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A FUZZY EXPERT SYSTEM FOR MEASURING THE DEGREE OF LEAN IMPLEMENTATION IN CONSTRUCTION PROJECTS

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ABSTRACT

Lean construction has emerged as a production management philosophy that can achieve significant performance improvements within the construction industry. However, the industry has not yet achieved full potential in terms of the implementation of Lean principles as compared to other industries. Such achievement necessitates continuous improvements throughout the project lifecycle. However, it is first necessary to understand the current level of Lean implementation to identify opportunities for improvement. Previous researchers have developed frameworks for measuring the degree of Lean implementation of an organization as a means to assess continuous improvements. However, being on the organizational level, these frameworks might not provide the means for assessing the incremental improvements toward transforming into a "Lean" construction company. There is a need to gauge the level of lean implementation at the project level, serving as a crucial stepping stone for overall organizational achievement. Accordingly, this study aims to develop a framework for measuring the degree of Lean implementation in a construction project using fuzzy expert systems (FES). This system provides decision-makers with an evaluation of the current implementation of Lean in construction which, in turn, provides a direction on further opportunities for improvement.

KEYWORDS

Lean construction, Lean implementation, fuzzy expert systems (FES).

INTRODUCTION

Lean is the application of a set of principles developed by Taiichi Ohno and Eiji Toyoda to reduce waste in processes and increase production efficiency (Koskela et al., 2007). This

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requires reducing the impact of factors that might not add value to the end user. If applied correctly, Lean principles can transform organizations to be more flexible and profitable in the long term (Womack & Jones, 1996).

In the construction industry, practitioners have been adopting several Lean tools in their projects including 5S, the Last Planner System, visual management, error proofing and many others. Such integration has shown to be beneficial in terms of reducing waste, reducing and mitigating mistakes, managing inventory, reducing rework, etc. (Koskela et al., 2007; Singh & Kumar, 2020). Despite these benefits, the construction industry has not yet achieved the level of improvement seen in other industries upon Lean implementation (Pantazis et al., 2022). As such, it is necessary to first understand the current status of Lean implementation in a construction project in order to identify potential opportunities and areas of improvement in the pursuit of continuous improvement. This can potentially be achieved by developing a Lean construction implementation index that helps quantify and assess the implementation of Lean tools and techniques (Cocca et al., 2019). Developing such an index can be supported with fuzzy logic approaches given their ability to mimic humans when making decisions especially when the context of the data is ambiguous (Tavana & Hajipour, 2020).

Numerous researchers have introduced metrics to assess the implementation of lean practices in the construction industry (Amaral et al., 2019; Cano et al., 2020; Comelli et al., 2019; Dragone et al., 2021; Elfving & Seppänen, 2022; Kallassy & Hamzeh, 2021; Salvatierra et al., 2020). However, existing studies have primarily concentrated on evaluating the extent of lean adoption at the company or organizational level. While this approach is advantageous, it may pose challenges for companies aiming to implement lean practices comprehensively from the outset. Therefore, it is crucial to establish a methodology for measuring the incremental progress toward transforming into a "Lean" construction company. Specifically, there is a need to gauge the level of lean implementation at the project level, serving as a crucial stepping stone for overall organizational achievement. Consequently, the objective of this paper is to formulate a fuzzy expert system (FES) designed for assessing the degree of lean implementation in construction projects either before or during execution. This involves the creation of a Lean Construction Implementation Index (LCII) that considers the unique characteristics of each project.

LITERATURE REVIEW

The literature review section is divided into 3 subsections. The first subsection tackles the successful implementation of Lean in the construction industry and the need for continuous improvement. The second subsection elaborates on the LCII along with the assessment approaches adopted in the manufacturing industry. As for the third subsection, it provides an overview of FESs.

LEAN CONSTRUCTION

It is well-know that the applications of Lean originated from the manufacturing industry. However, its principles were adopted to a wide spectrum of industries one of which is the construction industry. Several studies in the construction industry have investigated the application of Lean principles and tools in construction and identified the factors that could facilitate or impede their implementation (Singh & Kumar, 2020).

Some of the tools that were regarded as being efficient in the implementation of the Lean principles include the 5S, Last Planner System, Poka Yoke and visual management. The application of these tools was proven to be effective in terms of waste reduction, mistake proofing as well as inventory management (Li et al., 2019; Salvatierra-Garrido & Pasquire, 2011). Additionally, collaborative process making, Heijunka and Andon were proven to be beneficial in terms of reducing the amount of rework, standardizing scheduling and improving workplace cleanliness (Ansah & Sorooshian, 2017; Dombrowski & Mielke, 2013).

