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Barriers and Overcoming Strategies for Lean Construction Implementation in Ethiopia: An Integrated Fuzzy AHP and Fuzzy TOPSIS Framework

Achamyelew Maru[1], Wubishet Jekale[2] and Belachew Astrey[1]

[1] *Addis Ababa Science and Technology University, College of Engineering, Department of Civil Engineering, Addis Ababa, Ethiopia*

[2] *Addis Ababa University, Ethiopian Institute of Architecture Building Construction and City Development, Chairman of Construction Technology and Management Association, Addis Ababa, Ethiopia*

Corresponding author:
Achamyelew Maru
achamyelewe.maru@aastu.edu.et

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Faculty of Civil Engineering and Architecture Osijek
Josip Juraj Strossmayer University of Osijek
Vladimira Preloga 3
31000 Osijek
CROATIA

Abstract:
Lean construction (LC) is a valuable concept for waste reduction and project performance improvement. There is awareness of LC principles and tools among professionals and limited use in Ethiopian projects. However, adoption and implementation are still low. This study aims to identify and prioritize barriers and strategies for overcoming them to successfully implement LC in the industry. This study uses a multi-criteria decision-making (MCDM) approach by integrating the fuzzy analytical hierarchy process (AHP) and the fuzzy technique for order of preference by similarity to the ideal solution (TOPSIS). A review of the published articles along with expert guidance identified 28 barriers grouped into six categories. Furthermore, nine alternative strategies were proposed to address these barriers. The fuzzy AHP is used to determine the weights of the barriers as criteria, and the fuzzy TOPSIS method is used to obtain the final ranking of the overcoming strategies for LC implementation (LCI). The top four barriers hindering the smooth implementation of LC were "resistance to change", "lack of knowledge in lean", "lack of long-term philosophy", and "lack of government support". The most effective overcoming strategies were leadership and management, cultural change for continuous learning and improvement, and education and training. The study's sensitivity analysis robustness test confirmed the robustness and usefulness of the findings, which provides strategic insight for decision-makers and guides professionals to plan effective LC adoption.

Keywords:
project performance; multi-criteria decision-making; LC principles; robustness test.

1 Introduction

Ethiopia's construction sector is projected to grow at an average annual rate of more than 8 % between 2023 and 2026 [1]. However, 18,2 %, 37,6 %, and 44,0 % of the projects are overrun by planned schedules, budgeted costs, and quality requirements, respectively [2]. More than 80 % of construction projects in Ethiopia overrun budgets and experience delays [3]. Nearly 40 % of project time is wasted on non-value-adding activities [4]. Factors causing cost overruns and delays include poor planning, variations, inflation, inaccurate cost estimation, and excess quantity during construction [5, 6]. Construction waste management remains a significant challenge in Ethiopia [7]. New methods and approaches are required to overcome these challenges.

Over the past two decades, many manufacturing industries have introduced lean production method and techniques to shift traditional paradigms and improve performance. Lean construction (LC) has been implemented in various construction industries to improve performance, workflow reliability, planning, control, and waste reduction, particularly in developed and emerging countries. LC improves efficiency and profitability in the construction industry [8]; however, success depends on organizational and cultural factors, top management commitment, and site management support [9]. This could lead to sustainable innovation, competitiveness, and resource efficiency. Successful implementation is more likely in projects driven by organisations committed to lean principles and methods [10].

The Ethiopian government has set strategic goals for the growth of the construction sector, including the use of project management system tools and innovative technologies and construction techniques. A roadmap for the adoption and application of building information modelling (BIM) in 2019 has also been prepared by the Construction Project Management Institute. In recent years, a few companies, such as the Ethiopian Construction Works Corporation, have extended the use of information technology in the construction sector and started using LC concepts and technologies. Nonetheless, the construction industry currently has a poor level of LC acceptance and implementation.

The Ethiopian construction industry faces a critical gap in research on the linkage between LC barriers and solutions. Previous studies have identified barriers and drivers [11-16], but there is a lack of research on the links between LC barriers and strategies to overcome them. This study focuses on identifying, prioritising, and ranking strategies for overcoming LC barriers. Ethiopian construction companies and decision-makers can use the results to develop efficient policies and strategies to improve competitiveness. Studies have explored the implementation of LC and related ideas. A novel method was proposed using the fuzzy analytical hierarchy process (AHP) and a house of quality integrated matrices for selecting and evaluating lean concepts in off-site construction [17]. Similar integrated approach focused on sustainable energy to prioritise strategies for overcoming barriers [18].

The fuzzy technique for order of preference by similarity to the ideal solution (TOPSIS) analysis was used to identify barriers and strategies for Lean Six Sigma in small- and medium-sized construction businesses [19]. These studies highlight the potential of integrated fuzzy AHP and fuzzy TOPSIS frameworks for tackling barriers and prioritising strategies in real-world decision-making processes. This innovative approach accommodates the uncertainty and vagueness in real-world decision-making processes.

The combined framework considers the importance and effectiveness of overcoming strategies, and uses fuzzy logic to incorporate uncertainty into the decision-making process. A literature review was conducted and expert opinions were used to determine the barriers to LC implementation (LCI), which were classified into categories and prioritises using a fuzzy AHP approach. The fuzzy TOPSIS method was used to rank the solutions based on their effectiveness in handling the relevant barriers. The results and discussion are presented in the subsequent sections following the research methodology. The final section contains the conclusions, recommendations, and future research directions.

2 Literature review

2.1 Lean construction (LC) paradigm

LC is a management philosophy that focuses on minimising waste in production systems to generate maximum value. This is a contextual application of generic principles, methods, and tools. It uses principles such as standardise workflow, pull systems, and just-in-time (JIT) theory to maximise construction resources [20]. Lean concepts can transform the construction sector by streamlining processes and reducing time, money, resources, and effort, while increasing customer value. Numerous academics have proposed that continuous workflow, pull systems, standardise work, visual control, and the use of trustworthy technology are all aspects of the lean concept when viewed in the context of related processes and technological concepts [21-23]. However, the hard part of lean requires the involvement of people and culture, including leadership management, teamwork, and continuous improvement [24, 25]. Various techniques exist in the construction industry, including look-ahead planning, constraint analysis, concurrent engineering, Percent Plan Complete (PPC) measurement, resource management, JIT, standardisation, immediate problem detection, process evaluation, detection of incompatibility and discrepancy, use of visual indicators, team integration, and continuous improvement [26, 27].

2.2 LC Implementation

LC is a project management methodology that aims to minimise waste and increase value in the construction industry [28]. It encourages team collaboration and boosts productivity, profit, and innovation. Implementing lean tools leads to better outcomes, higher-quality construction, increased customer satisfaction, improved productivity, and enhanced safety [29, 30]. Studies have shown that lean principles can improve performance indicators such as manpower productivity, cost factors, construction speed, and timetable reduction [31]. Roslie [32] demonstrated the appropriateness and acceptability of lean principles for construction project performance in Malaysia. In Australia, Fauzan and Sunindijo [33] confirmed a strong correlation between LC principles and project performance indicators. In India, LC has demonstrated positive benefits in terms of scheduling, cost, safety, and quality [16]. In Bangladesh, lean practices lead to safety, quality, productivity, cost reduction, sustainability, customer satisfaction, and environmental impact reduction [34].

2.3 Barriers to the implementation of LC

The implementation of lean systems in the construction industry has been challenging because they are imported from the manufacturing industry. These barriers can be cultural, structural, or a combination of both depending on the organisation or setting. Challenges include management issues, financial issues, educational issues, government issues, technical issues, and human attitudinal issues [11, 14, 35, 36]. The model proposed by Albalkhy [37] categorizes barriers into three types: internal, input, and exogenous.

Major barriers to LC include technology and knowledge leadership and management barriers, culture and complexity barriers, engagement and relationship barriers, financial barriers, and communication barriers [38]. Mano [39] identified major barriers to implementing lean in the construction industry in India: lack of lean awareness, cultural and human attitude issues, commercial pressure, lack of proper training, long implementation time, lack of top management commitment, educational issues, lack of proper communication between clients and contractors, fragmentation and subcontracting, and financial issues. In-depth literature review of this study identified 28 barriers proposed in six major groups: financial, managerial, technical, workforce, culture, government, and communication, as shown in Table 1.

Table 1. Barriers to LCI

Category	Code	Barriers	References
Managerial	MB1	Misconception about lean practice	[11, 14, 18]
	MB2	Lack of top management support	[14, 19, 39, 40]
	MB3	Inefficiency in resource planning and control	[14, 16, 37]
	MB4	Lack of customer focus	[39, 41]
	MB5	Unsuitable organizational structure	[15, 37]
	MB6	Risk aversion in lean implementation	[14, 41, 43]
	MB7	Lack of training for workers	[14, 42, 46]
	MB8	Lack of continuous improvement	[37, 39, 44]
Technical	TB1	Lack of understanding and practice lean tools and techniques	[14, 15, 37, 37, 40, 45]
	TB2	Limited use of off-site construction technique	[44]
	TB3	Complexity of lean philosophy and terms	[18, 37, 41]
	TB4	Lack of process thinking and ownership	[37, 44]
	TB5	Work fragmentation and subcontracting	[39, 43]
Cultural & Attitudinal	CB1	Resistance to change	[34, 35, 37, 45]
	CB2	Lack of long-term philosophy	[14, 16, 39, 40]
	CB3	Lack of sustainable effort	[11, 14, 40]
	CB4	Diversity in adopting in lean culture	[11, 18, 39]
Governmental	GB1	Lack of government support for research and collaboration to lean	[16, 37, 41]
	GB2	Stringent requirement and approval	[11, 14]
	GB3	Lack of knowledge in lean	[11, 35, 37, 38, 43]
Communication & Workforce	CWB1	Problem in teamwork and diverging aims in lean	[14, 40]
	CWB2	Lack of organizational communication	[14, 37, 43]
	CWB3	Lack of information sharing and integrated change control	[37, 40]
	CWB4	Employers resistance to lean practice	[15, 18, 35]
Financial	FB1	Existence of market strategy	[36, 39, 40]
	FB2	Financial issue in terms of training cost	[15, 38]
	FB3	Consulting cost to lean	[37, 38, 42]
	FB4	Dimensional variation cost of lean tools	[17, 35]

2.4 Strategies for overcoming barriers to LCI

Belhadi et al. [46] reviewed nine lean implementation solutions in developing countries. Based on meaning and similarities, they were divided into five categories: policy, leadership, and management; funding, technology, and communication; culture, humans, and competencies; market, customers, and suppliers; and understanding, implementation, and monitoring. Ogunbiyi, [47] introduced 31 drivers and divided them into three dimensions: economic, social, and environmental. Hasan [53] proposed seven major enabler and barrier groups financial, managerial, and technical, workforce, culture, government, and communication with 27 components in each group. Dehdash and Elkhairi [49, 50] identified three critical success factors: management support, process-centred management, and training and education. To overcome the principal barriers to LC, applicable solutions are proposed under this study classified in nine categories: leadership and management, cultural change for continuous learning and improvement, utilisation technology (LC tools), education and training, teamwork and communication, establishment of a LC task force, development of a measurement and evaluation system, provision and support resources, and development of a system of transparency and accountability. The strategies used to overcome LC barriers are listed in Table 2.

