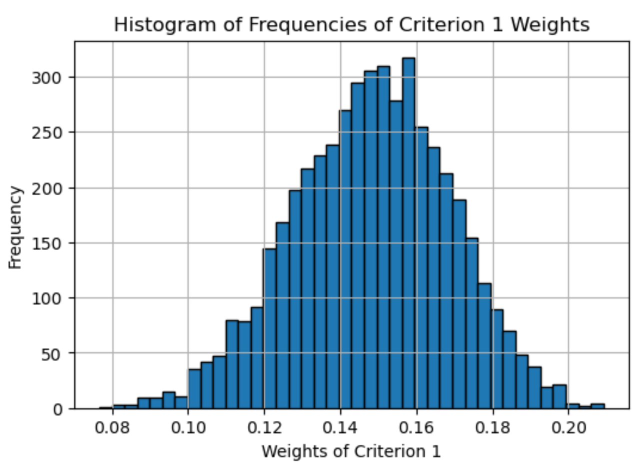


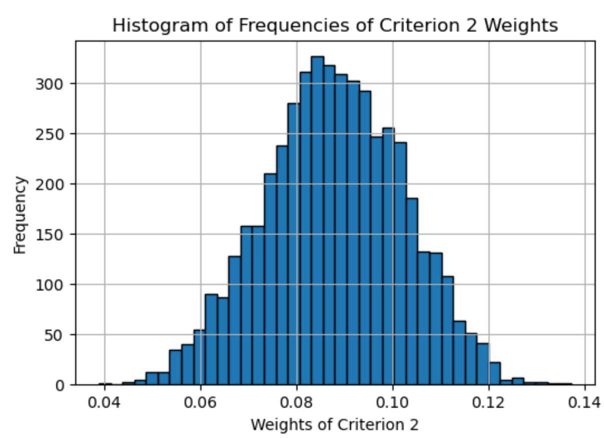


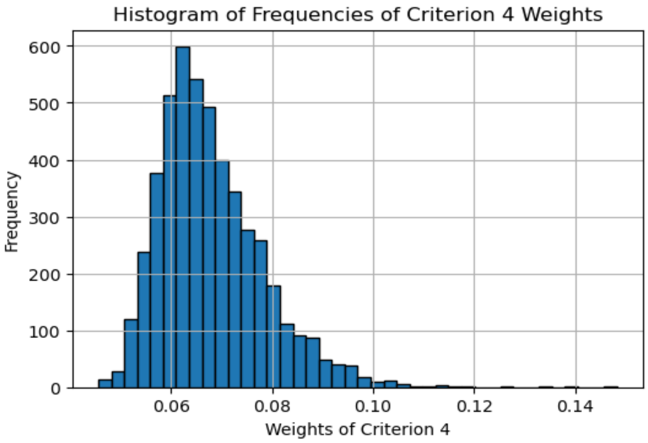


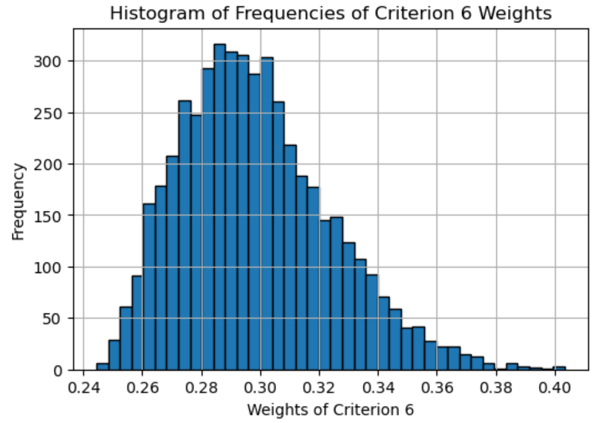
The following figures illustrate examples of histogram of frequencies of criteria according distributions in MC-AHP:

