Aslam M., Gao Z., Smith G., Huang Y., and Orr M. (2022). Development of Interpretative Structural Modelling (ISM) Based Lean Construction Implementation Framework. *Lean Construction Journal* 2022 pp 105-129 (Submitted 28Jun21;Accepted 11Dec22) www.leanconstructionjournal.org

Development of Interpretative Structural Modelling (ISM) Based Lean Construction Implementation Framework

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Abstract

Question: How to standardize Lean Construction (LC) implementation so that construction companies can implement lean practices to achieve rapid initial successes?

Purpose: LC implementation process is not yet standardized; therefore, there is variation of construction project performance improvement within the range of less than 10% to even greater than 30%. Although some researchers have endeavored to develop LC implementation frameworks, these frameworks are difficult for the construction companies to follow because they either only explain the theoretical aspects of LC or were developed based on the inputs only from few lean experts. Therefore, the purpose of this study is to develop an easy-to-follow LC implementation framework based on robust analysis of the contextual relationships among factors from successful lean projects.

Research Method: The method of this study included several steps: (1) Confirming LC successful factors from literature review, (2) Establishing relationships between factors using a questionnaire-based survey and Interpretative Structural Modeling (ISM) technique, (3) Developing ISM based matrices and model, and (4) Developing LC implementation framework.

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Findings: This study has developed a robust LC implementation framework based on 12 critical success factors (CSFs). Sixty-six pairwise comparisons between CSFs revealed the influential impact of one factor onto the others. Using the ISM technique, the hierarchy of these CSFs was established within the framework. The developed implementation framework contains four driving factors that have the most driving power, three dependent factors as well as five linkage factors for facilitating LC implementation. The top four most important and prerequisite factors for efficient implementation of LC are: Acquiring requisite knowledge and training regarding LC tools and techniques; Ensuring adequate commitment from all the stakeholders including the workforce; Improving collaboration, communication, and visualization; and Long term partnership and trust worthy relations.

Implications: The framework standardizes lean implementation processes and improves the lean culture within an organization. This is especially useful for the new LC companies moving towards lean, and also facilitates the successful implementation of LC for the entire construction industry.

Paper Type: Full Paper

Keywords: Lean Construction, Success factors, statistically analyzed relationships, LC Implementation Framework, Interpretative Structural Modeling

Introduction

Many researchers have tried to help new lean practitioners with implementation of Lean construction (LC) by developing strategies, frameworks, and models for guidance. Most of these efforts have identified LC principles and explored factors for successful LC implementation (Koskela, 2000; Swefie, 2013; Gao and Low, 2014). Others have endeavored to explain the modalities of incorporating LC practices within the lean environment (Ballard 2000; Al-Aomar, 2012). A few researchers developed LC maturity models to assess the level of implementation or degree of leanness in companies and thereby suggested measures to improve the overall LC implementation process (Diekmann et al., 2004; Sainath et al., 2018; Nesensohn, 2017). These efforts paved a way forward to the construction industry, but still LC implementation success is with a limited number of organizations using lean practices (Bashir et al., 2015; Mossman, 2009). Some organizations have witnessed cost and time improvements between 1% - 20% (CLIP, 2005; Conte and Gransberg, 2001; Agbulous, 2006) while others also experienced more than 30% improvement (Mao, 2008; Locatelli, 2013). These variations are due to the non-standardized LC implementation process causing all the organizations to interpret the implementation process as per their own understandings. As a result, the organizations following lean principles in true spirit can achieve better outcomes in comparison to others who are unable or do not know how to apply lean principles.

An analysis of the literature revealed that most of the existing guidelines or frameworks specify the principles or factors for successful implementation of LC, but lack explanation of the relationship between these principles/factors (Sarhan et al., 2019). A few researchers have shown a semi-structured approach in developing the LC implementation framework (Ballard et al., 2007; Swefie, 2013; El-Sabek et al., 2018);

however, the relationships defined in these frameworks are mostly theoretical without any robust analysis. The lack of a structured approach has reduced the efficacy of existing LC frameworks thereby making it harder for lean practitioners to implement. By recognizing this deficiency, Sarhan et al. (2019) has recently used the Interpretative Structural Modeling (ISM) approach in developing an LC implementation framework, but the relationships between factors are identified based on the inputs from 16 experts, who were not necessarily lean experts but have vast experience in construction.

These efforts show that the construction industry needs a fully structured framework consisting of various descriptive concepts, constructs, or variables and the relations between them to account for an LC phenomenon. The purpose of this paper is to develop an LC implementation framework using ISM techniques that is based on robust analysis of the contextual relationships among the successful factors from the input of LC companies in the US. The use of the ISM approach in developing the LC framework is well known for specifying frameworks in management research (Kumar et al., 2013; Haleem et al., 2012; Attri et al., 2013) but seldom used for LC management frameworks.

The factors for the successful implementation of LC as identified by Aslam et al. (2020) are used to develop the LC implementation framework. Moreover, a detailed statistical analysis technique is applied in which eighty-two (82) practicing LC construction companies were approached for their input on the relationship between factors. This approach increases the reliability of the developed LC framework as it only accounts for the opinions of lean experts and practitioners. The developed framework will help the companies adopting LC because it will incorporate the operational, cultural, organizational, and social aspects of the company.

Methodology

The methodology of this study includes several steps: (1) confirming LC successful factors using a literature review, (2) establishing relationships between factors using a questionnaire-based survey and ISM technique, (3) developing ISM based matrices and model, and (4) developing LC implementation framework. The overall methodology is shown in Figure 1. Details of some major steps follow in the next sections.

Identification of Factors

The first step in the ISM technique is to determine the critical success factors to implement LC. The literature successfully identified many of the CSFs for implementing LC. However, the latest exploration of these factors by Aslam et al., (2020) provided a comprehensive list of CSFs after analyzing the survey results from US lean experts. To increase the reliability of the CSFs, the list was further confirmed with previous studies and missing factors were added. The CSFs identified in previous work that are critical to the LC implementation framework are shown in Table 1:

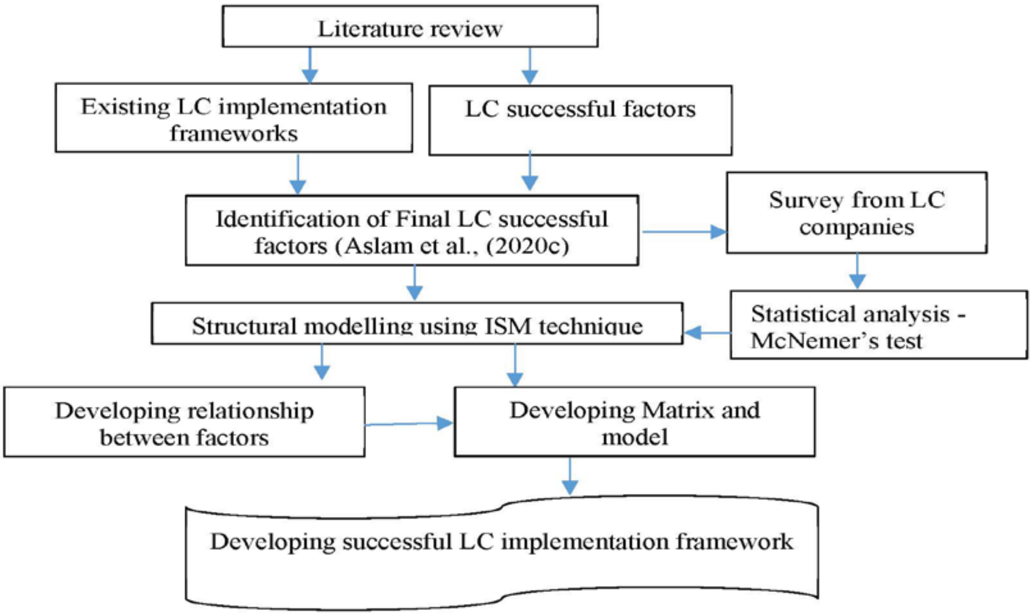

Figure 1. Research Methodology

Table 1. Critical success factors (CSFs)