Table 2. Alternative strategies for overcoming barriers to LCI

No	Overcoming strategies	Elaboration	References
1	Leadership and management	Develop comprehensive policies, standards that outlines the goals, objectives, and timeline for the Lean Construction implementation process.	[46-48]
2	Cultural change	Encourage and support a culture of continuous learning and development in order to ensure that the Lean Construction implementation is successful.	[46-49]
3	Utilize Technology: Lean Construction tools	Utilize technology to support collaborative design and project management. This will help to streamline and automate processes and reduce the amount of manual data entry.	[48]
4	Education and training	Make sure that all stakeholders have the necessary knowledge and skills to support and participate in the Lean Construction implementation process.	[47, 48]
5	Team work and Communication	Establish clear lines of communication between all stakeholders and ensure that everyone is kept informed of progress and changes	[49-52]
6	Establish a Lean Construction Task Force	Establish an internal team of people who are dedicated to the Lean Construction implementation and change process	[48, 53]
7	Develop Measurement and Evaluation System	Establish a system for measuring the effectiveness of the Lean Construction implementation process. This will help to identify areas of improvement and focus resources on the most important initiatives	[47, 52]
8	Provide and Support Resources	Provide and support resources to stakeholders in order to ensure that they have everything they need to be successful	[47, 49, 50]
9	Develop a System of Transparency and Accountability	Establish a system of accountability that ensures that stakeholders are held accountable for their actions and performance in order to ensure that the Lean Construction implementation process is successful	[49, 54]

2.5 Gap area based on literature review

The Ethiopian construction industry lacks research on identifying and prioritising barriers and overcoming strategies for implementing LC principles and tools. They found that more studies prioritised barriers in other industries, such as manufacturing and small- and medium-sized enterprises, than in the construction industry. Only a few studies [46, 49, 51, 53] have focused on solutions and strategies to overcome these barriers. There is also a lack of specific research on prioritising barriers and strategies for overcoming barriers to implementing LC principles and methods in the construction industry. The nature of barriers and the obstacles to overcoming them is multidimensional. This study did not find any research that contextualised the barriers and strategies for overcoming them in Ethiopia, particularly in the construction industry. Researchers have used multi-criteria decision-making (MCDM) techniques to rank LC barriers but have not prioritise or linked strategies to address these barriers. Additionally, researchers have neglected possibilities related to errors in human judgment, which could be a result of the lack of fuzzy treatment in the chosen MCDM. These gaps highlight the need to link the LC barriers to strategies for overcoming them.

3 Methodology

This study identified 28 barriers in the public construction industry and proposes nine strategies for overcoming them. An integrated fuzzy AHP and fuzzy TOPSIS technique was proposed to identify, weigh, prioritise, and rank these strategies. A survey pairwise comparison questionnaire was used for data collection that targeted senior project managers, BIM trainers, team leaders, researchers, and decision-makers. The fuzzy AHP technique was applied to calculate the weights of the barriers and strategies for overcoming them. A questionnaire was administered to 11 experts, who were asked to compare solutions to address all barriers using a 1-9 Likert scale fuzzy crisp value. The majority of respondents had more than 11 years of professional experience and a master's degree, and two respondents had a doctoral degree. This represents a good basis of personal professional experience and educational level in the sample. This study employs the MCDM approach by integrating fuzzy AHP and fuzzy TOPSIS for prioritisation purposes. MCDM is a method in operational research that aids individuals in making decisions based on multiple conflicting criteria by considering both quantitative and qualitative factors [54]. The methodology used in this study is illustrated in Figure 1.

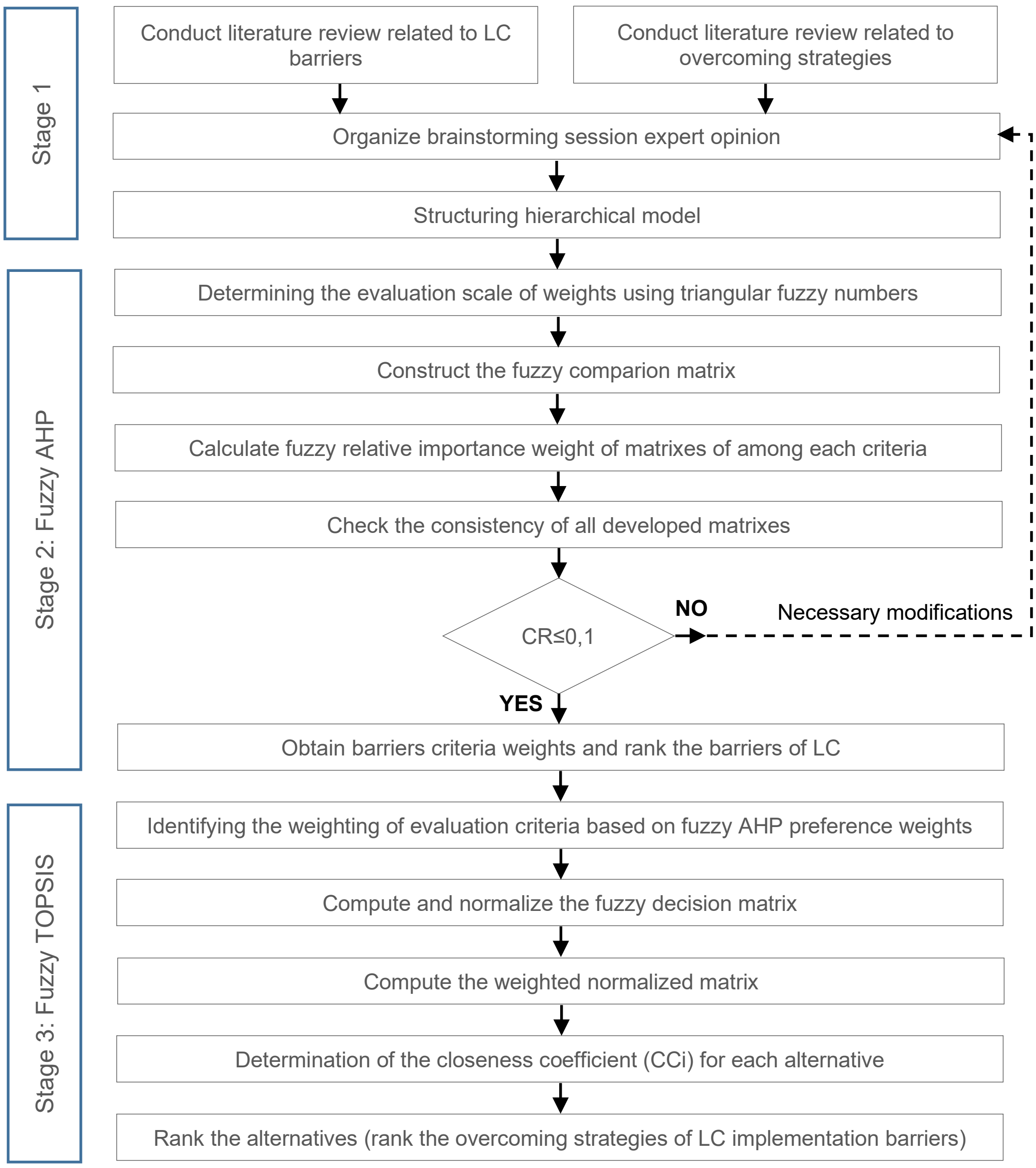


Figure 1. Proposed integrated fuzzy AHP and TOPSIS framework

3.1 Multi-criteria decision-making (MCDM)

Multi-Criteria Decision-Making (MCDM) is a comprehensive approach designed to address complex decision-making problems. It is broadly categorized into two types: multi-attribute decision-making (MADM) and multi-objective decision-making (MODM) [55]. Since its emergence in the 1970s, MCDM has been widely utilized across various fields, employing a range of techniques and hybrid methods. These include the Analytic Network Process (ANP), Analytic Hierarchy Process (AHP), and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Multi-Criteria Optimization and Compromise Solution (VIKOR), Data Envelopment Analysis (DEA), Decision-Making Trial and Evaluation Laboratory (DEMATEL), Simple Additive Weighting (SAW), and Elimination and Choice Translating Reality (ELECTRE). Table 3 highlights the diverse applications of integrated fuzzy AHP and fuzzy TOPSIS across different sectors, showcasing their versatility and effectiveness.

Table 3. Application of integrated fuzzy AHP and fuzzy TOPSIS

Area of application	Ref
The challenges of lean transformation and implementation in the manufacturing sector	[56]
Fuzzy logic based method to measure degree of lean activity in manufacturing industry	[57]
Key criteria influencing cellular manufacturing system	[58]
Selection framework of disruption analysis methods for megaprojects	[59]
Assessing and overcoming the barriers for healthcare waste management in India	[60]
Prioritization of production strategies of a manufacturing plant	[61]
Assessing and overcoming the renewable energy barriers for sustainable development in Pakistan	[62]
A corridor selection for locating autonomous vehicles	[63]
Selecting the best colour removal process using carbon-based adsorbent materials	[64]
Evaluation of outsource manufacturers.	[65]
Application of goal programming for the stock area selection problem of an automotive company	[66]
Transportation management through a new distance measure	[67]
Aircraft selection	[68]

3.2 Fuzzy AHP

Fuzzy AHP is a popular decision-making technique in MCDM and was developed by Saaty [69]. This technique involves building a hierarchy of criteria and assigning a weight to each criterion using fuzzy logic. This method is useful when multiple criteria must be considered and the weight of each criterion is unclear or challenging to determine. Fuzzy AHP enhances decision flexibility and accuracy by considering the ambiguity and uncertainty of the criteria. The AHP approach involves enumerating the main and sub-criteria, specifying the triangular fuzzy number (TFN) scale for forming the pairwise comparison matrix, establishing a fuzzy comparison matrix (FCM) for each criterion and sub-criterion, transitioning the FCM into a crisp comparison matrix (CCM), checking for consistency, and prioritising each criterion based on the final weight [70, 71]. This study used the following steps in the fuzzy AHP approach:

- Step1: Enumerate main and sub-criteria to build a hierarchal structure.
- Step 2: Specify the TFN scale adopted to form the pairwise comparison matrix.
- Step 3: Establish a FCM for each criterion and sub-criterion.
- Step 4. Transition of FCM into a CCM.
- Step 5. Carry out the check for consistency.
- Step 6. Prioritize each criterion according to the final weight obtained.

3.3 Fuzzy TOPSIS

Fuzzy TOPSIS is a widely used method for MCDM that ranks alternatives in a fuzzy environment. It was first developed by Hwang and Yoon in 1981, and encourages the selection of alternatives that are closest to the positive ideal solution (PIS) and furthest away from the negative ideal solution (NIS) [55]. The effectiveness of the method depends on the option chosen with the shortest separation from the positive perfect management and the greatest distance from the negative perfect arrangement [72]. In this study, a modified fuzzy TOPSIS technique proposed to evaluate solutions to the barriers to lean implementation. The data were arranged in a fuzzy representative matrix and the proximity coefficients of each method were calculated. The strategies are ranked based on their proximity coefficients. The approach with the maximum closeness coefficient is ranked first, whereas the approach with the lowest coefficient value is ranked last. This fuzzy modified technique is suitable for handling vagueness in real-life applications. The steps of the fuzzy TOPSIS approach include creating a decision matrix, normalizing the decision matrix, and calculating the distance between each alternative and the fuzzy positive and negative ideal solutions [73, 74]. This study used the following steps of the fuzzy TOPSIS approach:

- Step 1: Create a decision matrix.
- Step 2: Create the normalized decision matrix.
- Step 3: Create the weighted normalized decision matrix.
- Step 4: Determine the fuzzy positive ideal solution (FPIS, A*) and fuzzy negative ideal solution (FNIS, A^).
- Step 5: Calculate the distance between each alternative and the FPIS A^* and the distance between each alternative and the FNIS A^-.
- Step 6: Calculate the closeness coefficient and rank the alternatives.

4 Results

4.1 Fuzzy AHP process execution

The LCI barriers discussed in the previous section were prioritised using the fuzzy AHP technique. The steps listed below were used for prioritisation.