<u>Normal Distribution</u>

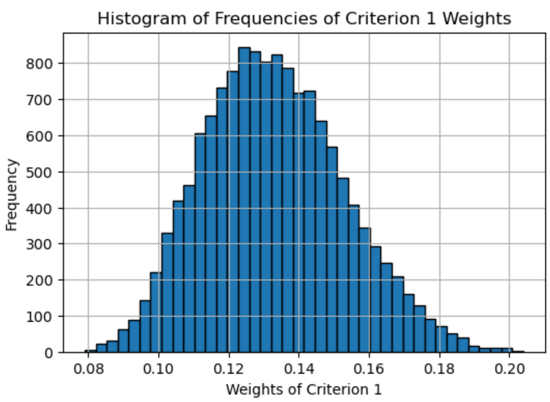


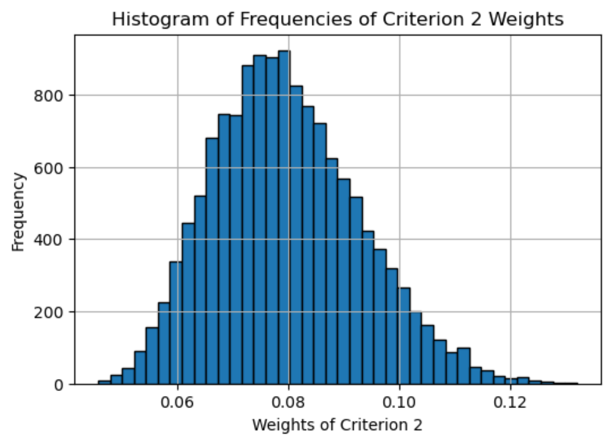


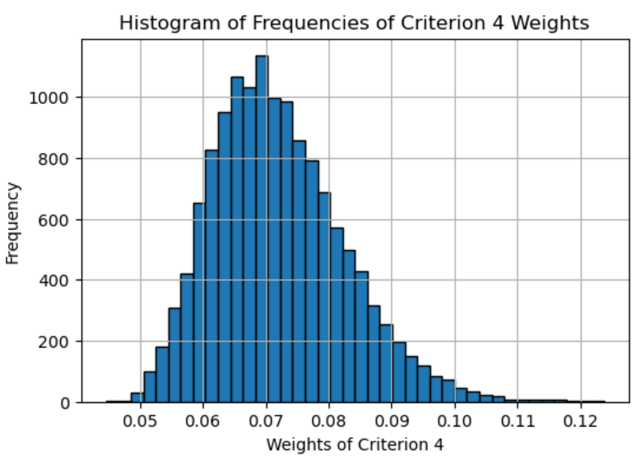


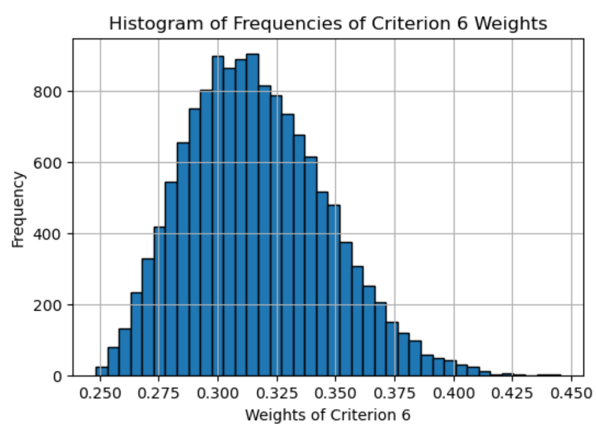


<u>Lognormal Distribution</u>

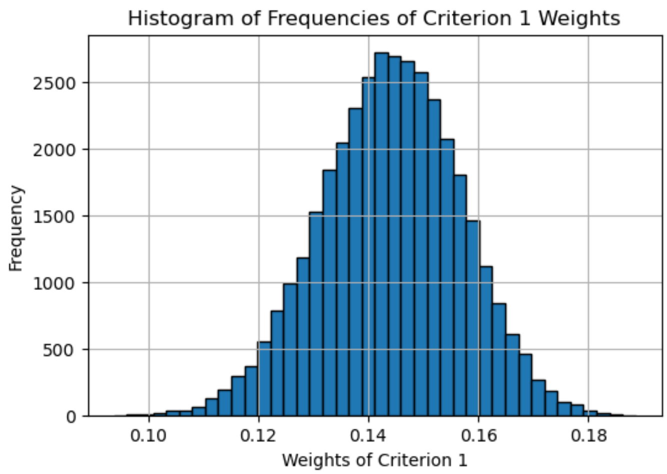


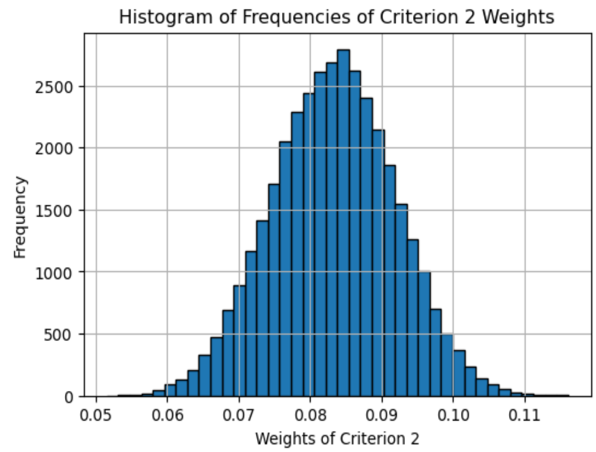


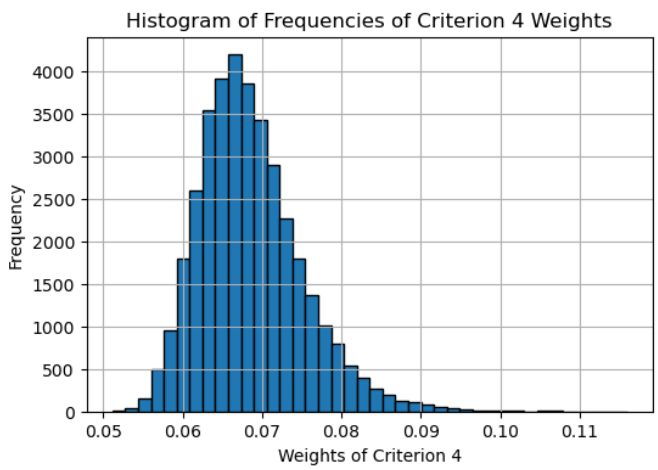


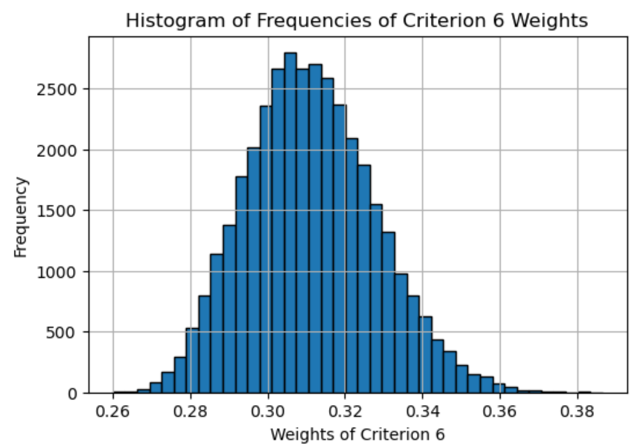


<u>Triangular Distribution</u>



