A Fuzzy-AHP and House of Quality integrated approach for Lean Construction Concepts Assessment in Offsite Construction

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ABSTRACT

Lean Construction (LC) combines theoretical research and industry best practices in an offsite industrialized construction environment that adopts Lean Manufacturing (LM) concepts and the know-how to reduce waste in the end-to-end lean construction process. Offsite construction industries strive to implement lean manufacturing theory and application to maximize the allocation of their resources, reduce construction waste, and optimize processes to be economically competitive. However, decision-makers usually encounter barriers while selecting the best lean tools for successful integration. Those barriers are organizational priorities, mass customization, process limitation, and improvement consensus. As a result, lean practitioners tend to implement tools such as Value Stream Mapping (VSM), Process Activity Mapping (PAM), Root Cause Diagram (RCD), Failure Mode Effect Analysis (FMEA), Pareto Analysis (PA) to analyze and propose improvements to a manufacturing process effectively. However, the construction industry lacks a tool that can assess the effectiveness of the lean construction concepts implementation. Thus, this paper proposes an innovative approach to select and evaluate the appropriate lean concepts implemented in an offsite industrialized factory. Firstly, the assessment matrix utilizes Fuzzy-AHP in a pairwise comparison to determine the relationships and calculate the correlations between lean concepts based on the designed hierarchy structure. Secondly, the House of Quality (HoQ) matrix will be integrated to prioritize the selection criteria based on the company's strategic requirements and customer requirements. Finally, the proposed multi-criteria multi-decision ranking matrix is able to prioritize the top lean concepts and demonstrate their combinational impact by eliminating participant's subjectivity, bias, and preferences. The proposed assessment matrix was implemented in an offsite panelized construction case study to prove its effectiveness and validity. The results presented the synergies between different lean concepts combinations and their importance in a lean construction environment.

KEYWORDS

Lean Construction (LC); Lean Manufacturing (LM); Fuzzy-AHP; House of Quality (HoQ); Assessment Matrix

INTRODUCTION

In an effort to improve the project lifecycle, the construction industry is shifting manual on-site construction activities to a more controlled factory environment (Goulding and Arif, 2013). Offsite construction is a construction method that “brings on-site construction works into a climatecontrolled facility where advanced machinery and manufacturing technologies can be utilized to prefabricate buildings in a standardized and efficient manner" (Liu, et al, 2017). The manufacturing process involves designing and fabricating units or modules in a factory-controlled environment to be shipped and erected on-site for final assembly. This process requires a project strategy that will affect how things are designed to be more manufacturing and installation compatible. In a broader spectrum, LC aims to reduce construction waste, project delivery schedule, and workforce effort to increase customer value. Lean construction processes and strategies are diverse and sometimes overwhelming for the decision-makers to select from to guide them through the project lifecycle. In other words, deciding which and how and when to use many tools can be challenging for decision-makers. Lean construction cannot provide a one-size-fits-all solution for offsite construction projects; however, it can help in waste optimization, compressing schedules, improving performance, and reducing risk while simultaneously reducing total cost.

The evolution of manufacturing has been an incremental process since the industrial revolution. Large machines have been invented and developed over the years to cater to the needs of humans. In this modern era, we are not only facing dilemmas in the design of equipment but also in humans performance. Efficiency, productivity, and profitability have been the primary focus in designing a system that can function within specified manufacturing parameters: delivery time, cost, pricing, and quality. A company must balance between cost, quantity, and quality, especially when it involves various product families. Today, both manufacturing and service companies have adopted some of the Lean Construction Concepts (LCC) in their processes. To maximize the company's full potentials, it is essential to choose the appropriate concept. This paper aims to formulate, analyze, and discuss the results of FAHP and its integration with HoQ in selecting LCC, particularly in an offsite panelized construction company. This paper also aims to answer the main management question: What type of LCC or combinations should an industrialized construction company adopt to satisfy its technical and customer requirements?