4.1.1 Step 1: Enumerate the main and sub-criteria to build a hierarchal structure

This study examined 28 potential LCI obstacles and nine strategies for overcoming them in the Ethiopian literature. It creates a hierarchy that prioritises barriers and solutions, grouped under managerial, technical, cultural, governmental, workforce, communication, and financial barriers. These 28 LCI barriers were grouped according to their respective criteria. The decision hierarchy for prioritising the barriers to LCI and the strategies for overcoming them are shown in Figure 2.

4.1.2 Step 2: Specify the TFN scale

The evaluation scale of the weights is determined using TFNs. A TFN Ã can be denoted by a triplet as Ã= (l, m, u), where l and u mean the lower and upper bounds of the fuzzy number Ã, and m is the modal value for Ã. Based on these three parameters of the symmetric TFN, the membership function μÃ (x) (scale of fuzzy number) is determined. The TFN scale 1–9 was used to enhance the accuracy of the solution to the selected problem. Table 4 presents the scale of relative importance in the pairwise comparison matrix.

$$\mu\tilde{A}(x) = \begin{cases} \dfrac{x-1}{m-1}, l < x < m \\ \dfrac{u-x}{x-m}, m \le x \le u \\ 0, \quad otherwise \end{cases} \tag{1}$$

Table 4. Linguistic data and fuzzy triangular scale

Value of a_{ij} (crisp value)	Explanation	TFN
1	Objectives i and j have equal importance	(1,1,1)
3	Objective i is weakly more important than objective	(1,3,5)
5	Experience and judgment indicate that objective i is strongly more important than objective j	(3,5,7)
7	Objective i is very strongly or demonstrably more important than objective	(5,7,9)
9	Objective i is absolutely more important than objective j	(7,9,9)
2,4,6,8 can be used to express intermediate values		(1,2,3), (2,4,6), (4,6,8), (6,8,9)

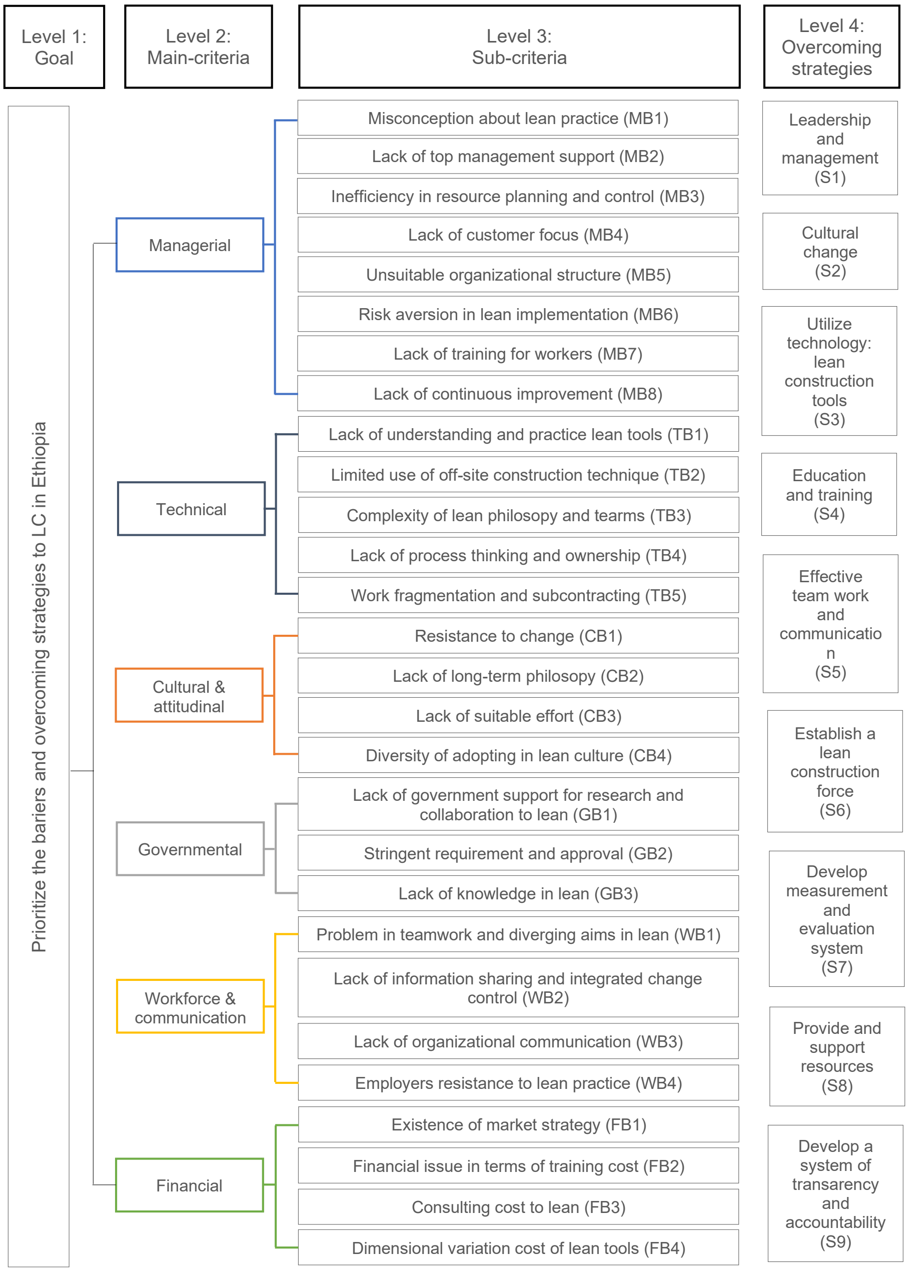


Figure 2. Decision hierarchy for prioritizing the barriers to LCI and the strategies for overcoming them

4.1.3 Step 3: Establish an FCM for each criterion and sub-criterion

Based on TFNs, the pairwise comparison matrices for the main criteria and sub-criteria are constructed by asking experts which of the two criteria is the most important. Each expert made the comparison individually. Due to space limitations, only the FCM developed by Expert 1 and the main criteria for LCI barriers are presented in Table 5. However, for calculation purposes, the mean FCM of all experts considered. Fuzzy pairwise comparison matrix (FPCM) $\tilde{X}$ prepared by performing a pairwise comparison between the defined attributes.

$$\tilde{X} = \begin{bmatrix} 1 & \widetilde{x_{12}} & \dots & \dots & \dots & \widetilde{x_{1n}} \\ \widetilde{x_{21}} & 1 & \dots & \dots & \dots & \widetilde{x_{2n}} \\ \dots & \dots & 1 & \dots & \dots & \dots \\ \dots & \dots & \dots & 1 & \dots & \dots \\ \dots & \dots & \dots & \dots & 1 & \dots \\ \widetilde{x_{n1}} & \widetilde{x_{n2}} & \dots & \dots & \dots & 1 \end{bmatrix} \tag{2}$$

In this case, x_{iju} is allotted a value of 1 if I is similar to j, and x_{iju} = (1,3,5,7,9) or 1-1,3-1, .., .., .., 9-1 if the value of I is not similar to j. This signifies the emphasis of attribute I on attribute j according to the TFN scale.

Table 5. Pairwise comparison of the main criteria

	Managerial	Technical	Cultural & attitudinal	Governmental	Communication & workforce	Financial
Managerial	(1,1,1)	(1,1,1)	(1,1,1)	(1,3,5)	(5,7,9)	(5, 7,9)
Technical	(1,1,1)	(1,1,1)	(1,1,1)	(1,3,5)	(1,3,5)	(5,7,9)
Cultural& Attitudinal	(1,1,1)	(1,1,1)	(1,1,1)	(1,3,5)	(3,5,7)	(5,7,9)
Governmental	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1,1,1)	(1,3,5)	(3,5,7)
Communication & workforce	(1/9,1/7,1/5)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1,1,1)	(3,5,7)
Financial	(1/9,1/7,1/5)	(1/9,1/7,1/5)	(1/7,1/5,1/3)	(1/7,1/5,1/3)	(1,1,1)	(1,1,1)

4.1.4 Step 4. Transition the FCM into a CCM

This study used the α-cut method for ranking purposes. The α-cut method unites the expert panel's assurance concerning the judgments made while building an FPCM in the last step. For calculation purposes, the value of α-cut is taken as 0,5, and the set (2, 3, and 4) is considered as presented in Figures 3 and 4, which implies that the assessments made by the decision group panel are balanced concerning case optimism. Hence, by substituting the value of μ in Eq. (1) of α-cut comparison matrix, the modified matrix values can be computed, enabling further analysis and interpretation within the decision-making framework.

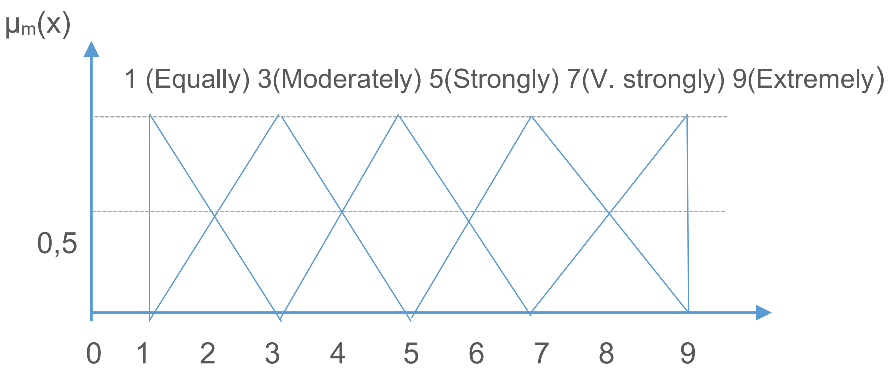
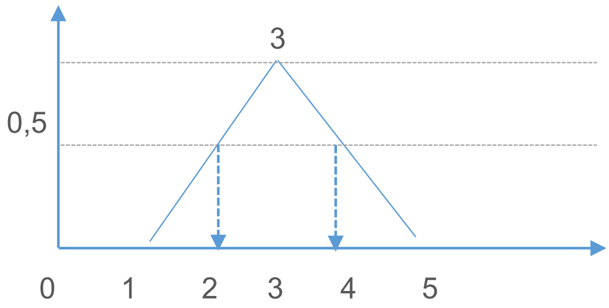


Figure 3. Fuzzy membership function



α 0,5= (2, 3, 4) = [2, 4]

Figure 4. The α-cut value

After defining the α value, the comparison matrix for α-cut can be prepared by using FPCM after adjusting the degree of optimism μ required to calculate the satisfaction level:

$$X^{\sim\alpha} = \begin{bmatrix} 1 & X^{\sim\alpha}{}_{12} & \dots & \dots & \dots & X^{\sim\alpha}{}_{1n} \\ X^{\sim\alpha}{}_{21} & 1 & \dots & \dots & \dots & X^{\sim\alpha}{}_{2n} \\ \dots & \dots & 1 & \dots & \dots & \dots \\ \dots & \dots & \dots & 1 & \dots & \dots \\ \dots & \dots & \dots & \dots & 1 & \dots \\ X^{\sim\alpha}{}_{n1} & X^{\sim\alpha}{}_{n2} & \dots & \dots & \dots & 1 \end{bmatrix} \quad (3)$$

Enhancement of μ values increases the degree of optimism. The optimism index is given by the following equation:

$$\tilde{x}_{ij}^{\alpha} = \mu^{\alpha}\tilde{x}_{ij1} + (1-\mu)\mu^{\alpha}x_{iju}, 0 \leq \mu \leq 1 \quad (4)$$

By substituting the μ value in the above equation, the α-cut FPCM is converted to CCM X:

$$X = \begin{bmatrix} 1 & \dot{x_{12}} & \dots & \dots & \dots & \dot{x_{1n}} \\ \dot{x_{21}} & 1 & \dots & \dots & \dots & \dot{x_{2n}} \\ \dots & \dots & 1 & \dots & \dots & \dots \\ \dots & \dots & \dots & 1 & \dots & \dots \\ \dots & \dots & \dots & \dots & 1 & \dots \\ \dot{x_{n1}} & \dot{x_{n2}} & \dots & \dots & \dots & 1 \end{bmatrix} \quad (5)$$

Owing to space constraints, only the main criteria calculations are presented in this study. Hence, the converted α-cut CCM for the main criteria is shown below:

$$x = \begin{bmatrix} 1 & 1 & 1 & 3 & 7 & 7 \\ 1 & 1 & 1 & 3 & 3 & 7 \\ 1 & 1 & 1 & 3 & 5 & 7 \\ 0,33 & 0,33 & 0,33 & 1 & 1 & 5 \\ 0,14 & 0,33 & 0,20 & 1 & 1 & 5 \\ 0,14 & 0,14 & 0,14 & 0,20 & 0,5 & 1 \end{bmatrix} \quad (6)$$

4.1.5 Step 5. Carry out the check for consistency

The eigenvalue is an important factor in the consistency of the fuzzy AHP. The consistency of fuzzy AHP is determined using the consistency ratio (CR). If the CR is greater than 0,1, the pairwise comparison matrix is considered inconsistent. The eigenvalue is the sum of the elements in each row or column of the matrix. If the eigenvalue is greater than the number of elements in each row or column, then the matrix is inconsistent. Thus, the eigenvalue is a key factor in determining the consistency of the fuzzy AHP.