Factor Number	Factor description	Confirmatory references
1	Imparting requisite knowledge and training regarding Lean Construction principles, tools/techniques, and objectives	(Ballard et al., 2007: Mostafa et al., 2013; Koskela, 1992)
2	The initial selection of appropriate construction processes	(Narayanamurthy and Gurumurthy, 2014; Lovatt and Shercliff, 1998; Aslam et al., 2020b)
3	Improving collaboration, communication, and visualization	(Ballard et al., 2007; Sacks et al., 2013; Koskela, 1992; Cano et al., 2015; Shou, 2016; Steven 2014)
4	Selection of appropriate lean tools and techniques/system	(Ward 2015; Pavnaskar et al., 2003; Swefie, 2013; Marhani et al., 2018, Aslam et al., 2020b)
5	Ensuring adequate commitment from Project teams	(Ballard et al., 2007: Sarhan et al., 2019; Yahya et al., 2016)
6	Ensuring adequate empowerment be given to the workforce.	(Bashir et al 2015, Kawish 2017; Diekmann et al., 2004)
7	Adoption of continuous improvement	(Ballard et al., 2007: Mostafa et al., 2013; Koskela, 1992; El-Sabek et al., 2018)
8	Standardizing the lean processes	(Diekmann et al., 2004; Ayarkwa et al. 2011; Bajjou et al., 2018)
9	Improving cultural adaptability and commitment towards lean construction	(Sarhan and Fox, 2013; Ballard et al., 2007; Diekmann et al., 2004)

Table 1. Critical success factors (CSFs) - continued

Factor Number	Factor description	Confirmatory references
10	Providing additional support and incentive to the lean teams and partners	(Bashir et al., 2015; Shou 2016; Yahya et al., 2016)
11	Long term partnership and trustworthy relations	(Ballard et al., 2007; Sarhan et al., 2019; Ayarkwa, 2011)
12	Implementing LPS® duly integrated with other tools (Aslam et al., 2020c)	(Lindhard and Wandahl, 2014; El-Sabek et al., 2018)

Determination of Relationships between Factors

After identifying the CSFs, the second step required establishing the pairwise relationships between the factors. The outcome of this step will have a huge impact in identifying the final hierarchy of factors within the proposed framework. In the formulation of ISM based frameworks, most researchers resort to the inputs from experts (the numbers of experts in previous studies vary from 5 to 20) to establish relationships (Atri et al., 2013; Ravi et al., 2005: Hasan et al., 2007; Sarhan et al., 2019). However, special care must be taken while formulating the pairwise comparisons, such as increasing the data from experts and using appropriate statistical analysis techniques.

To evaluate the pairwise relationships, a questionnaire survey was conducted using known company members of the Lean Construction Institute (LCI). The questionnaire comprised 12 questions in which the respondents were asked to identify all those factors, *j*, which can be achieved by factors, *i*. An example question related to Factor one (1) versus the other 11 factors is given in Figure 2.

1: Does imparting requisite knowledge and training regarding lean construction principles, tools/techniques, and objectives (factor 1) help in achieving any of the following factors? Choose all that apply

- ☐ 2. The initial selection of appropriate construction processes
- ☐ 3. Improving collaboration, communication, and visualization
- ☐ 4. Selection of appropriate lean tools and techniques/system
- ☐ 5. Ensuring adequate commitment from Project teams
- ☐ 6. Ensuring adequate empowerment be given to the workforce.
- ☐ 7. Adoption of continuous improvement
- ☐ 8. Standardizing the lean processes
- ☐ 9. Improving cultural adaptability and commitment towards LC
- ☐ 10. Providing additional support and incentive to the lean teams and partners
- ☐ 11. Long term partnership and trustworthy relations
- ☐ 12. Implementing LPS duly integrated with other tools

Figure 2. Example of questionnaire question

Conducting questionnaire survey

A total 251 companies in the US were provided a survey. Eighty-two (82) of which provided valid responses or a 33% response rate. The demographic information about the respondents is shown in Figure 3.