LITERATURE REVIEW

Lean Construction Concepts (LCC) have been accepted and practiced by almost all successful manufacturing companies. Hasty delivery schedules, escalating increases in downtimes and delays, skyrocketing overhead and operating costs, and other issues have driven organizations to implement a Lean system in their work environment. As a result, various LCCs have been introduced over time. A study by Vinodh, et al. (2011) showed that major Lean concepts appeal to most companies. In their research, experts in Lean manufacturing were interviewed to give their inputs about which Lean concepts helped them develop an efficient, eco-friendly, and economic system. According to the study, organizations implement eight-core lean methods. The eight Lean concepts mentioned in the study are as follows: The Kaizen Rapid Improvement Process, 5S Principles, Total Productive Maintenance (TPM), Cellular Manufacturing/One-Piece Flow Systems, JIT Production Systems/Kanban, Six Sigma, Pre-Production Planning (3P), and Lean Enterprise Supplier Networks. Numerous studies found in the literature investigated the importance of lean concepts in manufacturing (Mejabi 2003, Shah & Ward 2007, Abdulmalek et al. 2007, Doolen & Hacker 2005) however, few tried to explore the connection between these lean concepts and companies' needs. Amin & Karim (2013) attempted to study the relation between a set of lean strategies and manufacturing improvements, where a decision support system was generated based on a correlation matrix created for lean strategies. The authors utilized HoQ to map the relationships between lean concepts and waste reduction. House of Quality (HoQ) provides a conceptual and visual representation that facilitates the design of products (Oddershede et al., 2019). HoQ presents the means for inter-functional planning, communication and design between the customer and designer (Hauser and Clausing, 1988).

In addition, Dehdasht et al. (2020) investigated the fundamental drivers for the successful implementation of LCC. The study relied on Multi-Criteria Decision Making (MCDM) to identify and allocate appropriate weights for these lean construction drivers. According to Nowotarski et al. (2021), there isn't a good analysis on choosing adequate lean management tools in the construction industry. Therefore, the study suggested using Multi-Criteria assessment to create an algorithm for selecting the appropriate lean tools by employing the AHP method in assessing lean concepts. Furthermore, Vinodh et al. (2011) researched the application of AHP as an effective method for concept selection based on a set of criteria to increase the leanness of manufacturing processes. However, Fuzzy-AHP is a more powerful tool that considers uncertainties in the decision-making process, whether qualitative or quantitative, to select the best alternative, especially in complex manufacturing processes (Jenab et al., 2012). FAHP can transform inaccurate data into an outcome that incorporates all decision-making uncertainties (Ballı and Korukoğlu, 2009). Consequently, the lack of practical techniques that assist decision-makers in selecting LCC generated the drive behind this research. Remarkably, applying the adequate lean tools at the correct time, within budget, and according to the company's vision is necessary for any manufacturer development.

METHODOLOGY

In Lean Construction (LC), the Fuzzy theory was introduced to solve different problems related to productivity, layout optimization, resource utilization, equipment maintenance, and quality assurance. However, few researchers adopted the application of Fuzzy theory to select the best combination of concepts for LC implementation. Over the years, Lean Manufacturing (LM) concepts have proven their effectiveness, and their post-impact made a substantial change in how they were implemented. But the problem resides in the selection process between numerous lean concepts that can be applied in a construction environment to fit the company's business capabilities and customer requirements. Therefore, the FAHP integration with House of Quality was introduced as a solution agent-based to overcome and reduce the ambiguity and uncertainty in the selection process. Then a multi-criteria decision-making method was implemented for the final ranking of lean construction concepts alternatives as described in Figure 1.