Lambda (λ) is the eigenvalue if |A-λ| =0 Lambda Max (λ max) is the maximum eigenvalue of the matrix and it is needed to calculate the consistency index (CI). The ratio column in Table 7 represents the determination of λ max by dividing all the elements of the weighted sum matrix by the priority vector for each criterion. Thus, λ max, which is the sum of the ratio divided by n, becomes 31,5/6=5,251.

Table 6. Random CI values [73]

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0,00	0,00	1,52	0,89	1,11	1,25	1,35	1,40	1,45	1,49	1,52	1,54	1,56	1,58	1,29

Computation of CR as:

$$\lambda\text{max} = \frac{1}{n}\sum_{j=0}^{n}\frac{AWi}{wi} \tag{7}$$

$$CI = \frac{\lambda\text{max} - \text{n}}{n-1} \tag{8}$$

$$CR = \frac{CI}{RI} \tag{9}$$

Where RI is a normalized factor depending on the size of the n matrix.
Therefore, using a random index (RI) of 1,25 for n = 6 from Table 6, a CR of 0,05 was found, which is acceptable because it is less than 0,10. The CR verifies that the comparison is consistent and reliable enough to use the criteria weight for rating.

Table 7. Calculation of λ max

	C1	C2	C3	C4	C5	C6	Weighted sum value	Ratio
Managerial	0,346	0,288	0,339	0,280	0,349	0,261	1,863	5,387
Technical	0,242	0,288	0,339	0,280	0,130	0,181	1,459	5,073
Cultural& Attitudinal	0,242	0,216	0,207	0,202	0,240	0,261	1,368	6,609
Governmental	0,102	0,083	0,056	0,168	0,130	0,181	0,720	5,541
Communication & workforce	0,034	0,083	0,030	0,045	0,076	0,058	0,326	4,308
Financial	0,034	0,043	0,030	0,024	0,076	0,058	0,265	4,588
Criteria weight	0,346	0,288	0,207	0,130	0,076	0,058	1,104	31,506

4.1.6 Step 6. Prioritize each criterion according to the final weight obtained

Finally, the final weights for each criterion are obtained by multiplying the major criteria weight by the sub-criteria weight. Hence, the final weights of all the criteria are obtained, and all the criteria are prioritised as shown in Table 8.

Table 8. Criteria weight, CR, and rank

Main Criteria	Major criteria wt.	Sub-criteria name	CR	Sub-criteria weight	Final weight	Rank
Managerial	0,243	MB1	0,091	0,157	0,0382	12
		MB2		0,158	0,0384	11
		MB3		0,139	0,0338	17
		MB4		0,113	0,0275	19

		MB5		0,101	0,0245	21
		MB6		0,074	0,0180	23
		MB7		0,141	0,0343	16
		MB8		0,117	0,0284	18
Technical	0,230	TB1	0,01	0,229	0,0527	5
		TB2		0,190	0,0437	9
		TB3		0,206	0,0474	6
		TB4		0,191	0,0439	8
		TB5		0,184	0,0423	10
Cultural & Attitudinal	0,246	CB1	0,053	0,382	0,0940	1
		CB2		0,287	0,0706	3
		CB3		0,188	0,0462	7
		CB4		0,143	0,0352	14
Governmental	0,174	GB1	0,03	0,383	0,0666	4
		GB2		0,209	0,0364	13
		GB3		0,408	0,0710	2
Workforce & Communication	0,094	CW1	0,024	0,292	0,0274	20
		CW2		0,193	0,0181	22
		CW3		0,145	0,0136	24
		CW4		0,369	0,0347	15
Financial	0,012	FB1	0,018	0,387	0,0050	25
		FB2		0,296	0,0038	26
		FB3		0,220	0,0029	27
		FB4		0,098	0,0013	28

4.2 Fuzzy TOPSIS process execution

4.2.1 Step 1

Create a decision matrix. In this study, there are 28 criteria and nine alternatives are ranked based on the fuzzy TOPSIS method. Table 9 lists the type of criterion and the weights assigned to each criterion.

Table 9. Weight assigned to each criterion

Criteria	MB1	MB2	MB3	MB4	MB5	MB6	CWB3	CWB4	FB1	FB2	FB3	FB4
Weight	0,038	0,038	0,034	0,027	0,025	0,018	0,014	0,035	0,005	0,004	0,003	0,001

Table 10 shows the fuzzy scale used in the model.

Table 10. Fuzzy scale

Code	Linguistic terms	L	M	U
1	Very low	1	1	3
2	Low	1	3	5
3	Medium	3	5	7
4	High	5	7	9
5	Very high	7	9	9
2,4,6	intermediate values	--	--	--

Alternatives were evaluated in terms of various criteria, and the results of the decision matrix are listed in Table 11. If multiple experts participated in the evaluation, the matrix below represents the arithmetic mean of all experts.

Table 11. Decision matrix

	MB1	MB2	MB3	MB4	FB2	FB3	FB4
S1	(7,9,9)	(5,7,9)	(5,7,9)	(1,3,5)	(5,7,9)	(5,7,9)	(1,1,3)
S2	(7,9,9)	(7,9,9)	(1,3,5)	(3,5,7)	(4,6,8)	(4,6,8)	(4,6,8)
S3	(1,3,5)	(1,3,5)	(7,9,9)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)
S4	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(1,3,5)	(1,1,3)	(1,3,5)
S5	(1,3,5)	(1,3,5)	(3,5,7)	(3,5,7)	(1,3,5)	(1,3,5)	(1,3,5)
S6	(3,5,7)	(5,7,9)	(5,7,9)	(3,5,7)	(1,3,5)	(1,1,3)	(1,3,5)
S7	(1,1,3)	(1,1,3)	(1,1,3)	(3,5,7)	(1,1,3)	(1,1,3)	(1,1,3)
S8	(3,5,7)	(7,9,9)	(3,5,7)	(3,5,7)	(6,8,9)	(6,8,9)	(6,8,9)
S9	(1,3,5)	(5,7,9)	(5,7,9)	(5,7,9)	(4,6,8)	(2,4,6)	(1,3,5)

4.2.2 Step 2

Create the normalised decision matrix: Based on the positive and negative ideal solutions, a normalised decision matrix can be calculated using the following relation and the results shown in Table12:

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right),\ c_j^* = max_i\ c_{ij} \text{ Positive ideal solution} \quad (10)$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), a_j^- = min_i\ a_{ij} \text{ Negative ideal solution} \quad (11)$$

Table 12. The normalized decision matrix

	MB1	MB2	MB3	FB3	FB4
S1	(0,79,1,1)	(0,56,0,78,1)	(0,56,0,78,1)	(0,56,0,78,1)	(0,11,0,11,0,33)
S2	(0,78,1,1.)	(0,77,1.0,1.0)	(0,11,0,33,0,56)	(0,44,0,67,0,78)	(0,44,0,67,0,78)
S3	(0,1,0,33,0,56)	(0,11,0,33,0,56)	(0,79,1,1)	(0,11,0,33,0,56)	(0,11,0,33,0,56)
S4	(0,56,0,78,1)	(0,56,0,78,1)	(0,56,0,78,1)	(0,11,0,33,0,56)	(0,11,0,33,0,56)
S5	(0,11,0,33,0,56)	(0,11,0,33,0,56)	(0,33,0,55,0,78)	(0,11,0,33,0,56)	(0,11,0,33,0,56)
S6	(0,33,0,55,0,78)	(0,56,0,78,1)	(0,56,0,78,1)	(0,11,0,11,0,33)	(0,11,0,11,0,33)
S7	(0,11,0,11,0,33)	(0,11,0,11,0,33)	(0,11,0,11,0,33)	(0,11,0,11,0,33)	(0,11,0,11,0,33)
S8	(0,33,0,56,0,78)	(0,79,1,1)	(0,333,0,556,0,778)	(0,67,0,89,1)	(0,67,0,89,1)
S9	(0,11,0,33,0,56)	(0,56,0,78,1)	(0,56,0,78,1)	(0,22,0,44,0,67)	(0,11,0,33,0,56)

4.2.3 Step 3

Create the weighted normalise decision matrix: Considering the different weights of each criterion, the weighted normalise decision matrix can be calculated by multiplying the weight of each criterion in normalise fuzzy decision matrix according to the following formula:

$$\tilde{v}_{ij} = \tilde{r}_{ij}.\tilde{w}_{ij} \quad (12)$$

Where $\tilde{w}_{ij}$ represents weight of criterion c_j. Table 13 shows the weighted normalized decision matrix.

Table 13. The weighted normalized decision matrix

	MB1	MB2	CWB3	CWB4
S1	(0,030,0,038,0,038)	(0,021,0,30,0,038)	(0,006,0,009,0,011)	(0,019,0,027,0,037)
S2	(0,030,0,038,0,038)	(0,030,0,038,0,038)	(0,009,0,012,0,014)	(0,023,0,031,0,037)
S3	(0,004,0,013,0,021)	(0,004,0,013,0,021)	(0,008,0,011,0,014)	(0,019,0,027,0,037)
S4	(0,021,0,030,0,038)	(0,021,0,030,0,038)	(0,002,0,005,0,008)	(0,019,0,027,0,037)
S5	(0,004,0,013,0,021)	(0,004,0,013,0,021)	(0,011,0,014,0,014)	(0,027,0,035,0,037)
S6	(0,013,0,021,0,030)	(0,021,0,030,0,038)	(0,011,0,014,0,014)	(0,027,0,035,0,037)
S7	(0,004,0,004,0,013)	(0,004,0,004,0,013)	(0,005,0,008,0,011)	(0,012,0,019,0,028)
S8	(0,013,0,021,0,030)	(0,030,0,038,0,038)	(0,005,0,008,0,011)	(0,012,0,019,0,028)
S9	(0,004,0,013,0,021)	(0,021,0,030,0,038)	(0,008,0,011,0,014)	(0,004,0,012,0,020)

4.2.4 Step 4

Determine the fuzzy positive ideal solution (FPIS, A*) and the fuzzy negative ideal solution ($FNIS, A^{-}$). The FPIS and FNIS of the alternatives can be defined as follows:

$$A^{*} = \{\tilde{v}_1^{*}, \tilde{v}_2^{*}, \dots, \tilde{v}_n^{*}\} = \left\{\left(\max_j v_{ij} \mid i \in B\right), \left(\min_j v_{ij} \mid i \in C\right)\right\} \quad (13)$$

$$A^{-} = \{\tilde{v}_1^{-}, \tilde{v}_2^{-}, \dots, \tilde{v}_n^{-}\} = \left\{\left(\min_j v_{ij} \mid i \in B\right), \left(\max_j v_{ij} \mid i \in C\right)\right\} \quad (14)$$

Where $\tilde{v}_i^{*}$ the maximum is value of i for all alternatives and $\tilde{v}_1^{-}$ is the minimum value of i for all alternatives. *B* and *C* represent positive and negative ideal solutions, respectively.