The successful implementation of Lean principles and techniques in construction requires a cultural shift towards collaboration, continuous improvement, and stakeholder involvement. Effective leadership, communication, and training are also essential for creating a Lean culture and sustaining Lean practices. Successful implementation of Lean in construction can lead to improved project outcomes, including reduced waste, increased productivity, and enhanced stakeholder satisfaction (Al-Aomar & Hussain, 2018).

Some researchers argue that the construction industry has not yet reached its full potential in terms of Lean implementation as compared to other industries (Pantazis et al., 2022). As such, it is deemed necessary to understand the level of Lean implementation in a construction project in an effort to identify opportunities for continuous improvement. One potential way to achieve this is through developing certain indices or metrics that help quantify the level of Lean implementation.

LEAN MEASUREMENT APPROACHES

With the increased adoption and improvement of Lean applications in the construction industry (Elfving & Seppänen, 2022), it becomes significant to measure and evaluate its implementation. The development of Lean implementation metrics has the potential to support decision makers to first monitor and evaluate the current status of the project or organization given Lean tools implementation, and to second propose the integration of new tools and techniques based on the evaluation outcome. This approach ensures that the organization continuously pursues and adopts improvements (Cocca et al., 2019). For this reason, researchers have developed various Lean implementation metrics to quantify the impact of the introduced Lean tools and initiatives in the construction industry.

Nesensohn et al. (2014) proposed a Lean Construction Maturity Model (LCMM) designed to measure the maturity within organisations embedding Lean Construction. This model consists of five maturity levels, 11 key attributes and 60 defined behaviours. Subsequently, Nesensohn et al. (2016) validated the LCMM they proposed using focus groups. In 2017, Nesensohn (2017) established a self-assessment template of the LCMM to obtain the current maturity level of any organization. Comelli et al. (2019) developed an audit protocol to evaluate the level of Lean implementation. This protocol was initially shaped by existing literature and refined through its implementation in four companies. The refined protocol was evaluated and validated through interviews with Lean construction experts. Barth et al. (2019) adapted the performance metrics of five construction companies to assess the performance of Lean production system. Amaral et al. (2019) collected data from six construction companies to evaluate the impact of each criterion in the Lean Construction Assessment Tool (LCAT) on the level of Lean implement. Kallassy and Hamzeh (2021) developed a Lean Culture Index (LCI) to assess the readiness of construction companies in Lebanon to apply Lean. Results demonstrated that while some companies had a flexible and consistent approach, there remained room for improvement in training, trust, and human focus. Mohamed (2021) proposed a Lean Construction Assessment Tool (LCAT) to evaluate the lean awareness in a company. He provided nine steps for lean construction assessment, formed 20 questions covered in 10 categories, and generated 5 levels of maturity as results.

However, despite the development of valuable metrics in these studies, their focus remains primarily on the organizational level (i.e., the company). There are only a few researchers who developed metrics for Lean implementation at the project level. Salem et al. (2006) developed a new Lean assessment tool including six Lean construction elements to quantify the results of Lean implemenations in construction projects. The tool was tested in two teams in one project through on-site survey. Cano et al. (2020) proposed a model to assess the maturity level of construction project management. They identified the elements related to maturity by consulting existing literature and experts in Lean Construction. Salvatierra et al. (2020) established 12 main dimensions to evaluate the Lean approach in construction projects. These dimensions were identified, and their relative importance was evaluated through online questionnaires and interviews.

Despite their valuable exploration, the subjectivity cannot be completely avoided due to the use of site visits and interviews in assigning scores for questions. Furthermore, the interactions between metrics is often not considered. Thus, it is necessary to further investigate Lean implementation assessment tools at the project level in the construction industry, while integrating approaches that help reduce subjectivity such as fuzzy-based approaches.

FUZZY EXPERT SYSTEMS (FES)

Expert systems mimic the ability of humans to make decisions in a certain area of specialty. As such, they can be beneficial for decision makers when solving certain problems (Tavana & Hajipour, 2020). Given that real-world problems are often described ambiguously and might hold elements of uncertainty, FES can be used for reliable data-driven decision making (Zadeh, 1983).