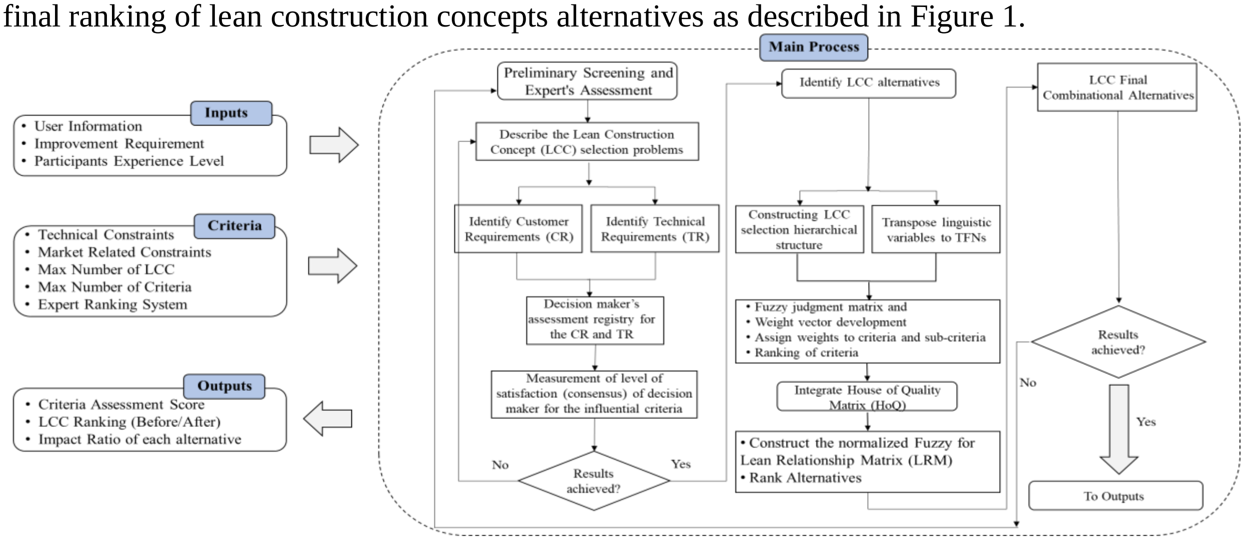

Figure 1. Overview of Methodology

Fuzzy AHP model

In this study, FAHP methodology based on Chang's (1996) method was utilized. A structured FAHP matrix based on customer requirements, technical requirements, and lean construction alternatives was developed to establish the preliminary screening process, and expert assessment weighted scores. The matrix registers all lean experts' assessments and ratings into a final lean decision matrix. A specific equation was derived to resolve the conflict of lean experts' opinions with respect to each lean criterion. A design expert *x* has the weight represented by W_x^e which is related to the lean expert experience and skill levels listed in Table 1. In this study, the weights are the years of technical expertise in lean manufacturing and construction.

Table 1. Design expert's weight (W_x^e)

Experts Weight ($\sum W = 10$)	**Expert Lean Experience (Years)**
0.8	0
1.7	5 ≤ Y ≤ 10
2	10 ≤ Y ≤ 15
2.5	15 ≤ Y ≤ 20
3	20 ≤ Y

According to Chang's (1996), the FAHP matrix can be constructed by the following steps:

Step-1: Determine the hierarchy structure for the lean construction concept (LCC) selection. The hierarchy structure will be transposed to the numerical pairwise comparison matrix.
Step-2: Select the Fuzzy-AHP scale to be used to transfer the expert's opinions on linguistic terms. In this case, the fuzzy triangular scale formulated by Saaty (2008) was used.
Step-3: Use the triangular fuzzy number (TFNs) and its reciprocal to create a pairwise comparison matrix for the criteria.
Step-4: Create a pairwise comparison matrix for the LCC alternatives based on each criterion discussed in the previous step.
Step-5: The first step in calculating the Fuzzy Synthetic Extent Values (S_i) is, to sum up all low (*l*), middle (*m*), and upper (*u*) in each vector column and place them in their respective column for *l*, *m*, *u*. All the M_{gi}^j are fuzzy triangular numbers, as explained in Equation 1.

$$S_i = \sum_{j=1}^{m} M^j g_i \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M^j g_i\right]^{-1} \times W_x^e \qquad (1)$$

Step-6: The next step is to multiply each column cell to the sum inverse in the same column using the fuzzy addition operation for finding *l*, *m*, *u* represented by Equation 2. Values derived from this operation will be used as inputs in finding the degrees of freedom within the alternatives.

