OPTIMIZING SELECTION AND IMPLEMENTATION PROTOCOLS OF LEAN CONSTRUCTION TOOLS AND TECHNIQUES FOR RAPID INITIAL SUCCESSES

A Dissertation
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

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In Partial Fulfillment of the Requirements
for the Degree of
DOCTOR OF PHILOSOPHY

Major Program:
Civil Engineering

May 2021

Fargo, North Dakota

North Dakota State University
Graduate School

Title

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

DOCTOR OF PHILOSOPHY

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ABSTRACT

Lean construction (LC) has been considered as one of the most promising project management philosophies to overcome low productivity and excessive waste issues impacting the construction industry. Despite strong philosophies and some successful implementations, the uptake of LC in the construction industry is very low due to convoluted implementing strategies. Specifically, the construction industry lacks effective evaluation criteria, selection framework, and integrated applications of LC principles, tools, and techniques. Moreover, there is a strong need for a practical framework and associated validation process for LC implementation. Therefore, the purpose of this research is to optimize the selection and implementation protocols of LC tools and techniques for rapid initial successes. The methodology used for this research includes (1) a systematic literature review (SLR), (2) an initial survey of LC practitioners, (3) development of selection and implementation frameworks, and (4) framework validation survey and analysis. Uniquely, interpretative structural modeling (ISM) was used to develop the initial LC implementation framework and structural equation modeling (SEM) was used for framework modification and validation. As a result of the study, an effective selection framework has been developed with recommended LC tools and techniques to achieve integrated LC. The study has also identified critical factors for rapid initial LC project success and developed a robust LC implementation framework and an innovative integrated Last Planner System (ILPS). The validated LC implementation framework can predict approximately 65% of the variance in the project outcomes based on eight performance outcome measures.

The major contribution of this study is that the construction industry can efficiently select and implement LC tools and techniques allowing them to significantly reduce waste and improve project performance. Additionally, the well-structured validation process developed in this study

has been proven efficient and valid and therefore can be used widely for other research in the future.

ACKNOWLEDGMENTS

First of all, I thank Almighty Allah who gave me the ability, strength, and courage to complete this challenging task.

I would like to extend my gratitude to my advisors Dr. Zhili (Jerry) Gao and Dr. Gary Smith. Without their advice, guidance, support, and timely feedbacks, I could not have completed this dissertation.

My special thanks to Dr. Megan Orr and Dr. Ying Huang for their support and assistance throughout my research. Dr. Megan Orr along with statistical consultant Curt Doetkott have helped me a lot in performing the complicated statistical analysis.

I would like to express my appreciation to all the faculty and administrative staff for working kindly and selflessly in NDSU to support the students. My thanks to the Department of Construction Management & Engineering that provided me with opportunities of teaching courses and conducting laboratories that further enhanced my teaching skills and knowledge. I am extremely thankful to all the construction companies who responded and participated in this research and delivered their valuable inputs to increase the quality of the research. My special thanks to the Government of Pakistan and the National University of Science and Technology (NUST) for providing me funding supports throughout my research period.

I would additionally like to thank all of my friends for giving me the motivation and energy to work even in stressful conditions.

Last but not the least, it wouldn’t be possible for me to complete this research without the support of my family. My heartfelt thankfulness to my wife, and three kids (Tanisha, Sahrish, and Muhammad Hassam) who supported, encouraged, and prayed for me throughout my studies and research work.