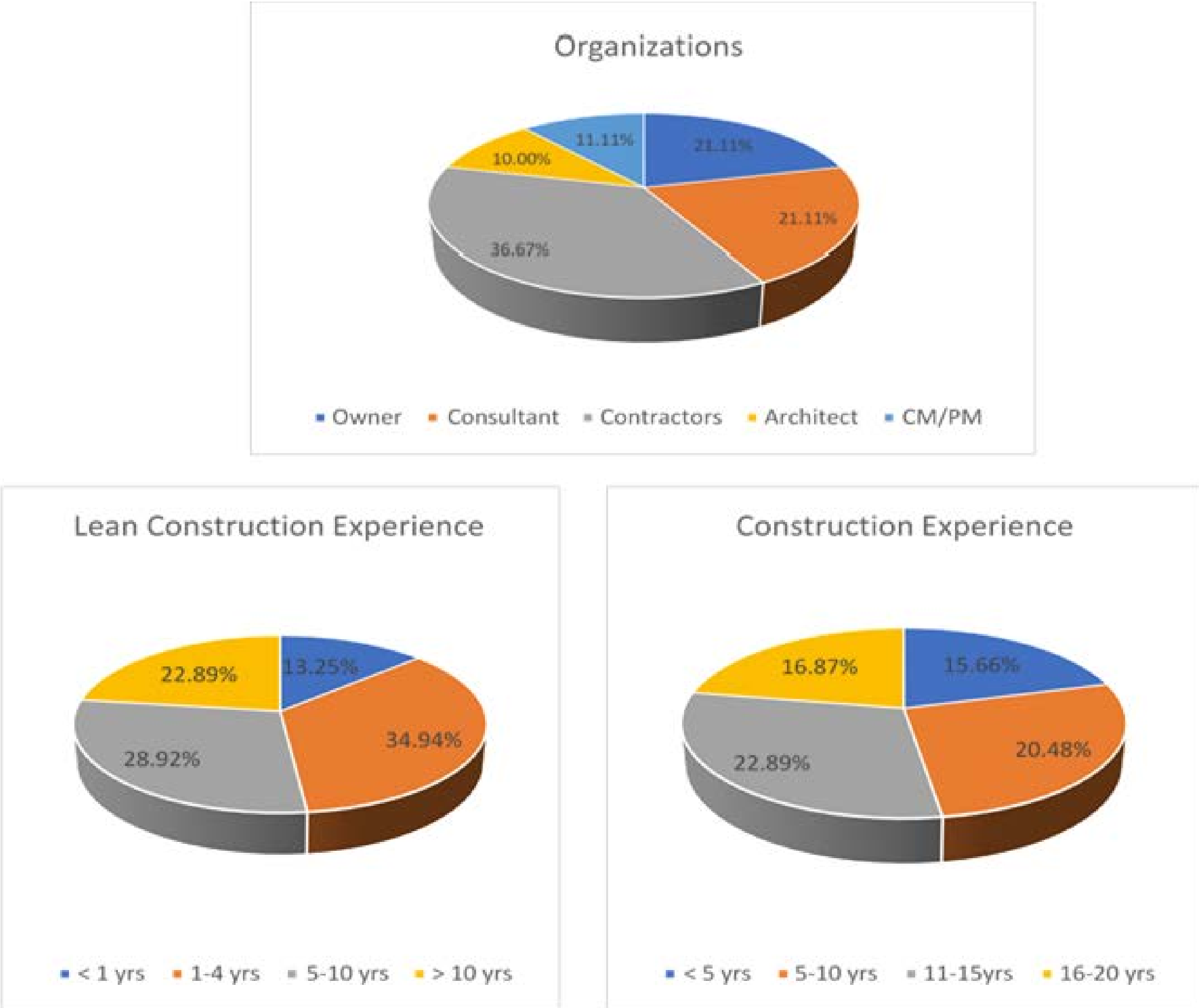

Figure 3. Demographic information about respondents

Figure 3. shows that the characteristics of respondents are almost evenly distributed among all different types of organizations (owner, architect, construction manager, etc.), and among different responsible personnel's (project manager, construction manager, lean managers, etc.). Additionally, more than 85% of the respondents have LC experience of greater than 5 years. The respondent demographics clearly show that the respondents belong to diverse groups of the construction industry and are very experienced in LC, thereby increasing the reliability of the responses.

Survey analysis

Two important characteristics of the data set are (1) the data is non-parametric/non-normal, (2) data values are not independent. Most non-parametric statistical tests like Binomial and Mann-Whitney could not be performed due to the lack of independence among the data. The relationship between factors exists if more than 50% of the respondents responded with influence of factors on others. McNemar's Chi-square test was performed in which frequencies of influence of factor (*i* on *j*), and factor (*j* on *i*), and both factors (*i* and *j*) influence on each other, are compared. P - values were compared with the alpha value of 0.05 to accept or reject the null hypothesis. In case the p-value is less than the alpha value, the null hypothesis (both factors equally influence each other) is rejected in favor of the alternate hypothesis (one factor influences more on the other and not vice versa). A total of 66 pairwise comparisons were evaluated. The Overall methodology is given in Figure 4. The following symbols used to denote relationships:

- V means if factor, *i*, helps more in achieving factor, *j*
- A means if factor, *j*, helps more in achieving factor, *i*
- X means if both, *i* and *j* help in achieving each other
- N means if, *i* and *j* does not help each other

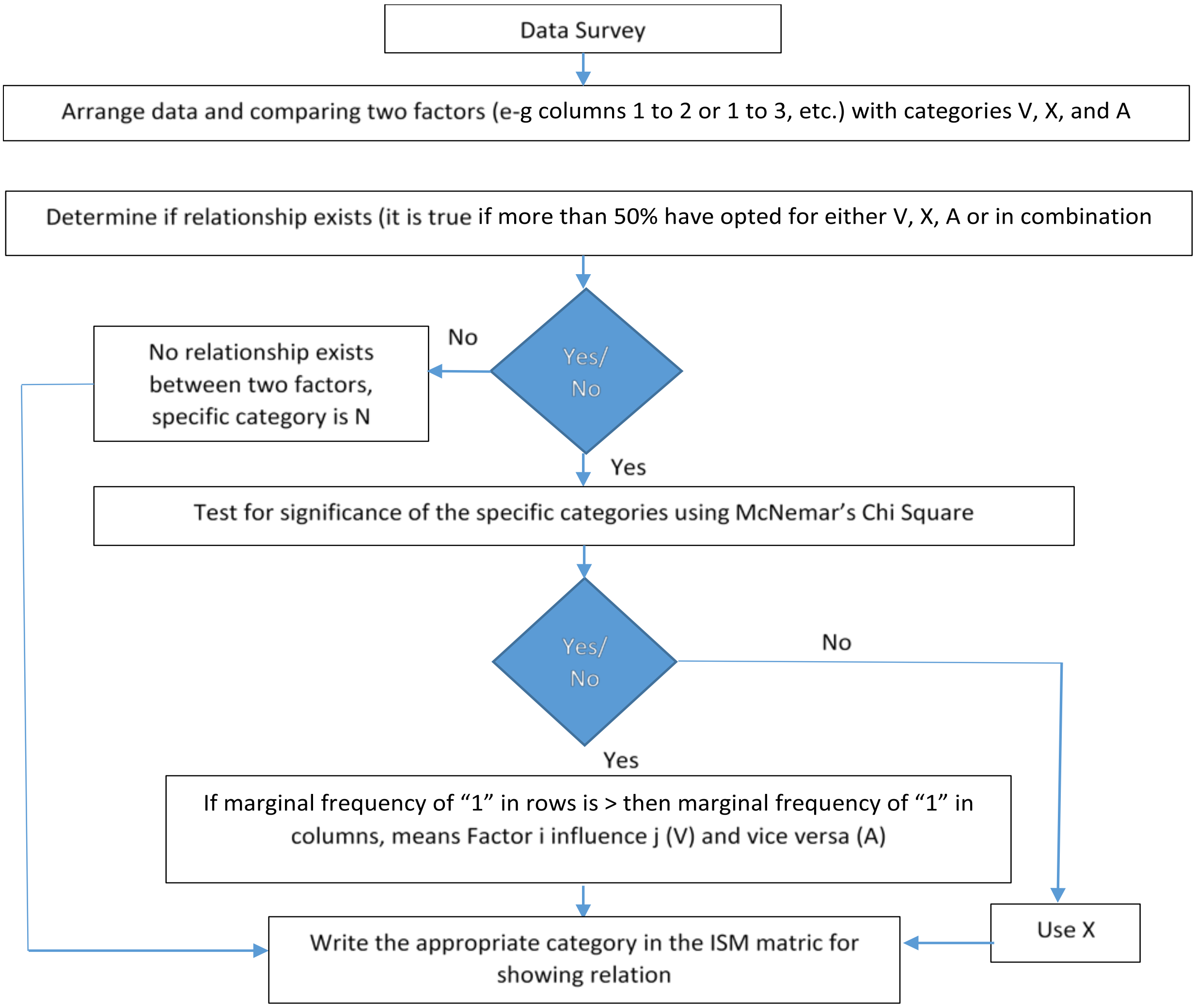

Figure 4. Methodology for pairwise comparison between factors to identify relationships

Literature Review and Background

No matter how well and logically a theory is explained hypothetically, still the success and acceptance by the masses would be dependent on its implementation and performance in the actual field. The results after its implementation would dictate the success/failure of the theory. Theories and philosophies related to LC are no exception. The concepts of LC have been exceptionally explained in the literature and well recognized by the construction industry (Ballard 2008, Koskela 1992, Abdelhamid 2003, Salem et al., 2006). Similarly, efforts are also being made in defining implementing strategies for the successful implementation of LC.

To efficiently implement LC, it is imperative to develop robust frameworks that have the capabilities of providing a complete roadmap for applying lean concepts and practices into the construction processes. The frameworks will provide the basic guidelines for implementing LC principles and will provide control for managing the lean activities at the construction site. Over time, researchers have endeavored to develop many frameworks and models that can guide the construction industry in sequentially adopting LC. Koskela (1992, 2000) provided the basic conceptual framework of incorporating the lean production theory in construction in a tripartite paradigm of transformation-flow-value famously known as TFV theory (Abdelhamid, 2003). Ballard (2000) further developed the Last Planner System® (LPS®) as a flow model for ensuring workflow reliability, value addition, and waste reduction by conducting a series of case studies. The LPS® model provided a way forward to the potential lean practitioners for controlling the construction processes in a series of collaborative planning stages and then continuously improving the system through measuring the outcomes. The LPS® model as developed by Ballard et al. (2000) is further improved to accommodate complex, constrained, and mega international projects by many researchers (Lindhard and Wandahl, 2014; El-Sabek et al., 2018).