A FES uses a collection of fuzzy membership functions and rules to emulate the reasoning process of a human expert within a specific domain of knowledge; it synthesizes knowledge and experience from different experts and makes it available to non-experts (Klir & Yuan., 1995). In order to reduce the subjectivity, other FES approaches were developed such as that proposed by Shaheen et al. (2009). In this method, he develops a structured approach to defining the if-then rule base rather than determining them subjectively in consultation with domain experts. Accordingly, FESs are useful in decision support, learning, diagnosis and research, and planning.

Given the above conducted literature review, there seems to be a gap in the effective evaluation of Lean implementation in the construction industry on a project level. As such, this paper aims to develop a FES to evaluate the level of Lean implementation in construction projects through developing a LCII.

RESEARCH METHOD

This section describes the research method used to develop the FES for measuring the degree of Lean implementation in a construction project. **Error! Reference source not found.**Figure 1 illustrates the steps the authors followed to develop the FES. The first step, factor identification and analysis, establishes the knowledge base pertaining to the problem, i.e. the input factors that will affect the final output. The second step involves the development of the fuzzy expert system including the fuzzy membership functions and fuzzy rules. Both steps will be described in further detail below. The different components will be encapsulated in the expert system shell to be re-used in the future.

FACTORS' IDENTIFICATION AND ANALYSIS

As discussed above, several factors have been employed in the literature to measure the degree of Lean implementation. The authors reviewed previous research studies to identify the relevant factors for construction projects and proposed a number of new factors that capture the degree of implementation of Lean construction.

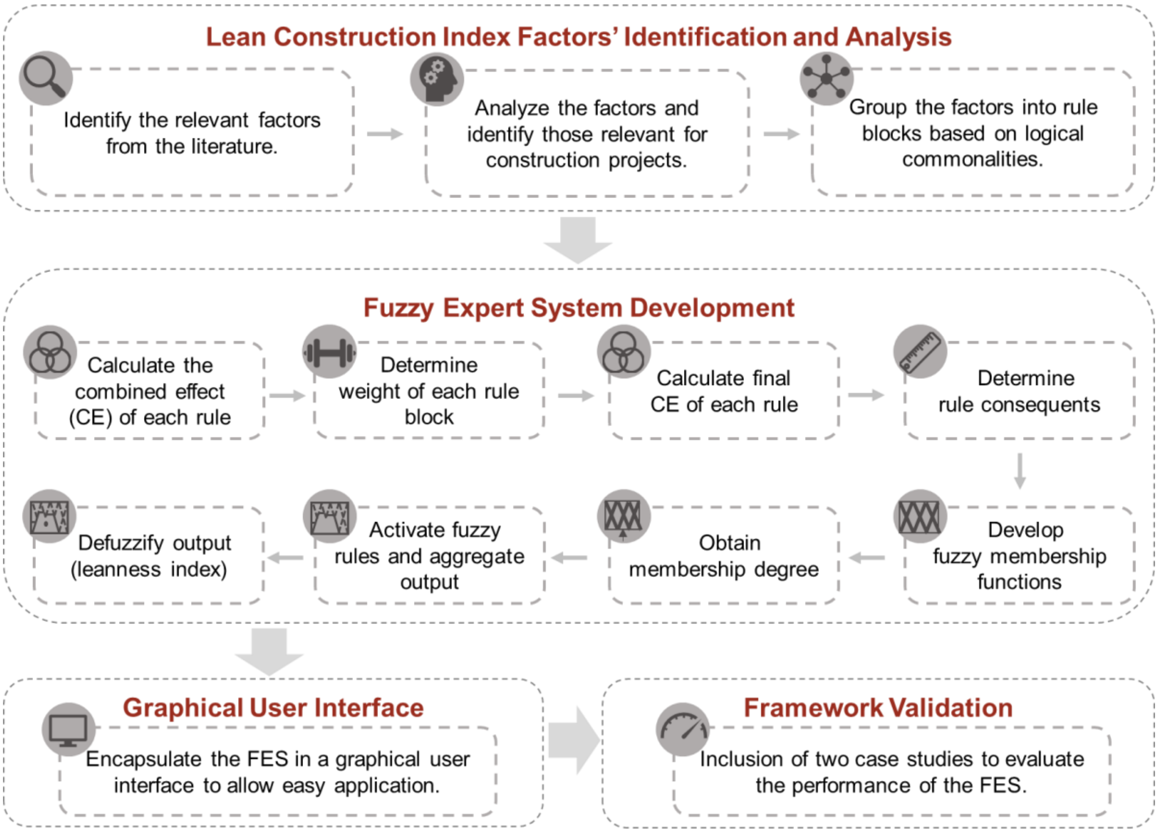

Figure 1 Research Method

Fuzzy Expert Rules

The development of the rule consequents for the FES follows the method proposed by (Shaheen et al., 2009). This structured approach reduces the subjectivity associated with defining the if-then rules that capture the experts' ways of thinking (Shaheen et al., 2009). Additionally, it