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M^j g_i = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i\right) \qquad (2)$$

Step-7: After aggregating the sum of all the *l*, *m*, *u* values into a matrix, the pairwise continuous membership function (Mikhailov and Tsvetinov, 2004) is then calculated using Equation 3.

$$V(M_2 \geq M_1) == \begin{cases} 1, & if\ m_2 \geq m_1 \\ 0, & if\ l_1 \geq u_2 \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, & otherwise \end{cases} \qquad (3)$$

Step-8: In this step, the degree of possibility shown in Equation 4 creates a vector by calculating the summation of the product of minimum values derived from Equation 3 and the total sum of the said vector.

$$V(M_2 \geq M_1) = sup\left[min\left(\mu_{M_1}(x), \mu_{M_2}(y)\right)\right], y \geq x \qquad (4)$$

Step-9: Aggregate all criteria-alternative weight vectors into a new matrix and multiply them by the criteria weight vector comprised of a vector to get the final results.

House of Quality (HoQ) model

The methodology used to integrate FAHP and HoQ will be derived from the case study done by Bakshi et al. (2012). The steps involved in the integration are shown in Figure 2.

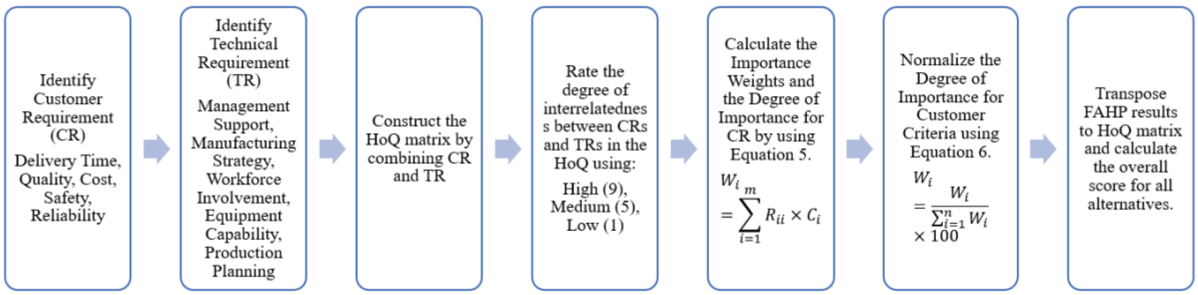

Figure 2. Integration Method for FAHP and HoQ

CASE STUDY

A qualitative case study involving a wood framing panelized manufacturing company (referred to herein as "XYZ plant") was selected to test and validate the proposed matrix. The main criteria governing this case study were the company's technical requirements and the customer requirement. Each company facing fierce market competition seeks to stay ahead of competitors by reducing process waste, increasing productivity, reducing costs, removing waste of resources, increasing profitability, and improving the efficiency of the manufacturing process by integrating lean construction concepts. At the time of the case study, this XYZ plant was under increasing pressure due to internal and external factors to ramp up production and throughput of panelized panels to meet customer demand and requirements. In what follows, all steps in the model are explained numerically and based on data from the company. First, five LCCs were selected from the Lean Relationship Model (LRM): 5S, JIT, TPM, Kaizen, and one-piece flow production. Next, the five chosen concepts were linked with the Technical Requirements (TR) to satisfy the Customer Requirement (CR) as illustrated in Figure 3.