In a study organized by the construction industry institute (CII), an LC wheel (showing 5 LC principles/16 sub principles) was developed after carefully reviewing the lean literature followed by interviews from lean experts and using expert judgment (Diekmann et al., 2004). Other researchers also endeavored to identify LC principles/subprinciples in developing LC implementation strategies (Swefie, 2013; Gao and Low, 2014; Bajjou et al., 2019). Based on the study of Diekmann et al. (2004), CII (2005) further identified 7 methods/steps of establishing the basis of lean in an organization including major steps such as:

1. Management commitment to identifying/driving out wastes
2. Standardizing the workplace
3. Developing a lean culture
4. Client involvement
5. Continuously improving the whole process

Later, Ballard et al. (2007) further refined the CII study and developed a detailed roadmap for implementing LC at the project level by using approaches like literature review, case studies, and field trials. This road map is further extended to different phases of construction (pre-project phase, definition phase, design phase, supply phase, assembly phase, and use phase). Paez et al. (2005) suggested a socio-technological framework through literature studies for implementing LC by comparing LC techniques with lean manufacturing and recommending seven (7) LC techniques for its efficient implementation:

1. Plan condition of the work environment (PCMAT)
2. Kanban
3. LPS
4. Concurrent engineering
5. Daily huddle meetings
6. Quality management tools
7. Visual inspections

Sarhan et al., (2019) developed a LC implementation framework by using 12 CSFs and further developing the relationships between the CSF using the ISM technique. The contextual relationships are first defined from the inputs of 16 lean experts and then structurally arranged to develop the relationships. Nesensohn et al. (2012) applied the concept of true north and developed 15-step guidelines that can be used by construction companies to become lean organizations, which start from training and end at reducing the workflow variability. Bygballe and Swärd (2014) endeavored to streamline the implementation process by highlighting implementation issues from a practical point of view. They pointed out that implementing lean should not be restricted to internal project organizations but should involve external actors like suppliers, subcontractors, and clients. The implementation process differs from project to project and individuals to individuals and there is no ready-to-use solution for LC. Implementing lean would be an ongoing process and it is only through practice and personnel involvement that implementation processes can be revised and optimized.

The detailed review of literature on LC implementation frameworks revealed that while the current frameworks are enriched with knowledge about LC concepts and principles/factors, there is a lack of clear guidelines of how to implement them during construction. The construction industry is looking towards a more structured and analytical approach that not only provides a detailed relationship between the factors but also specifies the hierarchy/order of implementation of these factors. Some researchers tried to provide step by step approach for implementing LC but mostly these approaches are judgmental/theoretical and need to be supported by some strong analytical techniques. These analytical approaches will help in developing the robust LC implementation frameworks that would increase their reliability and use by the construction industry.

Identification of Relationships and ISM Matrices Development

Identification of Relationships from Survey Data

Criteria for determining whether the relationship exists between any factors is shown in Figure. 4. The analysis shows that some relationship exists between all the factors. More than 50% of the respondents responded in a way that either factor, *i*, helps in achieving factor, *j*, or otherwise including those who consider both factors helpful in achieving each other. For further clarification, the McNemer test was performed on the data. The chi-square values and the test results are shown in Table 3. The relationships between factors are defined after testing for the pairwise comparison between two factors. Due to the length restriction, not all 66 pairwise comparisons are shown here; however, the pairwise comparisons along with the relationship of factors 1 and 2 are shown in Table 3. It can be seen that where all the chi-squares values are found to be significant, only the influence of factor 2 on 12 is insignificant. This implies that a statistically equal number of respondents considered factors 2 and 12 to influence each other. Hence the relationship between factor 2 and 12 is X. The complete comparison results are summarized in next section.

Table 3. Excerpts from McNemer's test results

Pairwise comparison between factors i to j	Frequency of Factor i influencing j	Frequency of Factor j influencing i	Chi-square	Significance	Results
a	b	c	d	e	f
1 to 2	49.81%	14.81%	<0.000	Yes	Frequency in Column b > c, so the relationship is V
1 to 3	49.38%	25.93%	0.004	Yes	Frequency in Column b > c, so the relationship is V
1 to 4	54.32%	25.93%	0.000	Yes	Frequency in Column b > c, so the relationship is V
1 to 5	53.05%	17.28%	<0.000	Yes	Frequency in Column b > c, so the relationship is V
1 to 6	49.38%	11.11%	<0.000	Yes	Frequency in Column b > c, so the relationship is V
1 to 7	53.05%	17.28%	<0.000	Yes	Frequency in Column b > c, so the relationship is V
1 to 8	58.01%	19.75%	<0.000	Yes	Frequency in Column b > c, so the relationship is V
1 to 9	60.49%	28.40%	<0.000	Yes	Frequency in Column b > c, so the relationship is V
1 to 10	43.21%	23.46%	<0.000	Yes	Frequency in Column b > c, so the relationship is V
1 to 11	43.21%	20.99%	0.003	Yes	Frequency in Column b > c, so the relationship is V
1 to 12	42.21%	24.69%	<0.019	Yes	Frequency in Column b > c, so the relationship is V
2 to 3	24.69%	50.62%	0.001	Yes	Frequency in Column c > b, so the relationship is A
2 to 4	49.38%	33.33%	0.028	Yes	Frequency in Column b > c, so the relationship is V
2 to 5	32.10%	53.09%	0.009	Yes	Frequency in Column c > b, so the relationship is A

Table 3. Excerpts from McNemer's test results (continued)

Pairwise comparison between factors i to j	Frequency of Factor i influencing j	Frequency of Factor j influencing i	Chi-square	Significance	Results
a	b	c	d	e	f
2 to 6	55.56%	25.93%	0.001	Yes	Frequency in Column b > c, so the relationship is V
2 to 7	54.32%	30.86%	0.003	Yes	Frequency in Column b > c, so the relationship is V
2 to 8	51.85%	20.99%	0.000	Yes	Frequency in Column b > c, so the relationship is V
2 to 9	49.38%	28.40%	0.006	Yes	Frequency in Column b > c, so the relationship is V
2 to 10	45.58%	17.28%	0.000	Yes	Frequency in Column b > c, so the relationship is V
2 to 11	19.75%	44.44%	0.001	Yes	Frequency in Column c > b, so the relationship is A
2 to 12	34.57%	20.99%	0.071	No	Both influence each other equally; the relationship is X

Development of Structural Self-Interactive Matrix (SSIM)

The relationships between factors as found above were summarized in a matrix for further analysis. The SSIM matrix is shown in a Matrix in Table 4.

Table 4. Structural self-interactive matrix (SSIM)

Factors	1	2	3	4	5	6	7	8	9	10	11	12
1		V	V	V	V	V	V	V	V	V	V	V
2			A	V	A	V	V	V	V	V	A	X
3				V	X	V	V	V	V	V	V	V
4					A	X	V	V	V	V	A	V
5						V	V	V	V	V	V	V
6							V	V	V	X	A	A
7								X	A	A	A	A
8									A	A	A	A
9										A	A	A
10											A	A
11												V
12												

Initial Reachability Matrix

Initial reachability matrix is developed by coding the relationships with 1 and 0. The matrix is shown in Table 5.