controls the exponential growth of the rule base by grouping factors based on logical commonalities, as performed above. **Error! Reference source not found.** illustrates the steps to defining the rule consequents based on this technique. In this method, the impact of each state of a certain factor on the output (degree of Lean implementation) and the relative importance (RI) of that factor are solicited from experts. For each rule, the combined effect (CE) is calculated as shown in equation (1):

$$CE(R_n) = (F_1)_{RI} \times F_1(state_1)_{Impact} + (F_2)_{RI} \times F_2(state_1)_{Impact} \\ + \cdots (F_m)_{RI} \times F_m(state_1)_{Impact}$$

Once the CE is calculated for each rule, the importance of each rule block relative to the final output is determined. Weights are assigned to each rule block and the normalized weight is calculated. Next, the final CE is calculated by multiplying the CE of each rule by the normalized weight of the rule block to which the rule belongs.

$$CE_{final}(R_n) = CE(R_n) \times Rule\ Block\ weight$$

The normalized combined effect is then calculated as:

$$CE_{Normalized}(R_n) = [CE_{final}(R_n) - CE_{min}]/[CE_{max} - CE_{min}]$$

The reader is referred to Shaheen (2009) for further details on the process. In this case, the factors correspond to those factors described in the previous section, and the states correspond to the 3 linguistic variables that describe the level of implementation of each factor (i.e., low, medium, and high). The relative importance of all factors is considered equal and the impact of being at a certain state is determined on a scale from 1-5, where 1 corresponds to very low and 5 corresponds to very high. Once the CE for each rule is calculated, the values are normalized using the equation above. The normalized combined effect is compared to a 5 -point scale where each interval corresponds to a linguistic term of the consequent (LCII) as shown in Figure 2.

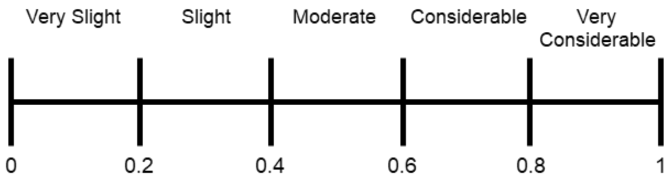

Figure 2 5-point scale for defining rule consequents

FUZZY MEMBERSHIP FUNCTIONS

The next step is to develop the fuzzy membership functions for the different factors. Although expert opinion or historical data are generally preferred for the development of membership functions, due to the limited time for this research, the authors assumed the values for the membership functions. Additionally, for ease of implementation, the same membership function was used for all the factors (inputs) as illustrated in Figure 3. The membership function for the output, the LCII, was also assumed (Figure 4).