4.2.5 Step 5

Calculate the distance between each alternative and the FPIS $A^{*}$and the distance between each alternative and the FNISA^{-}. The distance between each alternative and the FPIS and the distance between each alternative and the FNIS are, respectively, calculated as follows:

$$S_i^{*} = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^{*}), i = 1, 2, \dots, m \quad (15)$$

$$S_i^{-} = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^{-}), i = 1, 2, \dots, m \quad (16)$$

Where d is the distance between two fuzzy numbers, when given two TFNs (a_1, b_1, c_1) and (a_2, b_2, c_2), the distance between the two can be calculated as follows:

$$d_v(\widetilde{M}_1, \widetilde{M}_2) = \sqrt{\frac{1}{3}[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2]} \quad (17)$$

Note that $d(\tilde{v}_{ij}, \tilde{v}_j^{*})$ and $d(\tilde{v}_{ij}, \tilde{v}_j^{-})$ are crisp numbers. Table 14 shows the distance from the positive and negative ideal solutions.

Table 14. Distance from the positive and negative ideal solutions

	Distance from positive ideal	Distance from negative ideal
S1	0,11	0,568
S2	0,111	0,564
S3	0,326	0,361
S4	0,189	0,493
S5	0,376	0,309
S6	0,527	0,147
S7	0,618	0,053
S8	0,295	0,387
S9	0,4	0,29

4.2.6 Step 6

Calculate the closeness coefficient and rank the alternatives. The closeness coefficient of each alternative can be calculated as follows:

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (18)$$

The best alternative is the one closest to the FPIS and farthest from the FNIS. The closeness coefficients of the alternatives and their ranking order are presented in Table 15.

Table 15. Closeness coefficients

Alternative	CCi	rank
S1	0,838	1
S2	0,836	2
S3	0,525	5
S4	0,723	3
S5	0,451	6
S6	0,218	8
S7	0,079	9
S8	0,567	4
S9	0,420	7

5 Discussion

The integrated fuzzy AHP and fuzzy TOPSIS method helps the decision-maker choose the best alternative from the LC practice barriers and strategies to overcome them by prioritising and ranking processes. To decrease waste and enhance the performance of construction projects, companies should identify hurdles in the adoption of LC practices and work to overcome them.

5.1 Barriers

A literature search and expert opinions identified 28 barriers to LC practice, which were categorised as managerial, technical, cultural, governmental, workforce, communication, and finance, and the major criteria and weights are shown in Table 15. Cultural and attitudinal barriers were the most significant, accounting for approximately 24,6 % of the difficulties in LCI. The conservative nature of Ethiopian buildings coupled with the prevalence of traditional methods contributes to these barriers. Human attitudes, cultural mind sets, and the desire to use conventional project management ideas also pose challenges. People generally resist change because of their habitual nature, and the construction industry is large and old, making it difficult to change management styles. Maware et al. [57] also found that cultural barriers ranked first in the US manufacturing sector.

Table 16. Weight and rank of major criteria

Rank	Major Criterion name	Criterion weight
1	Cultural and Attitudinal	0,246
2	Managerial	0,243
3	Technical	0,230
4	Governmental	0,174
5	Workforce and communication	0,094
6	Financial	0,013

Managerial barriers emerged as the second highest priority, with a weight of 0,243, underscoring their critical role as obstacles to the effective implementation of lean construction (LC) practices. Common managerial challenges include a lack of knowledge, awareness, or commitment to lean principles, which often result in resistance to change, unclear leadership, and inadequate resource allocation. These issues can further lead to ineffective decision-making, poor communication, and a lack of collaboration between departments. Additionally, poor management can hinder the adoption of technology, complicating the construction process. To overcome these challenges, managers must commit to fostering a culture of continuous improvement and demonstrate a willingness to embrace the necessary changes for LC adoption.

The technical barrier ranked as the third most significant, with a weight of 0,230. This barrier often arises from insufficient knowledge or understanding of lean principles, a shortage of skilled personnel, and resistance to change, limited resources, and inadequate organizational support. Furthermore, factors such as project scope, complexity, and budget constraints can pose additional challenges to implementation. According to the prioritize barriers to LC, as highlighted in the table above, other key priorities include government-related issues, workforce limitations, communication gaps, financial constraints, and additional challenges.

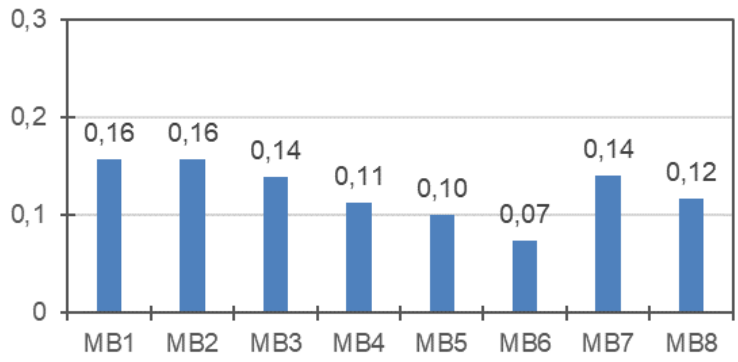


Figure 5. Managerial sub-criteria weight

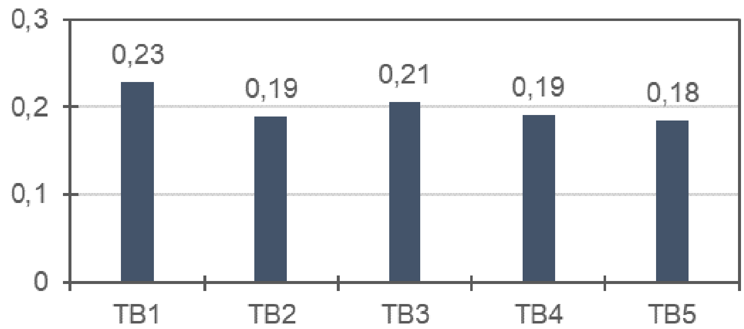


Figure 6. Technical sub-criteria weight

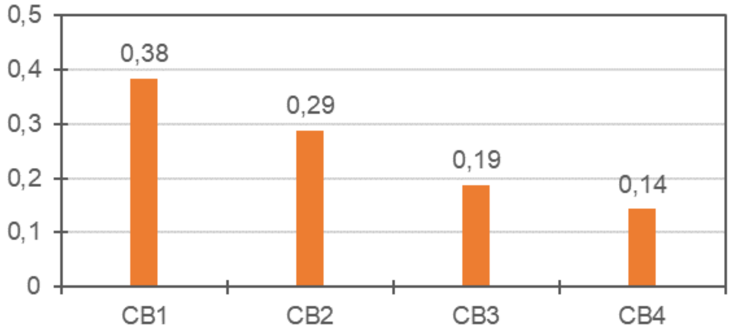


Figure 7. Cultural and attitudinal sub- criteria weight

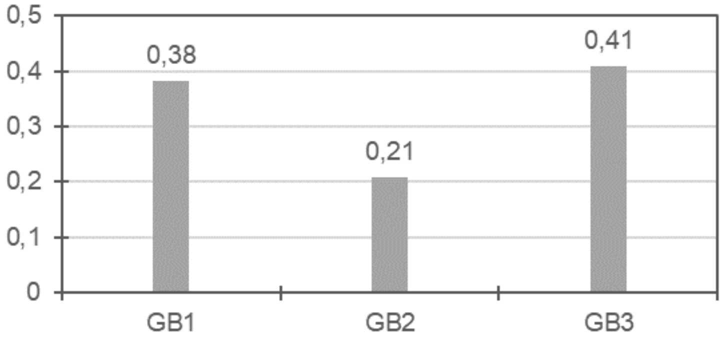


Figure 8. Governmental sub-criteria weight

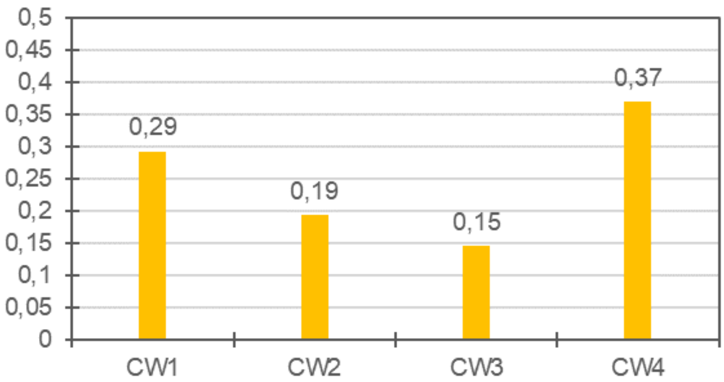


Figure 9. Workforce and communication weight

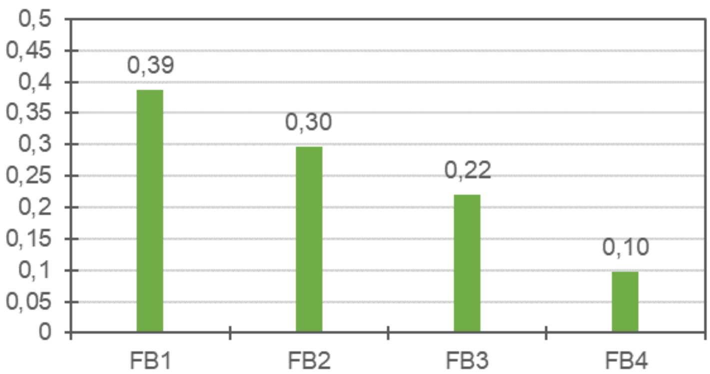


Figure 10. Financial sub-criteria weight

The sub-criteria in this study indicate that the managerial barrier sub-criteria ranking is MB2 > MB1 > MB7 > MB3 > MB8 > MB4 > MB5 > MB6, as shown in Figure 5, showing that a lack of managerial support is the first rank and next priorities are misconception about lean practice, lack of training for workers, inefficiency in resource planning and control, and risk aversion in lean implementation. The ranking values of the technical barriers are TB1 > TB3 > TB4 > TB2 > TB5 (Figure 6), in which a lack of understanding and practice of lean tools and techniques are the first and second priorities and work fragmentation and subcontracting are the last priorities. The cultural and attitudinal barrier rankings are CAB1 > CAB2 > CAB3 > CAB4, as shown in Figure 7, in which resistance to change has the highest weight, and diversity in adopting a lean culture has the lowest weight value. According to the governmental barriers shown in Figure 8, a lack of knowledge of lean is a priority. The next priority is the lack of government support for research and collaboration to meet lean and stringent requirements, and approval according to the obtained weights. The ranking values of workforce and communication barriers are WC4 > WC1 > WC2 > WC3, as shown in Figure 9, in which employer resistance to lean practices is the first priority, and lack of information sharing and integrated change control is the last priority. Finally, the financial sub-criteria are FB1 > FB2 > FB3 > FB4 in Figure 10, in which the existence of a market strategy is the first priority, followed by financial issues in terms of training cost, consulting cost for lean, and the dimensional variation cost of lean tools according to weight.