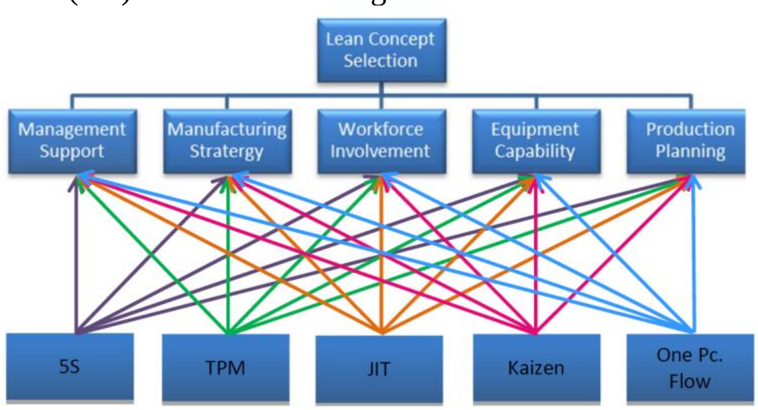

Figure 3. Lean Construction Concept Preliminary Hierarchy

Data collection

Lean Relationship Model (LRM) was developed to map the relationships and interdependencies between the seven common waste in lean manufacturing and calculate its relative weight. LRM consists of the lean relationship matrix in mathematical equations and the Lean Assessment Questionnaire (LAQ), a questionnaire-based survey reproduced from Rawabdeh (2005). The LAQ requires inputs and feedback from subject-matter experts that can vary in job title and relevant work experience years, as indicated in Table 1.

RESULTS AND DISCUSSION

The results are shown in Table 3 using FAHP methodology tied with the needs of XYZ based on the case study presented earlier for the Management Support criteria as a sample calculation. It is important to note that the criteria weight vector showed a high emphasis on Management Support with 37%, followed by Manufacturing Strategy with 31%, Equipment Capability with 18%, Workforce Involvement with 13%, and Production Planning with only 2%, as shown in Table 3. These results indicate that Management Support and Manufacturing Strategy have a significant influence on the final selection of LCC.

The relationship matrix and correlation matrix were developed, and RI, score and ranking were calculated using the equations given in the methodology. The developed HoQ with the ranking of TR is shown in Figure 4. The HoQ presents the interrelationship matrix between CR and TR after normalization and calculating the degree of confidence. From the results of the HoQ matrix, it can be seen that the ranking of TR shifted from Management Support with 37%, followed by Manufacturing Strategy with 31% in the case of FAHP, to Management Strategy with 29.3%, followed by Workforce Involvement with 18.2% respectively. This shift is because as lean implementation is a continuous improvement philosophy, the focus will be given to the elements that satisfy both the TR and the CR at the same time.

Table 2. FAHP Final Results

Alternatives	5S	TPM	JIT	Kaizen	One-pc. Flow
Management Support	0.3597	0.1774	0.0454	0.3380	0.0794
Manufacturing Strategy	0.1975	0.0315	0.2882	0.0743	0.4086
Workforce Involvement	0.3776	0.0845	0.0.0764	0.3618	0.1843
Equipment Capability	0.5003	0.3339	0.05471	0.4765	0.1658
Production Planning	0.0622	0.0257	0.3784	0.2245	0.3350
			x		
Weight Vector	Management Support	Manufacturing Strategy	Workforce Involvement	Equipment Capability	Production Planning
	0.3653	0.3051	0.1327	0.1767	0.0201
			=		
Results	0.3314	0.1334	0.1223	0.1987	0.2142
Ranking	1	4	5	3	2

The integration of FAHP and QFD only shows that even if the two methodologies are combined, the results are still consistent. Although the prioritization of the importance weights is slightly different from the FAHP criteria weight vector, the overall scores were still very similar.