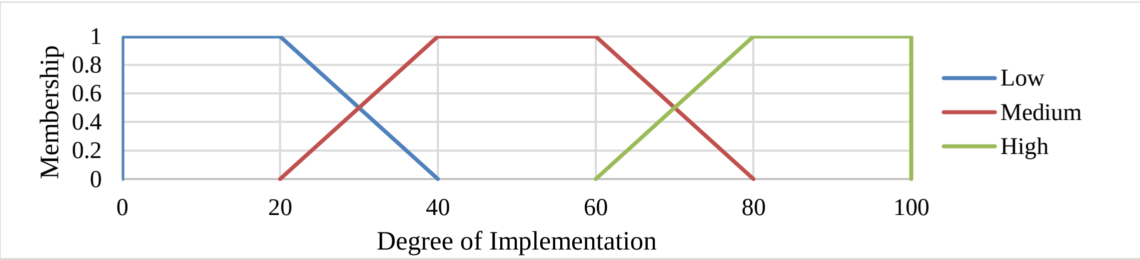

Figure 3 Membership function for factors

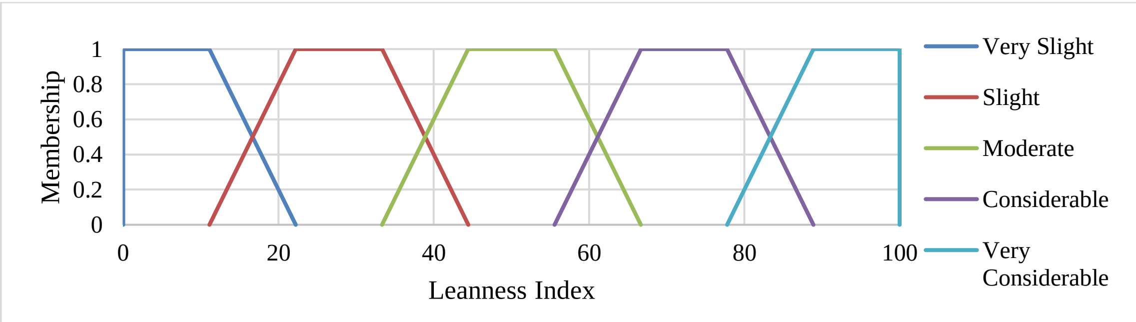

Figure 4 Membership function for LCII

FUZZY INFERENCE SYSTEM

Users of the FIS would input the level of implementation of each factor, whether expressed as crisp values or linguistic term, to calculate the degree of membership for each linguistic term defining those variables based on the fuzzy membership functions. The FIS model then uses the following operators: (1) input aggregation is minimum, (2) output aggregation is maximum, (3) implication method is minimum, (4) defuzzification method is the center of area method, and (5) all rules are given equal weighting. The LCII is then calculated as the defuzzied output of the model.

RESULTS

IDENTIFIED FACTORS

After an extensive literature review and analysis, several factors were identified from the literature. Table 1 shows the factors that were collected and the different categories that they were grouped into.

GRAPHICAL USER INTERFACE

A graphical user interface was developed on MATLAB to allow the user to enter scores for each of the defined factors to reach a LCII for the project being assessed. Figure 5 shows a sample of the interface window, where the user would drag the pointer assigned to each factor until the desired score is attained. The 30 factors are distributed over 5 pages, which the user can navigate between by selecting the required tab.

Once the scores are assigned to all the factors, and the user clicks on the "Evaluate" button on the last window, the model will calculate the LCII. The LCII will be displayed to the user in the same window, and a graphical representation of the equivalent degree of Lean implementation will also be generated to give the user a better sense of how Lean the project is.