5.2 Strategies for overcoming barriers

To overcome the above barriers to LC practice, a modified fuzzy TOPSIS MCDM approach was applied. Fuzzy TOPSIS also provides a method for evaluating various solutions and selecting the best one for a given situation. This can help identify the most efficient and effective way to implement an LC process. The goal of fuzzy TOPSIS is to achieve the best possible strategy for overcoming barriers in the least amount of time and at the lowest cost.

Table 17. The closeness coefficient and rank of each overcoming strategy alternative

Alternatives	Code	CCi	Rank
Leadership and management	S1	0,838	1
Cultural change	S2	0,836	2
Utilize Technology: Lean Construction tools	S3	0,525	5
Education and training	S4	0,723	3
Team work and communication	S5	0,451	6
Establish a lean construction task force	S6	0,218	8
Develop measurement and evaluation system	S7	0,079	9
Provide and support resources	S8	0,567	4
Develop a system of transparency and accountability	S9	0,42	7

The ranking of strategies for overcoming barriers to LCI in the Ethiopian construction industry has been recommended to decision-makers to choose the best alternative, as mentioned above in Table 17. Therefore, the highest closeness coefficient was used to rank the solutions. The findings revealed that the first-ranked solution, with the highest closeness coefficient of 0,938, was leadership and management (S1), followed by cultural change for continuous learning and improvement (S2), with a closeness coefficient of 0,826. The third and fourth priorities were education and training (S4) and providing and supporting resources (S8), with closeness coefficients of 0,723 and 0,567, respectively. The lowest-ranked closeness coefficient was that of the developed measurement and evaluation system (S7).

5.3 Sensitivity analysis (robustness test)

A robustness test is used to assess the performance of a system when changes in parameters occur. It determines whether a system is resilient to changes in the parameters, whereas sensitivity analysis evaluates its sensitivity to input variations. Robust results in the sensitivity analysis were consistent and reliable despite changes in certain parameters. This study conducted a robustness test to determine the feasibility of the findings, with the primary purpose of discovering a new ranking of alternatives by varying the weights of the criteria in various cases. Weight values were generated from a uniform distribution weight ranging from 0 to 1 based on expert judgment. The table outlines the results of 30 experiments (Expt1–Expt30), each involving varying weight configurations (wb1 to wb28) and their impact on the performance of nine samples (S1–S9). In Expt1, uniform weights of 0,036 were assigned to all variables (wb1 to wb28), resulting in S1 achieving the highest value (0,869, ranked 1st) and S7 the lowest (0,118, ranked 9th). In Expt2, with a uniform weight of 0,12, S1 retained its top position (0,766), while S7 again ranked last (0,126).

From Expt3 onward, a different approach was applied, where a specific variable was assigned a higher weight of 0,612, while the rest were set to 0,12. For example, in Expt3, wb1 was assigned 0,612, leading to S1 improving to 0,881, while S7 decreased slightly to 0,096. Similarly, in Expt4, when wb2 was assigned 0,612, S1 increased further to 0,887, maintaining its rank, while S7 remained the lowest with a value of 0,092. This trend continued in subsequent experiments, with the high weight shifting progressively to other variables (wb3 in Expt5, wb4 in Expt6, etc.). The results demonstrate that S1 consistently outperformed all other samples across the experiments, maintaining the highest ranking in every case. S2 also showed strong performance, often ranked 2nd, while S3 and S4 alternated between mid-level rankings (3rd to 5th). In contrast, S6 and S7 consistently displayed the lowest performance, frequently ranked 8th and 9th, respectively. S8 and S9 showed moderate performance, typically ranked between 3rd and 7th.By the final experiment (Expt30), where wb28 was weighted at 0,612, S1 reached its peak performance value of 0,884, while S7 remained the lowest at 0,094. Overall, the table highlights how shifting weight distributions influence sample performance, with certain samples like S1 and S2 demonstrating robust behaviour regardless of configuration, while others, such as S6 and S7, consistently underperform.

The final prioritisation order of strategies (S1-S9) determined by sensitivity analysis ranking the closeness of coefficients, remained the same in 27 experiments (S1 >S2 > S4 > S8 > S3 > S5 > S9 > S6 > S7), except for the ranking of the two alternative solutions. S4 and S8 were interchanged in three experiments: 7, 29, and 30 (S1 >S2 > S8 > S4 > S3 > S5 > S9 > S6 > S7).

Table 18. Weights of criteria with different experiments and rank of sensitivity analysis

	Expt1 (wb1-wb28=0,036)	**Expt2 (wb1-wb28=0,12)**	**Expt3 (wb1=0,612; wb2-wb28 =0,12)**	**Expt4 (wb2=0,612, wb1, wb3-wb28=0,12)**	**Expt5 (wb3=0,612; wb1-2, wb3-wb28=0,12)**	**Expt6 (wb4=0,612, wb1- wb3, wb5-wb28=0,12)**
S1	0,869(1)	0,766(1)	0,881(1)	0,887(1)	0,853(1)	0,789(1)
S2	0,689(2)	0,667(2)	0,735(2)	0,747(2)	0,684(2)	0,739(2)
S3	0,518(5)	0,377(5)	0,483(5)	0,471(5)	0,582(5)	0,467(5)
S4	0,636(3)	0,628(3)	0,667(3)	0,672(3)	0,672(3)	0,686(3)
S5	0,446(6)	0,351(6)	0,418(6)	0,409(6)	0,448(6)	0,445(6)
S6	0,266(8)	0,312(8)	0,258(8)	0,311(8)	0,311(8)	0,255(8)
S7	0,118(9)	0,126(9)	0,096(9)	0,092(9)	0,092(9)	0,143(9)
S8	0,557(4)	0,463(4)	0,526(4)	0,59694)	0,604(4)	0,611(4)
S9	0,421(7)	0,352(7)	0,396(7)	0,407(7)	0,388(7)	0,338(7)
	Expt7 (wb5=0,612, wb1-w4, wb6-wb28=0,12)	**Expt8 (wb6=0,612, wb1-wb5,wb7-wb28=0,12)**	**-----**	**----**	**Expt29 (wb27=0,612 , wb1-wb26, wb28=0,12)**	**Expt30 (wb28=0,61 2, wb1-wb27=0,12)**

S1	0,84(1)	0,789(1)	-----	-----	0,884(1)	0,884(1)
S2	0,791(2)	0,784(2)	-----	-----	0,748(2)	0,748(2)
S3	0,485(5)	0,556(5)	-----	-----	0,485(5)	0,485(5)
S4	0,652(4)	0,641(3)	-----	-----	0,610(4)	0,610(4)
S5	0,463(6)	0,400(6)	-----	------	0,421(6)	0,421(6)
S6	0,203(8)	0,209(8)	-----	-----	0,203(8)	0,203(8)
S7	0,094(9)	0,097(9)	-----	-----	0,094(9)	0,094(9)
S8	0,667(3)	0,611(4)	-----	-----	0,624(3)	0,624(3)
S9	0,359(7)	0,338(7)	-----	-----	0,284(7)	0,284(7)

The robustness of the test is clearly validated by Table 18, which highlights minimal variation in strategy rankings across multiple experiments conducted under the proposed hybrid framework. Sensitivity analysis further corroborates this stability, revealing negligible differences in the prioritization of strategies (leadership commitment consistently ranking highest), aligning with the earlier finding that 27 out of 30 experimental iterations retained consistent results despite parameter adjustments. The Fuzzy AHP/TOPSIS methodology effectively mitigated ambiguities in expert judgments, enhancing the credibility of the outcomes. While contextual specificity to Ethiopia's construction sector marked by cultural resistance and fragmented workflows remains a consideration. Thus, the results of the sensitivity analysis confirm that the rankings of strategies for addressing LCI barriers are both stable and reliable, providing valuable insights for effective implementation.

6 Conclusion

6.1 Findings

The construction industry often encounters complex decision-making scenarios based on uncertain criteria. Fuzzy logic, which can handle imprecise information, is beneficial in such situations. Fuzzy AHP and fuzzy TOPSIS use fuzzy logic to capture subjective judgments and linguistic assessments. The fuzzy AHP method aggregates subjective judgments from multiple stakeholders to establish priority weights for criteria, considering all relevant respondent preferences. The fuzzy TOPSIS method is useful for ranking alternatives based on their similarity to an ideal solution. In the Ethiopian construction industry, where resource constraints may be a concern, fuzzy AHP and fuzzy TOPSIS can help select the most suitable alternatives that align with the desired objectives.

Based on fuzzy AHP, the top-ranked barriers concern professionals in the construction industry. First, resistance to change: Change often leads to resistance among managers and decision-makers due to uncertainty or fear of negative impacts such as job security, role changes, or disruptions to routines and processes. Second, there is a lack of knowledge of LC: Many stakeholders in the Ethiopian construction industry have limited knowledge and understanding of LC principles and their potential benefits. Third, there is a lack of a long-term philosophy: Many Ethiopian construction organisations do not have a long-term strategy for using LC. Without a long-term perspective and plan, organisations may become overwhelmed by short-term goals and fail to make the necessary changes to achieve long-term benefits. Fourth, there is a lack of government support for research collaboration in LC: Government has not yet provided sufficient support for research and collaboration between different organisations to support the successful implementation of LC.

The strategies identified for overcoming the barriers were ranked in order of importance using the fuzzy TOPSIS method. First, leadership and management: LCI requires the commitment of strong leadership and management including understanding of its principles and benefits, creating the right policies and procedures, ensuring that resources are available to support implementation, and creating an environment in which professionals are motivated and empowered to contribute to the process. Second, cultural change: The Ethiopian construction industry can foster cultural change that embraces continuous learning and improvement. Over time, this cultural shift will lead to increased innovation, enhanced productivity, and improved project outcomes in LCI. Third, education and training are key to the successful implementation of LC: By proposing comprehensive education and training programs, the Ethiopian construction sector can improve project efficiency, cost savings, and overall performance by creating a knowledgeable workforce aware of LC principles and practices.

Lean principles and tools are highly beneficial and indispensable to the Ethiopian construction industry. By implementing a pull system, visual cues, and continuous flow, construction teams can avoid delays, minimise storage space requirements, and ensure that work is performed when needed. Lean concepts emphasise the use of reliable technology to modernise processes and reduce waste. Establishing standardise work processes can reduce errors, rework, and inefficiency, thereby enhancing overall performance. Strong leadership is crucial for adopting lean ideas and integrating all stakeholders into the construction process. Focusing on customer satisfaction can lead to increased customer loyalty, repeat business, and positive referrals. Encouraging a philosophy of continual learning and improvement can improve efficiency, quality, and general performance.

The Last Planner System increases productivity and reduces the unpredictability of construction projects by fostering social processes and increasing team commitment. Value stream mapping is a tool used to analyse material and information flows and identify waste and bottlenecks. Integrated Project Delivery is a collaborative approach that integrates people, systems, business structures, and practices to optimise efficiency throughout the project. Kaizen, a Japanese term meaning "continuous improvement", encourages a culture of continuous improvement by engaging workers in finding and implementing new ways of working. The 5S system encourages workers to organise their workspace for greater efficiency and safety. Kanban, which is an inventory control card, is used to pull materials and parts through a value stream on a JIT basis. Visual Management is a LC tool that uses visual cues to convey important project information such as timelines, resources, and budgets, allowing project managers and stakeholders to quickly identify problems and potential improvement areas.