Table 5. Initial reachability matrix

Factors	1	2	3	4	5	6	7	8	9	10	11	12
1		1	1	1	1	1	1	1	1	1	1	1
2	0		0	1	0	1	1	1	1	1	0	1
3	0	1		1	1	1	1	1	1	1	1	1
4	0	0	0		0	1	1	1	1	1	0	1
5	0	1	1	1		1	1	1	1	1	1	1
6	0	0	0	1	0		1	1	1	1	0	0
7	0	0	0	0	0	0		1	0	0	0	0
8	0	0	0	0	0	0	1		0	0	0	0
9	0	0	0	0	0	0	1	1		0	0	0
10	0	0	0	0	0	1	1	1	1		0	0
11	0	1	0	1	0	1	1	1	1	1		1
12	0	1	0	0	0	1	1	1	1	1	0	

Final Reachability Matrix

Transitivity adjustments are required only in factors 6, 10, and 12. As factor 6 is related to factor 4 and factor 4 is related to factor 12, hence factor 6 should be related to factor 12 also with a transitivity relation (this is marked with asterisk in table 6). Similarly, factor 10 is related to factor 6, and factor 6 is related to factor 4, so factor 10 is related to factor 4. Similarly, transitivity relationships are defined for factor 12 also. The total of each row and columns are shown indicating the dependence and independence power of the factors. As an example, Factor 1, 3, and 5 have strong driving power because of higher values in the column driving power. Similarly, factors 7 and 8 have the lowest driving power but they have higher dependencies on other factors (dependency row). The final reachability matrix is shown in Table 6.

Table 6. Final reachability matrix

Factors	1	2	3	4	5	6	7	8	9	10	11	12	Driving power
1	1	1	1	1	1	1	1	1	1	1	1	1	12
2	0	1	0	1	0	1	1	1	1	1	0	1	8
3	0	1	1	1	1	1	1	1	1	1	1	1	11
4	0	0	0	1	0	1	1	1	1	1	0	1	7
5	0	1	1	1	1	1	1	1	1	1	1	1	11
6	0	0	0	1	0	1	1	1	1	1	0	1*	7
7	0	0	0	0	0	0	1	1	0	0	0	0	2
8	0	0	0	0	0	0	1	1	0	0	0	0	2
9	0	0	0	0	0	0	1	1	1	0	0	0	3
10	0	0	0	1*	0	1	1	1	1	1	0	0	6
11	0	1	0	1	0	1	1	1	1	1	1	1	9
12	0	1	0	1*	0	1	1	1	1	1	0	1	8
Dependency power	1	6	3	9	3	9	12	12	10	9	4	8	86

Level Partitions

From the final reachability matrix, the reachability and antecedent sets are derived. The difference between these two sets is the power of the particular factor to impact others. The reachability set comprises factor, *i*, along with other factors, *j*, which factor, *i*, can influence. However, antecedent set comprises factor, *i*, along with other factors, *j*, which can influence factor, *i*. The intersection between these two sets is developed for all the factors. If the reachability set is fully intersected with an antecedent set, the respective factor is struck out and will not be considered for further iterations and will be assigned to the top level. This implies that this factor is dependent on other factors which have a relatively lesser level than this factor. The iterations are repeated until all factors attained some level. A total of 7 iterations as shown in Table 7 were performed before all factors attained a level within the hierarchy. Factor 7 and 8 were the factors removed in the first iteration, whereas factor 1 remained in the last iteration (Number 7). This shows that Factors 7 and 8 have the highest dependency on all the other factors and would be top in the hierarchy whereas Factor 1 was the most independent and no factor was found to be below Factor 1 in the hierarchy.

Table 7. Iteration process

Factors	Reachability set	Antecedent set	Intersection set	level
Iteration 1				
1	1 2 3 4 5 6 7 8 9 10 11 12	1	1	
2	2 4 6 7 8 9 10 12	1 2 3 5 11 12	2 4 12	
3	2 3 4 5 6 7 8 9 10 11 12	1 3 5	3 5	
4	4 6 7 8 9 10 12	1 2 3 4 5 6 10 11 12	4 6 10 12	
5	2 3 4 5 6 7 8 9 10 11 12	1 3 5	3 5	
6	4 6 7 8 9 10 12	1 2 3 4 5 6 10 11 12	4 6 10 12	
7	7 8	1 2 3 4 5 6 7 8 9 10 11 12	7 8	1
8	7 8	1 2 3 4 5 6 7 8 9 10 11 12	7 8	1
9	7 8 9	1 2 3 4 5 6 9 10 11 12	9	
10	4 6 7 8 9 10	1 2 3 4 5 6 10 11 12	4 6 10	
11	2 4 6 7 8 9 10 11 12	1 3 5 11	11	
12	2 4 6 7 8 9 10 12	1 2 3 4 5 6 11 12	2 4 6 12	
Iteration 2				
1	1 2 3 4 5 6 7 8 9 10 11 12	1	1	
2	2 4 6 7 8 9 10 12	1 2 3 5 11 12	2 12	
3	2 3 4 5 6 7 8 9 10 11 12	1 3 5	3 5	
4	4 6 7 8 9 10 12	1 2 3 4 5 6 10 11 12	4 6 10 12	
5	2 3 4 5 6 7 8 9 10 11 12	1 3 5	3 5	
6	4 6 7 8 9 10 12	1 2 3 4 5 6 10 11 12	4 6 10 12	
9	9	1 2 3 4 5 6 9 10 11 12	9	2

Table 7. Iteration process(continued)