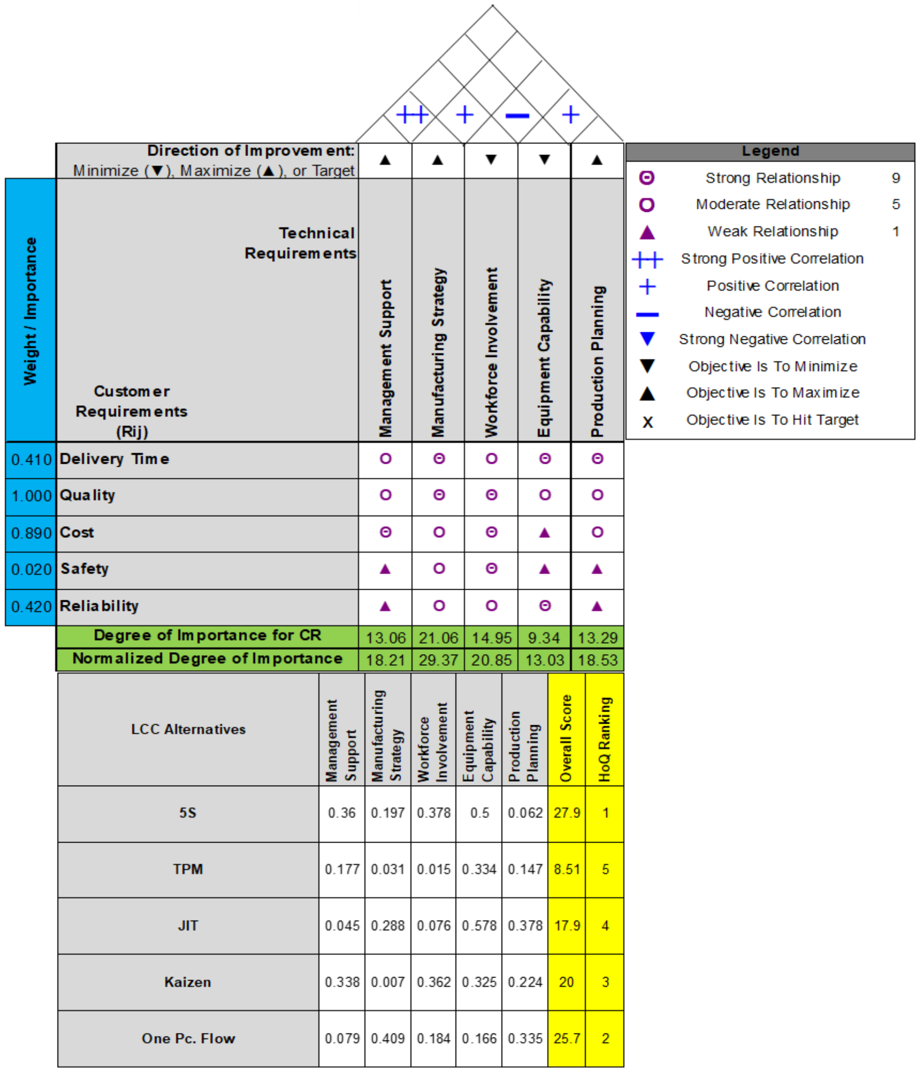

Figure 4. HoQ Matrix

This methodology's two best Lean concepts are 5S and One-Piece Flow, followed by Kaizen, JIT, and TPM. As an observation, JIT had a much higher score than TPM in this methodology than FAHP, primarily because of the customer requirements matrix. Further analysis shows that JIT has higher rankings for Manufacturing Strategy with 0.288 and Production Planning with 0.378 than TPM. Since Manufacturing Strategy and Production Planning also have high importance weights with 29.375 and 18.531, respectively, it boosted JIT's overall score. The results presented demonstrated how powerful it is to integrate two ranking systems into a multi-criteria decision-making system.