6.2 Recommendation

There is an acute shortage of LCI studies in Africa, and no studies in the literature are available on LC barriers and solutions for overcoming them specific to Ethiopia. LC could be highly rewarding for current Ethiopian construction performance improvement, and improvement of the current practice of the sector in light of implementing LC. This study offers a model for identifying and prioritising barriers and strategic solutions for LCI. It also helps researchers and practitioners in the field of construction technology and management by providing a checklist of all the important barriers and solutions for successful LCI. In addition, the results of this study can provide an overview and guidance to managers and decision makers in distinguishing the most important barriers and solutions for the selection of strategies that can effectively address these barriers. Further studies are recommended to assess the strategies identified and prioritised to overcome the critical barriers identified in this study.

6.3 Limitations and future scope

The first limitation is the number of experienced experts. This method depends, to a great extent, on feedback from experts regarding the scrutiny and shortlisting processes. If experts are less seasoned and experienced, the wrong choice of inputs may affect the prioritisation results. Therefore, this study purposively selected experts from the Ethiopian Construction Management Institute and Ethiopian Construction Work Corporation government organisations who had sufficient experience with LC principles and tools.

Fuzzy AHP and fuzzy TOPSIS are effective decision-making tools that help assess multiple criteria and alternatives, handle imprecise or uncertain data, and derive realistic priority weights. However, they have potential risks and limitations such as uncertainty in judgments, difficulty in constructing a pairwise comparison matrix, data quality issues, computational

complexity, interpretation difficulties, and lack of transparency. Therefore, careful attention must be paid to ensure the reliability and effectiveness of these methods.
Finally, to validate the results with the existing findings, a large-scale survey was conducted to generate more reliable outcomes. In addition, other fuzzy MCDM approaches can be employed to compare the findings. The authors believe that the prioritisation of barriers and solutions in this study will contribute significantly to the implementation of LC in the Ethiopian construction industry. Nonetheless, it is important to acknowledge that this study has limitations, and that future research should be conducted to further investigate this topic.
Future research on barriers to and strategies for LCI using fuzzy AHP and fuzzy TOPSIS frameworks should expand the scope of the study, investigate the role of technology, develop more robust decision-making frameworks, conduct longitudinal studies, examine the impact of external factors, enhance stakeholder engagement, and conduct comparative studies. They should also consider the long-term effects of LCI, examine the impact of external factors, enhance stakeholder engagement, and conduct comparative studies to identify best practices and areas for improvement. This will help researchers better understand the effectiveness of LC strategies and decision-making frameworks.

References

[1] Fei, D. Networked internationalization: Chinese companies in Ethiopia's infrastructure construction sector. *The Professional Geographer*, 2021, 73 (2), pp. 322-332. https://doi.org/10.1080/00330124.2020.1844572

[2] Wubishet, J. M. *Performances for Public Construction Projects in (Least) Developing Countries: Road & Educational Building Projects in Ethiopia: Business and Project Management*. [doctoral thesis], Norwegian University of Science and Technology, 2004.

[3] Sinesilassie, E. G.; Tabish, S. Z.; Jha, K. N. Critical factors affecting schedule performance: A case of Ethiopian public construction projects engineers' perspective. *Engineering, Construction and Architectural Management*, 2017, 24 (5). pp. 757-773. https://doi.org/10.1108/ECAM-03-2016-0062

[4] Ayalew, T.; Dakhil, Z.; Lafhag, Z. Assessment on Performance and Challenges of Ethiopian Construction Industry. *Journal of Architectural and Civil Engineering*, 2016, 2 (11), pp. 1–11.

[5] Nega, F. *Causes and effects of cost overrun on public building construction projects in Ethiopia*. [master thesis], Addis Ababa University, Addis Ababa, Ethiopia, 2008. Accessed: May 25, 2022. Available at: https://www.academia.edu/22778916/

[6] Melaku Belay, S. et al. Analysis of cost overrun and schedule delays of infrastructure projects in low income economies: case studies in Ethiopia. *Journal of Advances in Civil Engineering*, 2021, 2021 (1), 4991204. https://doi.org/10.1155/2021/4991204

[7] Tafesse, S. Material waste minimization techniques in building construction projects. *Ethiopia Journal of Science and Technology*, 2021, 14 (1), pp. 1–19. https://dx.doi.org/10.4314/ejst.v14i1.1

[8] Salem, O. M.; Solomon, J.; Genaidy, A.; Legring, M. Site Implementation and Assessment of Lean Construction Techniques. *Lean Construction Institute Journal of Lean Construction*, 2005, 2 (2). https://doi.org/10.60164/e2i9e2h1d

[9] Raghavan, N. et al. Implementing lean concepts on Indian construction sites: Organizational aspects and lessons learned. In: *22nd Annual Conference International Green Lean Construction Improve Project Based Production (IGLC)*, Kalsaas, B. T.; Koskela, L.; Saurin, T. A. (eds.). June 25-27, 2014, Oslo, Norway, The International Group for Lean Construction; 2014, pp. 1181–1890. Accessed: June 12, 2022. Available at: https://iglc.net/papers/Details/1021

[10] Ballard, G.; Kim, Y. Implementing lean on capital projects. In: *15th Annual Conference International Group for Lean Construction (IGLC)*, Pasquire, C.; Tzortzopoulos, P. (eds.). July 2007, East Lansing, Michigan, USA, The International Group for Lean

Construction; 2007, pp. 88–97. Accessed: May 25, 2022. Available at: https://iglc.net/Papers/Details/460

[11] Sarhan, S; Fox, A. Barriers to Implementing Lean Construction in the UK Construction Industry. *The Built & Human Environment Review*, 2013, 6 (1); pp. 1-17.

[12] Shang, G.; Sui Pheng, L. Barriers to lean implementation in the construction industry in China. *Journal of Technology Management in China*, 2014, 9 (2), pp. 155-173. http://dx.doi.org/10.1108/JTMC-12-2013-0043

[13] Devaki, M. R.; Jayanthi. Barriers to Implementation of Lean Principles in the Indian Construction Industry. *International Journal Engineering Research & Technology*, 2014, 3 (5), pp. 1189-1192.

[14] Sarhan, J. et al. Barriers to implementing lean construction practices in the Kingdom of Saudi Arabia (KSA). *Construction Innovation*, 2018, 18 (2), pp. 246-272. https://doi.org/10.1108/CI-04-2017-0033

[15] Akinradew, O. et al. Benefits of adopting lean construction techniques in the South African construction industry. In: *Proceedings of the International Conference on Industrial Engineering and Operations Management*. 2018, South Africa, IEOM Society International; 2018, pp. 1271-1277. Accessed: July 24, 2022. Available at: https://ieomsociety.org/southafrica2018/papers/418.pdf

[16] Ayarkwa, J.; Agyekum, K.; Dinyira, E. Barriers to Sustainable Implementation of Lean Construction in the Ghanaian Construction Industry. In: *Proceedings 6th Built Environment Conference*. July 30- August 2, 2011, South Africa; 2011, pp. 67-83. Accessed: July 01, 2022. Available at: https://www.researchgate.net/publication/306057984

[17] Badreddine, A. et al. A Fuzzy-AHP and House of Quality integrated approach for Lean Construction Concepts Assessment in Off-site Construction. *Modular and Offsite Construction (MOC) Summit Proceedings*, 2022, pp. 130-137. https://doi.org/10.29173/mocs274

[18] Iqbal, M. et al. Uptake and adoption of sustainable energy technologies: Prioritizing strategies to overcome barriers in the construction industry by using an integrated AHP-TOPSIS approach. *Advanced Sustainable Systems*, 2021, 5 (7), 2100026. https://doi.org/10.1002/adsu.202100026

[19] De Silva S. H.; Ranadewa, K. A. T. O.; Rathnasinghe, A. P. Barriers and strategies for implementing lean six sigma in small-and medium sized enterprises (SMEs) in construction industry: a fuzzy TOPSIS analysis. *Construction Innovation*, 2025, 25 (2), pp. 510-551. https://doi.org/10.1108/CI-09-2022-0225

[20] Trivedi J., Kumar R. Optimisation of construction resources using lean construction technique. *Journal of International Engineering Management and Economics*, 2015, 4 (3-4), pp. 213-228. https://doi.org/10.1504/IJEME.2014.066941

[21] Koskela, L. *Application of the New Production Philosophy to Construction*. Center for Integrated Facility Management, Technical Report, 1992. Accessed: July 24, 2022. Available at: https://stacks.stanford.edu/file/druid%3Akh328xt3298/TR072.pdf

[22] Roos, D.; Womack, J. P.; Jones, D. T. *The machine that changed the world: The Story of Lean Production*. Harper Perennial, 1990.

[23] Liker, J. K. *The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer*. 1st Edition, McGraw-Hill Education, 2004.

[24] Aziz, R.; Hafez, S. M. Applying lean thinking in construction and performance improvement. *Alexandria Engineering Journal*, 2013, 52 (4), pp. 679-695. http://dx.doi.org/10.1016/j.aej.2013.04.008

[25] Korb, S. "Respect for people" and lean construction: Has the boat been missed? In: *24th Annual Conference International Green Lean Construction*, Pasquire, C. L.; Alves, T. C. L.; Reginato, J. M. (eds.). July 20-22, 2016, Boston, Massachusetts, USA, International Group for Lean Construction IGLC; 2016, pp. 43-52. Accessed: July 1, 2022. Available at: https://iglc.net/Content/Proceedings/IGLC-2016-Conference-Proceedings-Volume-1-of-2.pdf

[26] Minas, M. *A Framework for Improving Construction Project Performance in Ethiopia*. LAP LAMBERT Academic Publishing, 2017.

[27] Kallassy, J.; Hamzeh, F. Developing a Lean culture index in construction. In: *Lean Construction in Crisis Times: Responding to the Post-Pandemica AEC Industry Challenges*, Alarcon, L. F.; Gonzalez, V. A. (eds.). July 14-17, 2021, Lima, Peru, International Group for Lean Construction IGLC; 2021, pp. 504-513. https://doi.org/10.24928/2021/0192

[28] Babalola, O.; Ibem, E. O.; Ezema, I. C. Implementation of Lean Practices in the Construction Industry: A Systematic Review. *Building and Environment*, 2018, 148, pp. 34-43. https://doi.org/10.1016/j.buildenv.2018.10.051

[29] Zhang, L.; Chen, X. Role of Lean Tools in Supporting Knowledge Creation and Performance in Lean Construction. *Procedia Engineering*, 2016, 145, pp. 1267-1274. http://dx.doi.org/10.1016/j.proeng.2016.04.163

[30] Nwaki, W. N.; Eze, C. E. Lean Construction as a Panacea for Poor Construction Projects Performance. *ITEGAM - Journal of Engineering Technology and Industrial Application (JETIA)*, 2020, 6 (26), pp. 61-72. http://doi.org/10.5935/jetia.v6i26.723

[31] Alarcón, L.F. et al. R. Assessing the Impacts of Implementing Lean Construction. *Revista Ingenieria de Construction*, 2008, 23 (1), pp. 26-33.

[32] Rosli, M. F. et al. The Effects of Suitability and Acceptability of Lean Principles in the Flow of Waste Management on Construction Project Performance. *International Journal of Construction Management*, 2023, 2 3(1), pp. 114-125. https://doi.org/10.1080/15623599.2020.1853006

[33] Fauzan, M.; Sunindijo, R. Y. Lean construction and project performance in the Australian construction industry. *IOP Conference Series: Earth and Environmental Science*, 2021, 907, 012024. https://doi.org/10.1088/1755-1315/907/1/012024

[34] Ahmed, S.; Hossain, M. M.; Haq, I. Implementation of lean construction in the construction industry in Bangladesh: awareness, benefits, and challenges. *International Journal of Building Pathology and Adaption*, 2021, 39 (2), pp. 368-406. Available at: https://doi.org/10.1108/IJBPA-04-2019-0037

[35] Cano, S. et al. Study of Barriers and Success Factors in Lean Construction. Exploration in a Pilot Context. In: *Global knowledge – Global solutions*, Seppänen, O.; González, V. A.; Arroyo, P. (eds.). July 29-31, 2015, Perth, Australia, The International Group for Lean Construction IGLC; 2015, pp. 631-641.