Factors	Reachability set	Antecedent set	Intersection set	level
10	4 6 7 8 9 10	1 2 3 4 5 6 10 11 12	4 6 10	
11	2 4 6 7 8 9 10 11 12	1 3 5 11	11	
12	2 4 6 7 8 9 10 12	1 2 3 4 5 6 11 12	2 4 6 12	
Iteration 3				
1	1 2 3 4 5 6 7 8 9 10 11 12	1	1	
2	2 4 6 7 8 9 10 12	1 2 3 5 11 12	2 12	
3	2 3 4 5 6 7 8 9 10 11 12	1 3 5	3 5	
4	4 6 7 8 9 10 12	1 2 3 4 5 6 10 11 12	4 6 10 12	3
5	2 3 4 5 6 7 8 9 10 11 12	1 3 5	3 5	
6	4 6 7 8 9 10 12	1 2 3 4 5 6 10 11 12	4 6 10 12	3
10	4 6 7 8 9 10	1 2 3 4 5 6 10 11 12	4 6 10	3
11	2 4 6 7 8 9 10 11 12	1 3 5 11	11	
12	2 4 6 7 8 9 10 12	1 2 3 4 5 6 11 12	2 4 6 12	3
Iteration 4				
1	1 2 3 ~~4~~ 5 ~~6~~ ~~7~~ ~~8~~ ~~9~~ ~~10~~ 11 ~~12~~	1	1	
2	2 ~~4~~ ~~6~~ ~~7~~ ~~8~~ ~~9~~ ~~10~~ ~~12~~	1 2 3 4 5 11 ~~12~~	2	4
3	2 3 ~~4~~ 5 ~~6~~ ~~7~~ ~~8~~ ~~9~~ ~~10~~ 11 ~~12~~	1 3 5	3 5	
5	2 3 ~~4~~ 5 ~~6~~ ~~7~~ ~~8~~ ~~9~~ ~~10~~ 11 ~~12~~	1 3 5	3 5	
11	2 ~~4~~ ~~6~~ ~~7~~ ~~8~~ ~~9~~ ~~10~~ 11 ~~12~~	1 3 5 11	11	
Iteration 5				
1	1 ~~2~~ 3 ~~4~~ 5 ~~6~~ ~~7~~ ~~8~~ ~~9~~ ~~10~~ 11 ~~12~~	1	1	
3	~~2~~ 3 ~~4~~ 5 ~~6~~ ~~7~~ ~~8~~ ~~9~~ ~~10~~ 11 ~~12~~	1 3 5	3 5	
5	~~2~~ 3 ~~4~~ 5 ~~6~~ ~~7~~ ~~8~~ ~~9~~ ~~10~~ 11 ~~12~~	1 3 5	3 5	
11	~~2~~ ~~4~~ ~~6~~ ~~7~~ ~~8~~ ~~9~~ ~~10~~ 11 ~~12~~	1 3 5 11	11	5
Iteration 6				
1	1 ~~2~~ 3 ~~4~~ ~~5~~ ~~6~~ ~~7~~ ~~8~~ ~~9~~ ~~10~~ ~~11~~ ~~12~~	1	1	
3	~~2~~ 3 ~~4~~ ~~5~~ ~~6~~ ~~7~~ ~~8~~ ~~9~~ ~~10~~ ~~11~~ ~~12~~	1 3 5	3 5	6
5	~~2~~ 3 ~~4~~ ~~5~~ ~~6~~ ~~7~~ ~~8~~ ~~9~~ ~~10~~ ~~11~~ ~~12~~	1 3 5	3 5	6
Iteration 7				
1	1 ~~2~~ ~~3~~ ~~4~~ ~~5~~ ~~6~~ ~~7~~ ~~8~~ ~~9~~ ~~10~~ ~~11~~ ~~12~~	1	1	7

Directed Graph (Diagraph)

Based on the final reachability matrix (Table 6) and levels attained (Table 7), the initial diagraph including the transitive links is developed. The diagraph shows the links between all the factors as shown in the final reachability matrix. After removing the transitivity links and indirect relations, a final diagraph is shown in Figure 5. The diagraph shows the dependencies of all factors in terms of nodes and links. It should be noted that this diagraph uses an upside-down format, i.e., the highest-level factors determined in Table 7 are shown at the top of the graph (Factors 7 and 8), whereas the lowest level factors are shown at the bottom (factor 1). The relationships between the factors as determined in the SSIM are shown with arrows. The diagraph removes all the indirect relationships from one level to the next levels and only the relationship between the succeeding/preceding levels are shown in Figure 5.

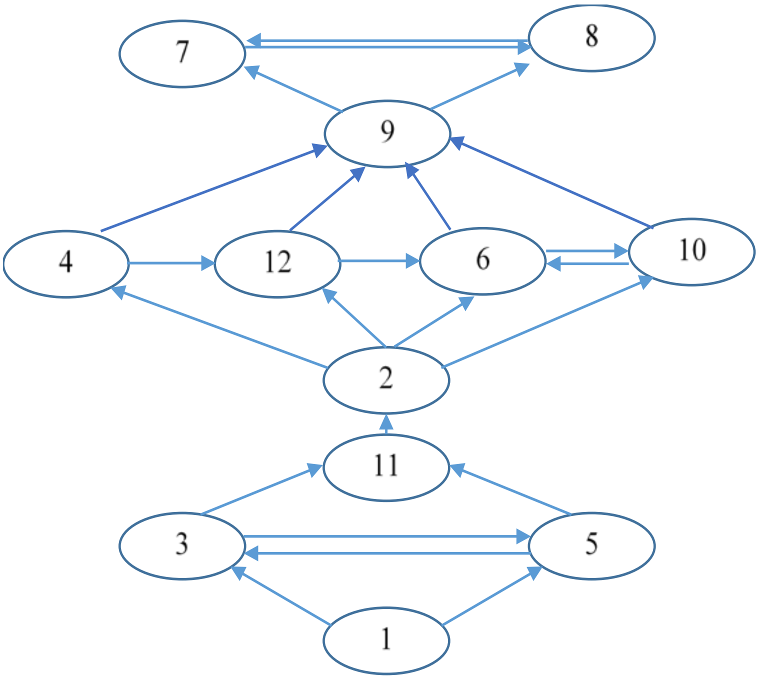

Figure 5. Directed graph (Diagraph)

ISM Model Development

The diagraph as shown in Figure 5 is converted to an ISM model by replacing the nodes of the diagraph into the factor statements as shown in the Method section (Table 1). The final ISM Model is shown in Figure 6 which shows the top three most important factors for efficient implementation of LC are:

1. Acquiring requisite knowledge and training regarding LC tools and techniques
2. Ensuring adequate commitment from all the stakeholders including the workforce
3. Improving collaboration, communication, and visualization.

However, the adoption of continuous improvement and standardizing the lean processes with effective modifications and adjustments are highly dependent on other factors.

The Matrix of Cross-Impact Multiplication (MICMAC Analysis)

The matrix of cross-impact multiplication was applied to analyze the dependence and driving power of all the factors. The basis for this analysis is the final reachability matrix shown in Table 6. Both the driving and dependence powers of each factor are plotted on a diagraph as shown in Figure 7. According to matrices d'impacts cross-multiplication appliqúe a classmate (MICMAC) analysis, factors are classified into four distinct categories based on their cluster in the diagraph: (1) autonomous factors, (2) driving factors, (3) dependent factors, and (4) linkage factors (Sarhan et al., 2019; Attri et al., 2013; Thirupathi & Vinodh, 2016).

The autonomous factors have weak driving and dependence power, which don't contribute much to the framework. The driving factors have strong driving power but weak dependence power. The dependent factors also have weak driving power but have strong dependence power. The linkage factors have strong driving and dependence power.