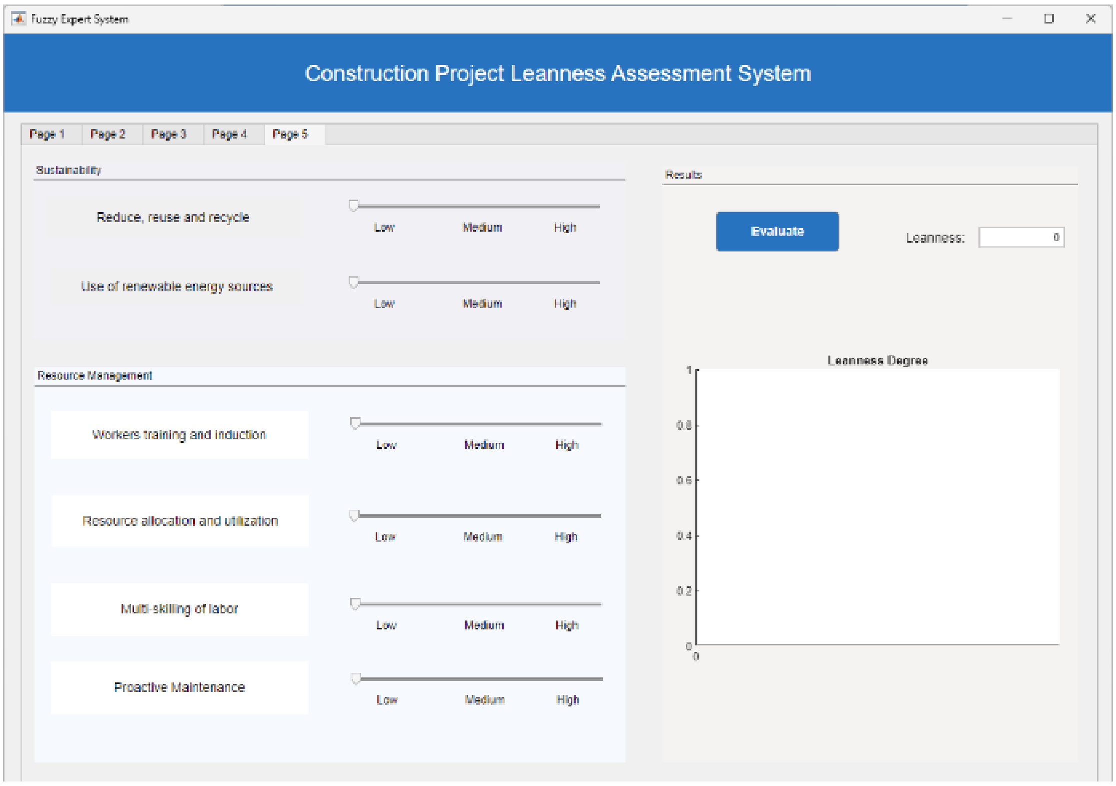

Figure 5 FES User Interface

Table 1 LCII Factors

Category	Factor	References
Collaboration	F1: Transparency in information sharing	(Cano et al., 2020; Comelli et al., 2019; Salem et al., 2006)
	F2: Efficient communication system	Proposed
Construction Methods	F3: Integration of prefabricated and modular construction	Proposed
	F4: Adoption of autonomation tools	Proposed
	F5: Incorporation of the Last Planner System or its alternatives	(Salem et al., 2006; Smith & Ngo, 2017)
Continuous Improvement	F6: Implementation of kaizen strategy	(Comelli et al., 2019; Dragone et al., 2021; Saleeshya & Binu, 2019; Salem et al., 2006; Salvatierra et al., 2020)
	F7: Implementation of the 5 Why's and Root Cause analysis	
Customer Value	F8: Incorporation of customer feedback	(Dahda et al., 2020)
	F9: Capturing customer requirements	
	F10: Sharing work status information	Proposed
Delivery and Supply	F11: Just in time procurement of materials and equipment	(Dahda et al., 2020; Smith & Ngo, 2017)
	F12: Involvement of suppliers	(Salvatierra et al., 2020)
	F13: Supplier evaluation/feedback	(Amaral et al., 2019; Saleeshya & Binu, 2019)
General Site Conditions	F14: Order and cleanliness of the site	(Smith & Ngo, 2017)
	F15: Effective planning of laydown areas	(Saleeshya & Binu, 2019)
Management	F16: Empowerment of workers (Andon systems)	(Comelli et al., 2019)
	F17: Providing employee incentives	(Susilawati et al., 2015)
	F18: Timely disbursement of due payments to suppliers and subcontractors	Proposed
Process	F19: Utilization of work cells	(Dahda et al., 2020)
	F20: Implementation of Kanban system	(Dragone et al., 2021)
	F21: Implementation of visual management	(Susilawati et al., 2015)
	F22: Use of tool kits	Proposed
Quality	F23: Minimizing the percentage of rework	Proposed
	F24: Use of tested and reliable technology (drones, computer vision, etc.)	(Salvatierra et al., 2020)
Resource Management	F25: Workers' training and induction	(Amaral et al., 2019)
	F26: Resource allocation and utilization	(Dahda et al., 2020)
	F27: Multi-skilling of labor	
	F28: Proactive maintenance	Proposed
Sustainability	F29: Reduce, reuse and recycle	(Comelli et al., 2019; Salem et al., 2006)
	F30: Use of renewable energy sources	Proposed

ILLUSTRATIVE EXAMPLE

In order to evaluate the proposed FES's capability to assess the degree of Lean implementation in construction projects, the model was tested on two construction case studies. The first project is an industrial project that follows a traditional project delivery method (non-IPD) while the second one is a wastewater treatment facility project that follows an IPD project delivery method. The authors selected an IPD project and a non-IPD project to showcase the model's potential in providing a reasonable LCII as it is anticipated that the non-IPD project is likely to have low Lean implementation as opposed to the IPD one. The authors interviewed an expert on each of the two projects and were able to get a general idea about the Lean implementation on each of the two projects. In the first one, although the expert was well informed about the different Lean tools and techniques that can be potentially applied in the project, it did not seem that these were implemented. As for the second project, the interviewed expert was comfortable discussing the different applications of Lean tools in the project. As such, the authors collected data from the experts on the 30 factors previously identified using the developed interface. Tables 2 below summarize the scores obtained for the case studies.