[36] Bashir, A. M. et al. Overcoming the Challenges facing Lean Construction Practice in the UK Contracting Organizations. *International Journal Architect Engineering Construction*, 2015, 4 (1), pp. 10-18.

[37] Albalkhy, W.; Sweis, R. Barriers to adopting lean construction in the construction industry: a literature review. *International Journal Lean Six Sigma*, 2021, 12 (2), pp. 210-236. https://doi.org/10.1108/IJLSS-12-2018-0144

[38] Nwaki, W.; Eze, E.; Awodele, I. Major Barriers Assessment of Lean Construction Application in Construction Projects Delivery. *CSID Journal of Infrastructure Development*, 2021, 4 (1), pp. 63-82. https://doi.org/10.32783/csid-jid.v4i1.206

[39] Mano, A. P.; Gouvea da Costa, S. E.; Pinheiro de Lima, E. Criticality assessment of the barriers to Lean Construction. International Journal of Product Performance Management, 2021, 70 (1), pp. 65-86. https://doi.org/10.1108/IJPPM-11-2018-0413

[40] Gupta, S.; Ahmadi, M. A.; Kumar, L. Identification of the barriers of lean construction implementation in construction projects-A review. *International Journal of Innovative Research in Computer Science & Technology (IJIRCST)*, 2020, 8 (3). pp. 182-187. https://doi.org/10.21276/ijircst.2020.8.3.27

[41] Kawish, S. E. Identifying and Prioritizing Barriers and Overcoming Strategies in Implementing Lean Construction Principles and Methods within Transportation Projects. [master thesis], Michigan State University, USA, 2017. https://doi.org/doi:10.25335/yp3c-z750

[42] da Silva, E. N.; de Brito Mello, L. C. B. Barriers to Implementing Lean Construction Practices in the Brazilian Construction Industry. *International Journal of Development Research*, 2021, 11 (07), pp. 48386-48392.

[43] Abdullah, S. et al. Towards Producing Best Practice in the Malaysian Construction Industry: The Barriers in Implementing the Lean Construction Approach. In: *International Conference of Construction Industry*. July 30-August 1, 2009, Padang Indonesia, 2009.

[44] Ahmed, S.; Sobuz, M. H. R. Challenges of implementing lean construction in the construction industry in Bangladesh. *Smart and Sustainable Built Environment*, 2020, 9 (2), pp. 174-207. https://doi.org/10.1108/SASBE-02-2019-0018

[45] Bajjou, M. S.; Chafi, A. Barriers of lean construction implementation in the Moroccan construction industry. *AIP Conference proceedings*, 2018, 1952, 020056. https://doi.org/10.1063/1.5032018

[46] Belhadi, A.; Touriki, F. E.; Elfezazi, S. Evaluation of Critical Success Factors (CSFs) to Lean Implementation in SMEs Using AHP: A Case Study. *International Journal of Lean Six Sigma*, 2019, 10 (3), pp. 803-829. https://doi.org/10.1108/IJLSS-12-2016-0078

[47] Ogunbiyi, O. E. Implementation of the lean approach in sustainable construction: a conceptual framework. [doctoral Thesis], University of Central Lancashire, UK, 2014; Accessed: April, 14 2022. Available at: https://clok.uclan.ac.uk/10563

[48] Bayhan, H. G.; Demirkesen, S.; Jayamanne, E. Enablers and Barriers of Lean Implementation in Construction Projects. *IOP Publishing Conference Series: Materials Science and Engineering*, 2019, 471 (2), 022002. https://doi.org/10.1088/1757-899X/471/2/022002

[49] Dehdasht, G. et al. A hybrid approach using entropy and TOPSIS to select key drivers for a successful and sustainable lean construction implementation. *PLOS ONE*, 2020, 15 (2), e0228746. https://doi.org/10.1371/journal.pone.0228746

[50] Elkhairi, A.; Fedouaki, F.; El Alami, S. Barriers and critical success factors for implementing lean manufacturing in SMEs. *IFAC-PapersOnLine*, 2019, 52 (13), pp. 565-570. https://doi.org/10.1016/j.ifacol.2019.11.303

[51] Demirkesen, S.; Bayhan, H. G. A Lean Implementation Success Model for the Construction Industry. *Engineering Management Journal*, 2020, 32 (3), pp. 219-239. https://doi.org/10.1080/10429247.2020.1764834

[52] Bhargav, D. et al. Implementing lean in construction: Lean construction and BIM. Construction Industry Research and Information Association CIRIA, Accessed: February 21, 2025. Available at: https://eprints.qut.edu.au/71034/1/71034.pdf

[53] Yunus, R. et al. Critical success factors for lean thinking in the application of Industrialized Building System (IBS). *IOP Conference Series: Materials Science and Engineering*, 2017, 226, 012045. https://doi.org/10.1088/1757-899X/226/1/012045

[54] Ebbs, P. J. et al. Lean Construction Theory and Practice: An Irish Perspective. In: *Global knowledge – Global solutions*, Seppänen, O.; González, V. A.; Arroyo, P. (eds.). July 29-31, 2015, Perth, Australia, The International Group for Lean Construction IGLC; 2015, pp. 496-506.

[55] Azhar, N. A.; Radzi, N. A. M.; Ahmad, W. S. H. M. W. Multi-criteria Decision Making: A Systematic Review. *Recent Advances in Electrical & Electronic Engineering*, 2021, 14 (8), pp. 779-801. http://dx.doi.org/10.2174/2352096514666211029112443

[56] Maware, C; Parsley II, D. M. The challenges of lean transformation and implementation in the manufacturing sector. *Sustainability*, 2022, 14 (10), 6287. https://doi.org/10.3390/su14106287

[57] Susilawati, A. et al. Fuzzy logic based method to measure degree of lean activity in manufacturing industry. *Journal of Manufacturing Systems*, 2015, 34, pp. 1-11. https://doi.org/10.1016/j.jmsy.2014.09.007

[58] Sharma, V.; Kumar, S.; Meena, M. L. Key criteria influencing cellular manufacturing system: a fuzzy AHP model. *Journal of Business Economics*, 2023, 92, pp. 65-84. https://doi.org/10.1007/s11573-021-01043-y

[59] Okudan, O.; Cevikbas, M.; Işık, Z. Selection framework of disruption analysis methods for megaprojects: an integrated fuzzy multi-criteria decision-making approach. *Engineering, Construction and Architectural Management*, 2025, 32 (1), pp. 59-86. https://doi.org/10.1108/ECAM-02-2023-0105

[60] Raj, A.; Samuel. C. Assessing and overcoming the barriers for healthcare waste management in India: an integrated AHP and Fuzzy TOPSIS approach. *Journal of Health Organ Management*, 2023, 37 (6/7), pp. 483-501. https://doi.org/10.1108/JHOM-09-2022-0264

[61] Karasan, A.; Erdogan, M.; Ilbahar, E. Prioritization of production strategies of a manufacturing plant by using an integrated intuitionistic fuzzy AHP & TOPSIS approach. *Journal of Enterprise Information Management*, 2018, 31 (4), pp. 510-528. https://doi.org/10.1108/JEIM-01-2018-0001

[62] Solangi, Y. A.; Longsheng, C.; Ali Shah, S. A. Assessing and overcoming the renewable energy barriers for sustainable development in Pakistan: An integrated AHP and fuzzy TOPSIS approach. *Renewable Energy*, 2021, 173, pp. 209-222. https://doi.org/10.1016/j.renene.2021.03.141

[63] Dogan, O. et al. corridor selection for locating autonomous vehicles using an interval-valued intuitionistic fuzzy AHP and TOPSIS method. *Soft Computing*, 2020, 24 (12), pp. 8937-8953. https://doi.org/10.1007/s00500-019-04421-5

[64] Azari, A. et al. Integrated Fuzzy AHP-TOPSIS for selecting the best color removal process using carbon-based adsorbent materials: multi-criteria decision making vs. systematic review approaches and modeling of textile wastewater treatment in real conditions. *International Journal of Environmental Analytical Chemistry*, 2023, 102 (18), pp. 7329-7344. https://doi.org/10.1080/03067319.2020.1828395

[65] Kahraman, C. et al. An Integrated Intuitionistic Fuzzy AHP and TOPSIS approach to Evaluation of Outsource Manufacturers. *Journal of Intelligent Systems*, 2020, 29 (1), pp. 283-297. https://doi.org/10.1515/jisys-2017-0363

[66] Küçükoglu, D. et al. Application of Goal Programming Integrated Multi-Criteria Decision Making Approaches for the Stock Area Selection Problem of an Automotive Company. *International Journal of Supply Chain Management*, 2017, 6 (3), pp. 187-198.

[67] Sarkar, B.; Biswas, A. Pythagorean fuzzy AHP-TOPSIS integrated approach for transport management through a new distance measure. *Soft Computing*, 2021, 25 (5), pp. 4073-4089. https://doi.org/10.1007/s00500-020-05433-2

[68] Kiraci, K.; Akan, E. Aircraft selection by applying AHP and TOPSIS in interval type-2 fuzzy sets. *Journal of Air Transport Management*, 2020, 89, 101924. https://doi.org/10.1016/j.jairtraman.2020.101924

[69] Eltarabishi, F. et al. Multi-criteria decision making methods and their applications—A literature review. In: *Proceedings of the International Conference on Industrial Engineering and Operations Management*, Ahad, A. (ed.). March 10-12, 2020, Dubai, United Arab Emirates, IEOM Society International; 2020, pp. 2654–2663. Accessed: May 16, 2022. Available at: https://www.ieomsociety.org/ieom2020/papers/656.pdf

[70] Vaidya, O. S.; Kumar, S. Analytic hierarchy process: An overview of applications. *European Journal of Operational Research*, 2006, 169 (1), pp. 1-29. https://doi.org/10.1016/j.ejor.2004.04.028

[71] Belhadi, A.; Touriki, F. E.; El fezazi, S. Prioritizing the solutions of lean implementation in SMEs to overcome its barriers: an integrated Fuzzy AHP-TOPSIS approach. *Journal of Manufacturing Technology Management*, 2017, 28 (8), pp. 1115-1139. https://doi.org/10.1108/JMTM-04-2017-0066

[72] van Laarhoven, P. J. M.; Pedrycz, W. A Fuzzy Saaty's Extension Priority of Theory. *Fuzzy Sets and Systems*, 1983, 11 (1-3), pp. 229-241. https://doi.org/10.1016/S0165-0114(83)80082-7

[73] Triantaphyllou, E. et al. Multi-Criteria Decision Making: An Operations Research Approach. In: *Encyclopedia of Electrical and Electronics Engineering*, Webster, J. G. (ed.). New York, USA: John Wiley & Sons; 1988, 15, pp. 175-186. Available at:

Accessed: May 18, 2022. Available at: https://bit.csc.lsu.edu/trianta/EditedBook_CHAPTERS/EEEE1.pdf

[74] Mehregan, M. R.; Safari, H. Combination of fuzzy TOPSIS and fuzzy ranking for multi attribute decision making. In: *Artificial Intelligence and Soft Computing – ICAISC 2006*, Rutkowski, L.; Tadeusiewicz, R.; Zadeh, L. A.; Żurada, J. M. (eds.). June 25-29, 2006, Zakopane, Poland, Springer; 2006, 4029. https://doi.org/10.1007/11785231_28