CONCLUSION

This paper's main contribution lies in proposing a new LCC selection matrix that is practical and flexible to bridge the gap between the expert and the application of LCC in an offsite construction setting. The combination of FAHP and HoQ is a very effective tool in gathering information and transforming that information into numerical and logical data. This new approach not only provides guidelines for LCC selection given the company's needs, which are based on quantitative and qualitative technical requirements but at the same time, achieves the desired customer requirements over the whole project lifecycle. This study focus is limited to the following: a lean offsite construction setting, only five lean techniques are investigated and considered in the HoQ analysis, the model inputs depend on design experts' values and assessment criteria, and the analyzed sample of the data is limited to twenty design experts and the fuzzy ranking system. Furthermore, future research can explore how to reform the gaps between each criterion and its relative LCC combination by applying the Interactive Network Relationship Map (INRM) methodology and calculating the relationship's complexity factor.

REFERENCES

Abdulmalek, F.A. and Rajgopal, J., 2007. Analyzing the benefits of lean manufacturing and value stream mapping via simulation: a process sector case study. International Journal of Production Economics, 107 (1), 223–236.

Amin, M. A., & Karim, M. A. (2013). A time-based quantitative approach for selecting lean strategies for manufacturing organisations. International Journal of Production Research, 51(4), 1146-1167.

Bakshi, T., Sarkar, B., & Sanyal, S. K. (2012). A novel integrated AHP-QFD model for software project selection under fuzziness. International Journal of Computer Applications, 54(7).

Ballı, S., & Korukoğlu, S. (2009). Operating system selection using fuzzy AHP and TOPSIS methods. Mathematical and Computational Applications, 14(2), 119-130.

Chang, D. Y. (1996). Applications of the extent analysis method on fuzzy AHP. European journal of operational research, 95(3), 649-655.

Dehdasht, G., Ferwati, M. S., Zin, R. M., & Abidin, N. Z. (2020). A hybrid approach using entropy and Topsis to select key drivers for a successful and sustainable lean construction implementation. *PLOS ONE*, *15*(2). https://doi.org/10.1371/journal.pone.0228746

Doolen, T.L. and Hacker, M.E., 2005. A review of lean assessment in organisations: an exploratory study of lean practices by electronics manufacturers. Journal of Manufacturing Systems, 24, 55–67.

Goulding, J., Arif, M., Rahimian, F. P., & Sharpe, M. (2013). Offsite construction: sustainable innovation futures using SMART approaches.

Hauser, J. R., Clausing, D. (1988) The House of Qualify. Harvard Business Review.

Jenab, K., Khoury, S., & Sarfaraz, A. R. (2012). Manufacturing complexity analysis with fuzzy AHP. International Journal of Strategic Decision Sciences (IJSDS), 3(2), 31-46.

Li, S. and Ma, Q. (2017) "Barriers and challenges to implement integrated Project delivery in China". Proc. 25th Ann. Conf. of the IGLC, Heraklion, Greece, pp.341-348.

Mejabi, O.O., 2003. Framework for a lean manufacturing planning system. International Journal of Manufacturing Technology and Management, 5 (5), 563–578.

Mikhailov, L., & Tsvetinov, P. (2004). Evaluation of services using a fuzzy analytic hierarchy process. Applied Soft Computing, 5(1), 23-33.

Nowotarski, P., Pasławski, J., & Dallasega, P. (2021). Multi-criteria assessment of lean management tools selection in construction. Archives of Civil Engineering, 67(1).

Oddershede, A. M., Quezada, L. E., Valenzuela, J. E., Palominos, P. I., & Lopez-Ospina, H. (2019). Formulation of a manufacturing strategy using the House of Quality. Procedia Manufacturing, 39, 843–850.

Rawabdeh, I. A. (2005). A model for the assessment of waste in job shop environments. International Journal of Operations & Production Management.

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. International journal of services sciences, 1(1), 83-98.

Shah, R. and Ward, P.T., 2007. Defining and developing measures of lean production. Journal of Operations Management, 25 (4), 785–805.

Vinodh, S., Shivraman, K. R., & Viswesh, S. (2012). AHP-based lean concept selection in a manufacturing organization. Journal of Manufacturing Technology Management.