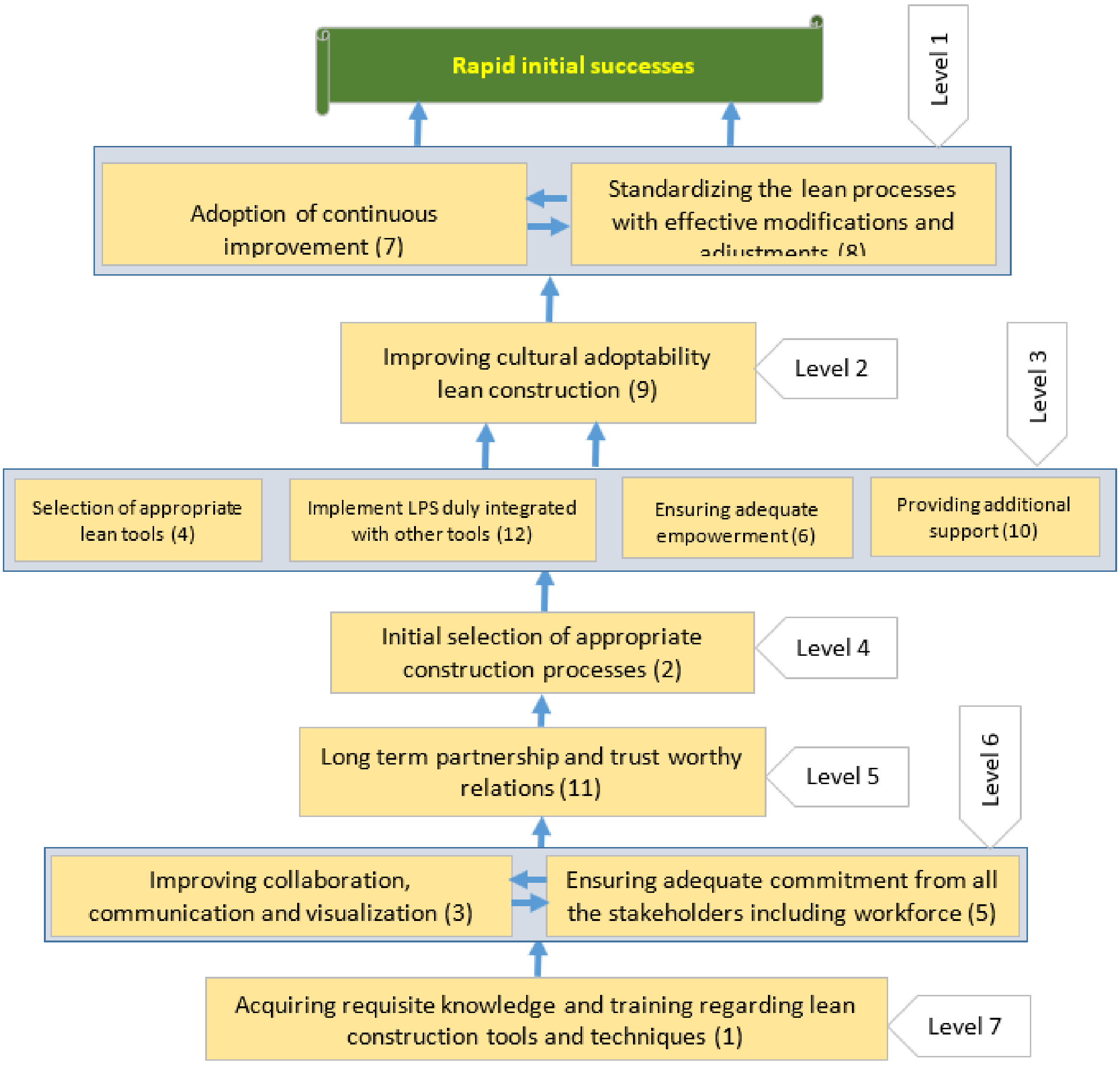

Figure 6. LC implementation framework for rapid successes

Linkage factors are important as they are responsible for the effect of independent factors on the dependent factors. Any change to these factors will simultaneously affect other factors within the framework. Driving factors can be regarded as the most important factors and without these factors, it is almost impossible to achieve the desired outcome. Each quadrant in the diagraph shows a category and any factor falling within that quadrant is assigned the relative category. As seen from Figure 7, none of the factors fall within the category of autonomous factors, thereby suggesting that all the factors are important and have to be retained within the framework. Four factors (1, 3, 5, 11) are classified as independent factors, however, factors 7,8, and 9 falls under the category of dependent factors. As per the analysis, there are five linkages factor (2, 4, 6, 10, 12). Factor 10 (Providing additional support to the lean teams and partners) is on the borderline between linkage and dependent factors however, considering the impact of this factor on cultural adaptability by helping the companies to achieve immediate successes that could motivate the companies to adopt LC culture, this factor was kept within the linkage factor category.

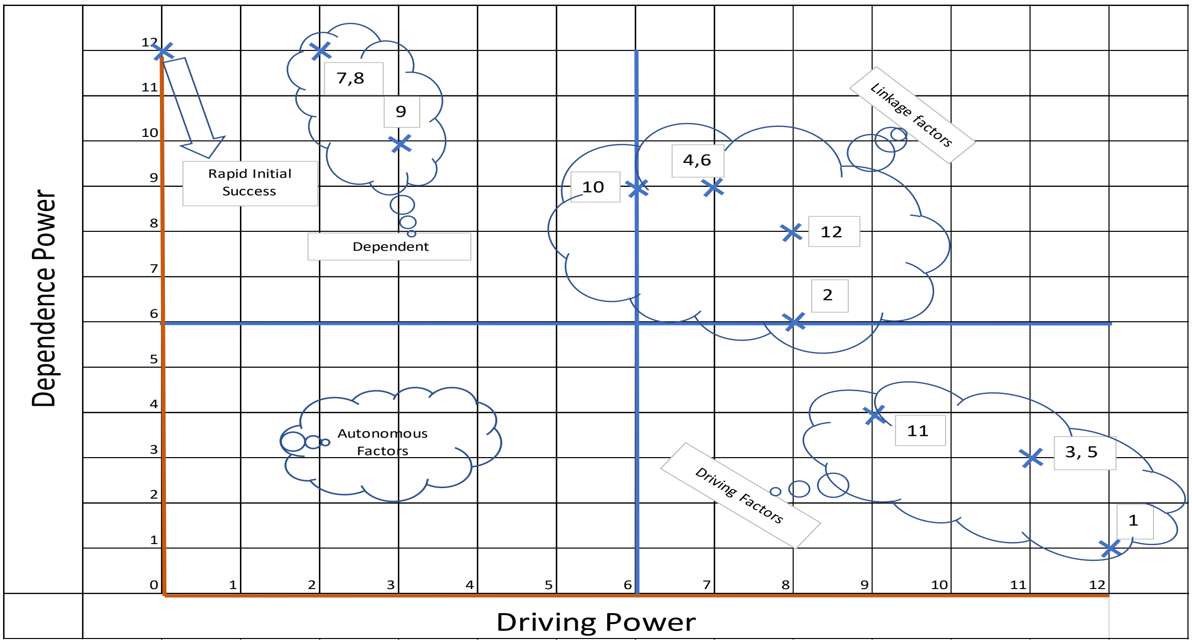

Figure 7. MICMAC analysis

Validation of the LC Implementation Framework

The final framework in Figure 6 is checked for any inconsistencies and conceptual differences. Moreover, the framework is compared with the already available existing frameworks for the successful implementation of LC. Although some sequential differences or detail of factors within frameworks are observed, no major inconsistencies were found. As an example, the framework developed by Sarhan et al. (2019) has top management commitment as the most important factor followed by promoting and education/training provision activities. Whereas, per this study, knowledge and training is regarded as the most important factor followed by commitment and collaboration. Similarly, cultural adaptability is relatively at the bottom of the model by Sarhan et al. (2019), however, the same factor is among the top-level within this framework. This difference is acceptable considering the countries where the research studies were applied. According to Ballard et al. (2007), rapid successes can help in changing the organizational culture towards LC and the developed framework leads to rapid success which in turn improves lean culture. Similarly, the outcome of this study, the selection of the right partners who are willing and trustworthy is regarded among the initial actions for starting the lean journey by Ballard et al (2007).

Impacts and Contribution of Developed LC Implementation Framework

Impact of Relationships

The McNemer's test revealed that all factors have a relationship with other factors, and no two factors are without a relationship. Factors like acquiring knowledge and training, improving collaboration, and ensuring adequate commitment level are found to help in achieving most of the other factors (having the greatest number of relationships as V), the factors like providing additional support, improving culture adaptability, continuous improvement and standardization are the factors that are mostly dependent on other factors (having the greatest number of relationships as A). Factors such as improving collaboration and ensuring adequate commitment levels are found to be interdependent. Similarly, interdependencies are also observed between: 1) selection of appropriate processes with implementing integrated LPS®, 2) appropriate tools selection with adequate empowerment, and 3) continuous improvement with standardization.