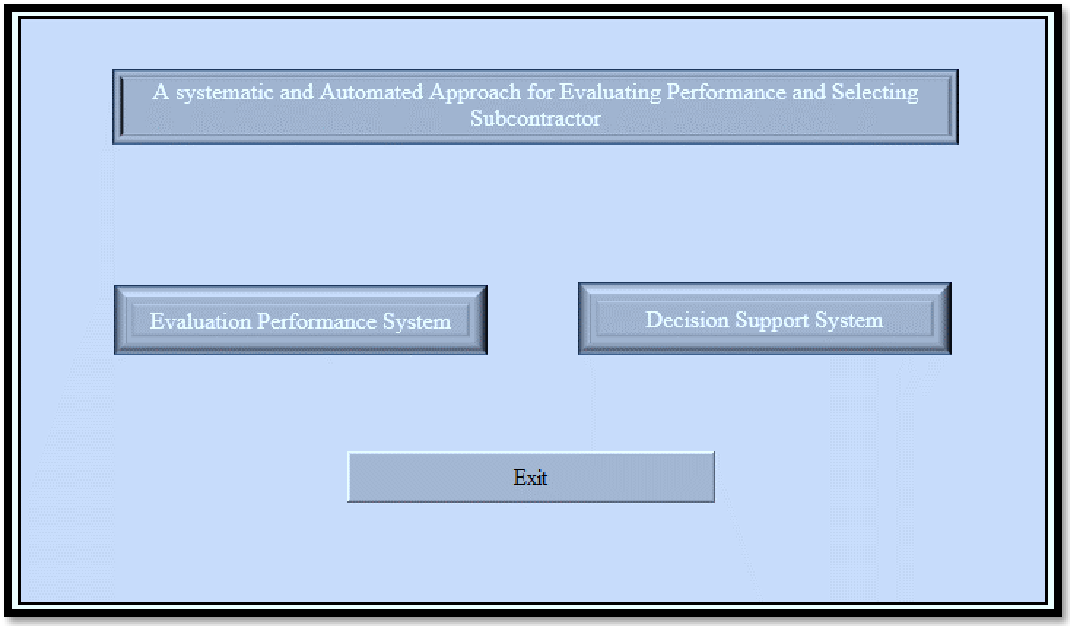




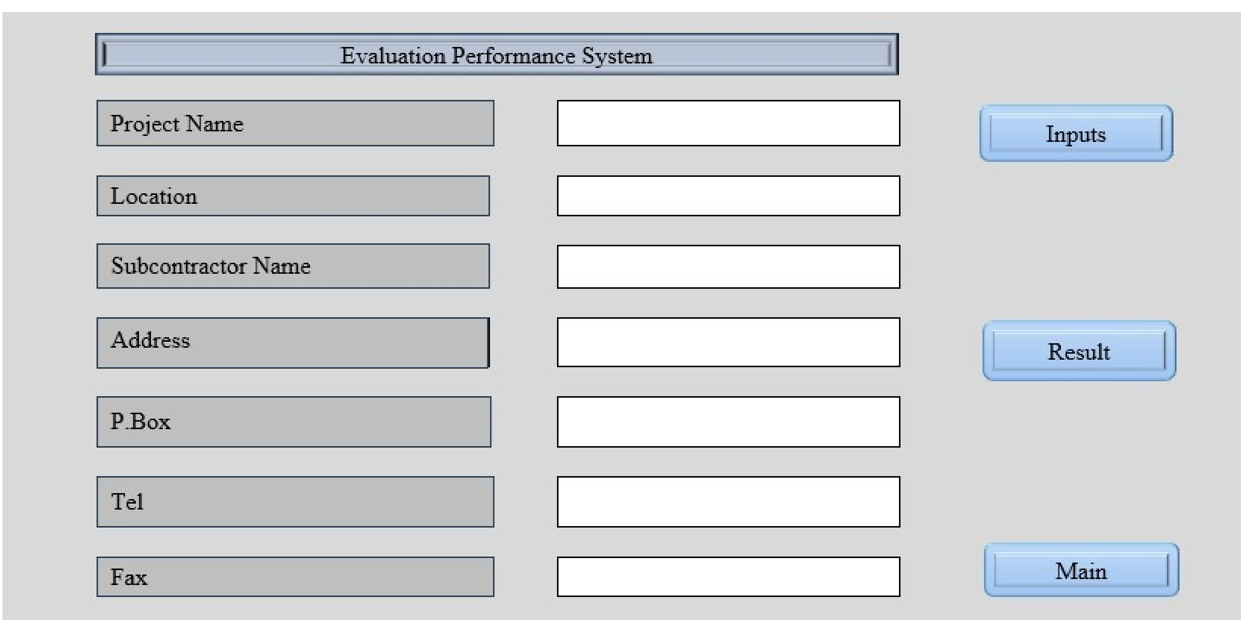


Appendix B: Application of Evaluation Performance and Decision Support Systems

Main Interface:



Evaluation Performance System Interface



Inputs – Project

Data Collected from Site	
Project Data	
Revised contract period (RC) - days	302
Revised Contract Value (RV) - $	$505,820.00
Commencement date	2022-03-20
Finished date	2023-02-19
Construction Time (CT)	336
Number of required technicians according to contract	2
Number of required professional certificate according to contract	1
Number of specialized equipment according to contract	1
Number of official letters (sent + responded) from general contractor	30
Number of meetings that subcontractor should be attended as contract	10
Number of documents as contract for closing project	12
Number of changes required by general contractor	4

Inputs - Subcontractor Performanc Data (Example)