Table 2 Case studies' data

Case study 1						**Case study 2**					
Factor ID	Score	**Factor ID**	Score	**Factor ID**	Score	**Factor ID**	Score	**Factor ID**	Score	**Factor ID**	Score
F1	20	**F11**	5	**F21**	80	**F1**	100	**F11**	80	**F21**	50
F2	50	**F12**	5	**F22**	15	**F2**	100	**F12**	90	**F22**	50
F3	55	**F13**	60	**F23**	10	**F3**	33	**F13**	66	**F23**	66
F4	65	**F14**	80	**F24**	10	**F4**	33	**F14**	90	**F24**	85
F5	15	**F15**	65	**F25**	65	**F5**	90	**F15**	95	**F25**	85
F6	65	**F16**	15	**F26**	60	**F6**	75	**F16**	90	**F26**	85
F7	40	**F17**	55	**F27**	10	**F7**	40	**F17**	75	**F27**	66
F8	60	**F18**	85	**F28**	15	**F8**	95	**F18**	85	**F28**	80
F9	15	**F19**	50	**F29**	10	**F9**	95	**F19**	66	**F29**	66
F10	65	**F20**	45	**F30**	10	**F10**	85	**F20**	50	**F30**	66
LCII: 30.64						**LCII: 55.92**					

Given the above scores, the LCII for each project was obtained. The first case study has a slight implementation of Lean tools and techniques whereas the second one has a moderate to considerable implementation. As expected, the LCII obtained for the second case study is higher than that for the first case study. As such, the developed FES model to measure the degree of Lean implementation in a construction project portrayed modeling robustness.

MODEL VERIFICATION

Sargent (2007) defines model verification as "ensuring that the computer program of the computerized model and its implementation are correct" Since the FES described in this study was developed in MATLAB, it was important to verify it. The authors performed a sensitivity analysis where the values of the inputs were changed to observe the effect on the output. Accordingly, the authors performed two tests, where the values of all the factors were set to '0' in the first test and to ‘100’ in the second test. The results of the sensitivity analysis are shown in Table 3.

Table 3 Sensitivity Analysis

Test	Input Value for Each Factor	LCII
1	0	8.38
2	100	91.61

The results of the sensitivity analysis align with the predicted expectations. Notably, when all factors receive a rating of 0, the LCII is determined to be "very slight," whereas a rating of 100 for all factors results in a "very considerable" LCII. However, contrary to initial assumptions, the LCII is not necessarily 0 and 100 when all inputs are 0 and 100, respectively. This observation can be attributed to the influence of the FES design on the output, including the selection of operators and the consequences of the fuzzy expert rules.

CONCLUSION AND RECOMMENDATIONS

In summary, this study has made a valuable contribution to the development of frameworks for measuring the degree of Lean implementation in the construction industry. By proposing a fuzzy expert system, decision makers now have a reliable and easily applicable tool for evaluating the current level of Lean implementation on construction projects. Additionally, the use of fuzzy logic allows decision makers to capture and evaluate uncertain information, leading to more accurate and reliable evaluations. The proposed framework can help decision makers to identify opportunities for improvement and guide future Lean initiatives in the construction industry. Additionally, decision makers can use the proposed tool on projects that are already in the execution phase and on projects that are to be executed given that the identified factors used in the evaluation process apply to both.

One limitation of this study is that the fuzzy membership functions were assumed. Future research could involve experts in the development of these functions to improve the accuracy of the system. Additionally, future research could investigate the use of different quantifiable indicators that can objectively capture the level of implementation of each factor to reduce bias. Improvements to the GUI also have the potential to enhance the application and make it more user-friendly. These include labelling the inputs and outputs to provide a clearer explanation of the different categories and adding different features such as the ability to save and export results.

The proposed framework has the potential to facilitate the adoption and implementation of Lean principles in construction projects. This can lead to better project outcomes, such as improved productivity, reduced waste, and increased profitability. Moreover, the adoption of Lean principles can contribute to overall industry performance and competitiveness.

In conclusion, the development of a FES for evaluating the degree of Lean implementation on construction projects is an important step towards achieving continuous improvement throughout the project lifecycle. Furthermore, while the proposed framework is designed for project-level application, its adaptability allows implementation in organizations and broader contexts. Future research can build upon the findings of this study to further refine the FES and explore additional factors.

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