The interdependencies mean that both factors should be equally considered while making the decisions. As an example, interdependence between appropriate integrated LPS® tools and construction processes shows that either for selecting the construction processes or integrated LPS® tools and techniques, the compatibility between both these factors should be checked. Similarly, due to interdependency between factors like the adoption of continuous improvement and standardization, consideration should be given to both these factors to achieve any one of these two factors. This shows that even after standardizing the process, the process of continuous improvement should be routinely carried on (Ballard et al., 2007).

Contribution of Independent Factors

The developed LC implementation framework along with MICMAC analysis revealed four independent factors, including (1) acquiring knowledge and training, (2) improving collaboration, (3) ensuring adequate commitment level and (4) long-term partnership and trustworthy relations. These can be considered the most important factors because failure in their implementation can derail the successful implementation of LC. However, among these independent factors, acquiring knowledge and training will help in developing adequate commitment and collaboration among the stakeholders. Early involvement of all stakeholders will help in improving the collaboration and commitment between stakeholders whereas early involvement of the workforce will help in increasing the commitment of the workforce. Once the collaboration and commitment aspects are dealt with, organizations should try to build long-term partnerships and trustworthy relationships with the stakeholders. These four factors as shown in the bottom three levels are the prerequisite for starting the LC journey.

Contribution of Linkage Factors

After initial implementation of the independent factors, the company should look for the construction processes that would best be improved using LC. These may include all the construction activities or a few selected ones especially when the companies are new to LC. However, the selection of processes and tools/techniques should be carried out simultaneously to ensure the compatibility of lean tools/techniques with the construction processes.

There can be several LC tools/techniques like the LPS®, JIT, 5S, VSM, FRS, KAN, etc., which should be checked for their compatibility with the construction processes. With the advent of LPS®, a system has been developed to implement LC at the construction site (Ballard G., 2000); however, other tools and techniques should also be considered for integrated implementation of LPS® for efficiently achieving all the principles of LC (Aslam et al., 2020c). Selection of tools/techniques requires adequate inputs from the employees or the persons who must implement LC tool/techniques (normally supervisors or foreman). These employees should be given adequate empowerment to select and implement the LC tools and techniques. That is the reason that factors like selection of appropriate LC tool/techniques, integrated implementation of LPS®, and empowerment to the employees are at the same level in the developed framework because all these factors are mostly dependent on each other.

Once the tools/techniques are selected and employees are adequately empowered, the LC teams should be provided the additional support required like training or confidence for implementation or resources for implementing the LC tools and techniques. Five factors are considered as the linkage factors necessary for implementing the LC, including (1) appropriate selection of construction processes, (2) selection of LC tools/techniques, (3) empowering the employees, (4) integrated implementation of LPS, and (5) providing additional support.

Contribution of Dependent Factors

The framework development revealed three dependent factors of the LC implementation, including (1) cultural adaptability, (2) continuous improvements and (3) standardization of processes. After introducing and working with the independent and linkage factors, companies should look towards the cultural changes needed for adopting LC within their organizations. It is always difficult for the companies to change the existing culture which has been followed for so many years. However, the companies that have truly adapted to a lean culture have witnessed continued successes and improvements within their organizations. The main motivation for bringing cultural changes will come through the benefits being observed after introducing the independent and linkage factors. That is why the factor of cultural adaptability is among the dependent factors group.

Many companies fail to adapt to a lean culture before realizing the benefits of LC. Once the benefits are envisaged by ensuring the implementation of bottom-level factors (Figure 6), the companies will start moving towards a lean culture. This cultural adaptability will lead to continuous improvements and standardization of LC implementation processes. Implementation of LC is a continuous process in which companies endeavor to achieve excellence by improving through implementation. Outcomes will be measured and lessons learned recorded, prompting further modifications/improvements to be made and finally implementation is carried out. However, the same process of continuous improvement and standardization is repeated after each implementation.

Using Developed Framework: A Caution

Currently ISM-based models only show the direct relationships between the factors; however, many indirect relationships could exist between the factors (Attri et al., 2013). From Table 4 (SSIM), the preceding four discussed factors can help in achieving all the factors at higher levels because the determined relationship between them is V (Factor, *i*, only helps in achieving the factor, *j*). As an example, factors like acquiring knowledge and training, improving collaboration, and ensuring adequate commitment level will help in achieving all the factors from a long-term partnership and trustworthy relation to the standardization of lean process. This implies that for ensuring the implementation of succeeding factors, due importance should be given to all the preceding factors also. For example, while selecting the construction processes and tools/techniques or performing continuous improvements, or standardizing the lean processes, factors such as knowledge/training, collaboration, and commitment along with other preceding factors should always be taken into consideration.

Additionally, companies applying the developed LC implementation framework should be aware of the fact that where all the other factors are quite general and can easily be understood, the companies should know all the LC tools/techniques along with their objectives and functions. The LC tools/techniques will facilitate implementing LC especially during the actual construction stage and will impact LC implementation to a great extent.

Significance of Developed Framework

The major critique about the existing LC frameworks was that most are theory-based, only explain the principles/sub principles of LC, and lack the modalities for implementing the LC. This study tried to overcover some of these critiques by developing the framework using a highly structured approach (ISM) after duly incorporating the inputs of the LC firms who have been implementing LC for many years. It is also believed that the ISM approach is too interpretative hence there is a likely chance of biasedness (Attri et al., 2013). To overcome this shortcoming of ISM, the relationships between factors were determined after statistically analyzing the inputs from 82 LC companies. Moreover, the developed framework is also compared with the existing frameworks to check for any inconsistencies. All these actions are taken to increase the degree of confidence of the developed framework.

The final developed framework provides complete guidelines and a step-by-step procedure for implementing LC and achieving successful results. The construction companies who are hesitant in implementing LC due to fear/uncertainty or consider LC too complex to be implemented can utilize this easily understandable framework to implement LC successfully. Moreover, the clarification of the implementation processes within the developed framework also provides a way forward to the potentially new LC companies with their implementation journey.

Conclusion

Efficient implementation of LC involves theoretical knowledge about LC concepts, socio-culture aspects as well as the operational understanding of how different actions/activities can sequentially be organized to support the efficient LC implementation. An effort has been made in this study to integrate all the key factors that are essential for the implementation of LC by developing a framework using the ISM technique. The analysis revealed that acquiring knowledge and training about LC is key for starting the lean journey. The knowledge and training will increase the commitment of the upper management/workforce and help in implementing the key principles of LC such as collaboration and early involvement of all stakeholders with a long-term partnership and trustworthy relationship. The driving and linkage factors identified will help in achieving the immediate initial successes that would motivate the companies in developing the required commitment and culture of the LC. Once the culture is developed, it is easy for the organization to look for continuous improvements and finally standardizing their implementation process for ongoing use.

One of the most important contributions of this study is the reliability of the developed framework as it incorporated the years of experience of professionals from LC company. Whereas previous research mostly focused on developing theoretical frameworks, which in some cases relied on input from general construction companies whether they were familiar with LC or not.

To further increase the efficacy of the framework in this research, it is imperative to validate the framework by comparing the construction industrial practices used in implementing LC with the overall impact on the project outcomes. This validation process will determine the utility of the developed framework as well as suggest the modifications required within the developed framework to provide a more detailed and robust version of the framework.

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