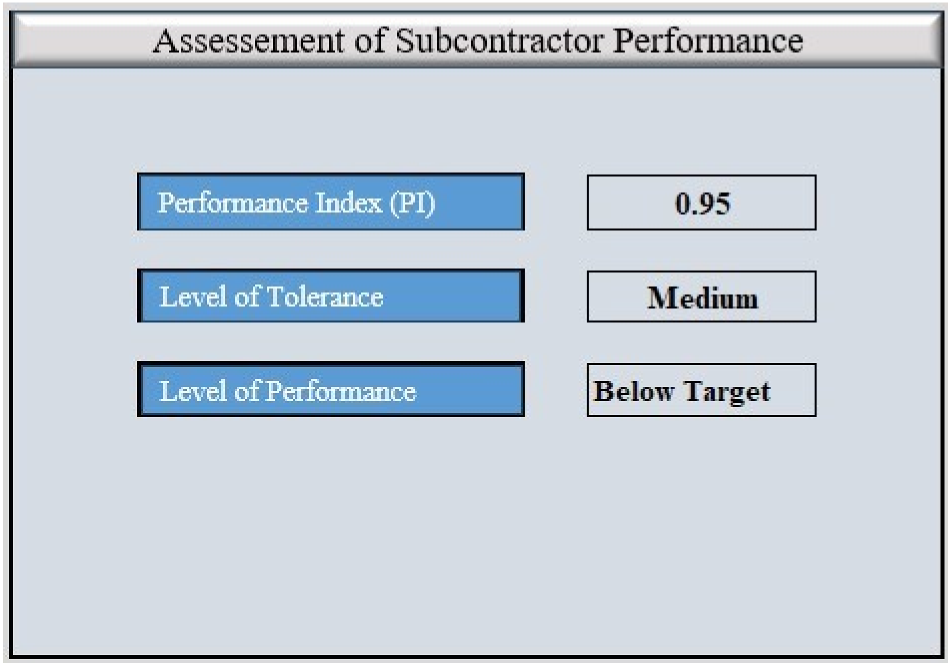
Subcontractor Performance Data

Cost and Finance		
Financial claims (FC)		0
Frequency of subcontractor submissions of invoices to the general contractor prior to the contractual dates		2
Cost Saving (Tasks)		
Cost (Task- A)	$	18,000.00
Modified cost (Task- A)	$	13,000.00
Cost (Task- B)	$	42,082.00
Modified cost (Task- B)	$	34,902.00
Assessing the frequency of delayed payments (workers and material suppliers) throughout the project.		1

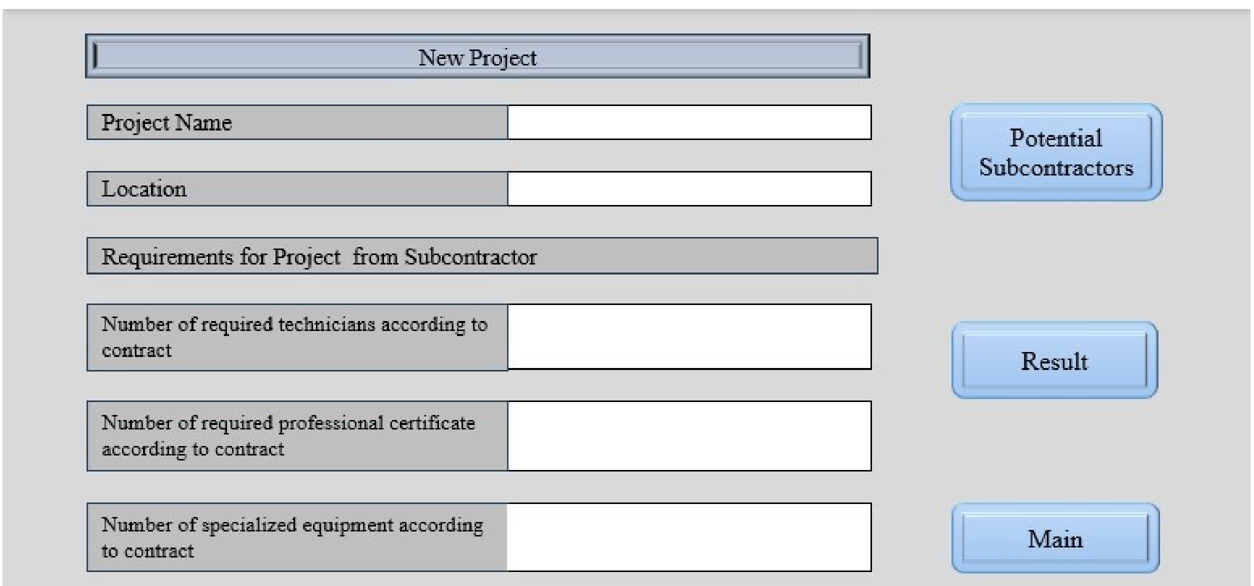
Quality	
Number of non-conformance reports (NCRs) regarding materials	6
Number of non-conformance reports (NCRs) related to work requiring rework.	2
Number of non-conformance reports (NCRs) related to finished production	3

Resource Adequacy	
Number of techenicians and professional certificates (Subcontractor)	1
Number of specialized equipment (Subcontractor)	0
Total of days of delay in the delivery of materials - days	23

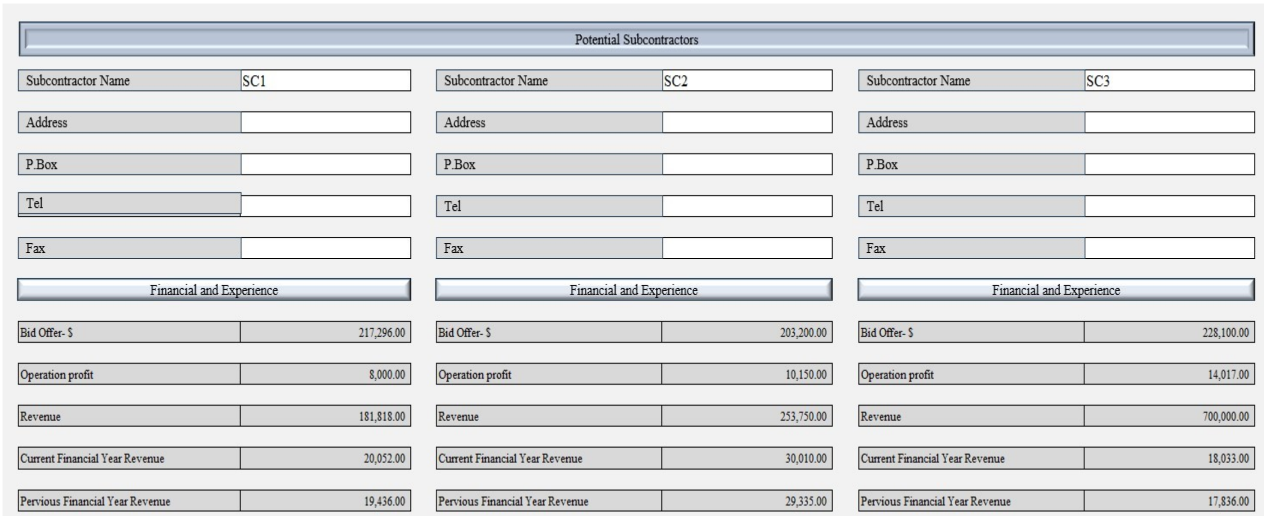
Result - Assessment Performance Subcontractor



Interface- DSS



Collect Data – Potential Subcontractors



Potential Subcontractors

Subcontractor Name	SC1	Subcontractor Name	SC2	Subcontractor Name	SC3
Address		Address		Address	
P.Box		P.Box		P.Box	
Tel		Tel		Tel	
Fax		Fax		Fax	
Financial and Experience		Financial and Experience		Financial and Experience	
Bid Offer- $	217,296.00	Bid Offer- $	203,200.00	Bid Offer- $	228,100.00
Operation profit	8,000.00	Operation profit	10,150.00	Operation profit	14,017.00
Revenue	181,818.00	Revenue	253,750.00	Revenue	700,000.00
Current Financial Year Revenue	20,052.00	Current Financial Year Revenue	30,010.00	Current Financial Year Revenue	18,033.00
Pervious Financial Year Revenue	19,436.00	Pervious Financial Year Revenue	29,335.00	Pervious Financial Year Revenue	17,836.00

Result- Ranking