DEDICATION

I would like to dedicate this dissertation to my Mother and my late Father

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LIST OF ABBREVIATIONS

LC ....Lean Construction

US ....United States

IGLC ....International Group of Lean Construction

TFV ....Transformation Flow Value

LPS...Last Planner System

ILPS ....Integrated Last Planner System

SLR ....Systemic Literature Review

ISM ....Interpretative Structural Modelling

PLS-SEM ....Partial Least Square – Structural Equation Modeling

CSF ....Critical Success Factor

EPA ....Environmental Protection Agency

CLMA ....Construction Labor Market Analyzer

CURT ....Construction User's Roundtable

DB ....Design-Build

TQM...Total Quality Management

CM@risk..Construction Manager at Risk

CAD ....Computer Aided Drawing

BIM ....Building Information Modeling

TPS...Toyota Production System

JIT ....Just in Time

TQC..Total Quality Control

CE ....Concurrent Engineering

IMVP..International Motor Vehicle Program

DBB ....Design Bid Build

IGLC ....International Group of Lean Construction

LPDS..Last Planner Delivery System

VDC ....Virtual Design and Construction

IPD ....Integrated Project Delivery

PPC ....Percent Plan Complete

PDCA...Plan Do Check Act

5S ....Sort, Straighten, Shine, Standardize, Sustain

DMAIC ....Define, Measure, Analyze, Improve and Control

DFSS..Define for Six Sigma

VM ....Visual Management

DHM ....Daily Huddle Meeting

FRS ....First Run Study

FSQS..Fail-Safe for Quality and Safety

PY ....Poka Yoka

SS ....Six Sigma

KAN...Kanban

KAIZ..Kaizen

PREFAB ....Prefabrication

MOD ....Modular

TOC..Theory of Constraints

SP ....Standardized Process

IPD ....Integrated Project Delivery

SBD..Set Based Design

TVD ....Target Value Design

VSM...Value Stream Mapping

LCI .... Lean Construction Institute

AGC .... Association of General Contractors

PMI .... Project Management Institutes

ASCE .... American Association of Civil engineers

FMEA .... Failure Mode and Effect Analysis

PF/MOD .... Prefabrication/Modular

L of B .... Line of Balance

IT .... Information Technology

OSCM .... Operations and Supply Chain Management

PDM .... Project Delivery Method

RII .... Relative Importance Index

PHOC-FRIED .... Friedman and Post-Friedman Test

BOT .... Built Operate Transfer

SE .... Sufficient Evidence

CII .... Construction Industry Institute

PCMAT .... Plan Condition of the Work Environment

SSIM .... Structural Self-Interactive Matrix

MICMAC .... Matrix of Cross-Impact Multiplication

IRB .... Institutional Review Board

AVE .... Average Variance Extracted

HTMT .... Heterotrait-Monotrait

f^2 .... Effective Size

Q^2 .... Predictive Relevance

VIF .... Variance Inflation Factor

SRMR .... Standardized Root Means Square Residual

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1. GENERAL INTRODUCTION

This chapter starts with the background knowledge in which the existing literature about the Lean construction (LC) and prevalent gaps are summarily discussed. Later on, the motivation/aim of this study, problem statement, objectives, overall research methodology, and significance of this dissertation will be presented. Finally, the chapter-wise summary of the whole dissertation will be explained.

1.1. Background

The construction industry is a major contributor to the United States (US) economy with an average gross output of more than 1.4 trillion dollars since 2016 which is almost 4.1 percent of the gross domestic product (GDP) in the US (US Central Bureau, 2019; BEA, 2020). With these figures, the construction market in the US is considered to be one of the largest in the world and is expected that new construction put in place will total approximately 1.5 trillion dollars by 2022 (Statista, 2019). According to Mcdermott (2009), skilled labor shortages, availability of management staff, lack of competent contractors, and environmental issues are the top four trends likely to affect the construction industry in the coming years. At present, the construction industry is suffering from the dilemma of cost and time overrun (Aslam et al., 2019; Yap and Skitmore, 2018; Sarhan et al. 2017; Hussin et al., 2013), low productivity (Sarhan et al. 2017; Stevens, 2014a; Mossman 2009, Koskela, 1993) and quality issues (Muhammad et al.,2013; Thamilarasu et al., 2017).

Many authors have highlighted that the challenges being faced by the construction industry are due to the presence of tremendous wastes within its material and process handling. Moreover, in a study conducted by Diekmann et al., (2004) for Construction Industry Institute, it was found that construction contributes to wastage of labor time by 57% compared to just 12%

in the manufacturing industry. This implies that the laborers are consuming just 50% of the time in delivering the value-added outcomes in construction and the rest of the time is simply a waste. This has reduced the productivity of construction to almost half. According to Koskela (1993), non-value-adding activities like waiting, rework, inspection, overproduction, large inventories, and moving are major contributors to a generation of lots of waste. Apart from waste handling, other significant issues with the construction industry leading to low performances are its fragmentation and uncertainty, adversarial relationship, lack of collaboration and long-lasting partners, isolation of design phase from construction, and lack of involvement of the downstream players (Mossman 2009; Aslam et al., 2019; Navigate construction forum, 2012; Sinesilassie et al. 2018; Koskela et al., 2002; World Economic Forum, 2017; Stevens 2012; Ballard et al., 2007).

To sustain such a huge industry, the construction industry is striving hard to develop and update those means, methodologies, and processes that can increase its performance and make it a more productive industry. Many construction professionals look towards Lean construction (LC) for improving construction practices. LC is derived from the concepts and philosophies that mostly exist in the Lean production system (LPS) and commonly used by the manufacturing industries like Toyota motors and Ford since the 1940s. Koskela in 1992, initiated lean production in the construction industry and formulated a production management paradigm for conceptualizing production in three complementary ways, namely (1) Transformation; (2) Flow; and (3) Value generation (TFV). Where the existing construction management only focus on value-adding activities (transformation of value-adding activities), LC was developed for 1) eliminating all non-value-adding activities to minimize the waste, 2) adding value to the product by meeting the customers' requirement through collaboration and early involvement of major stakeholders, and 3) maintaining a continuous flow between all the activities and processes. The development of an International Group of Lean Construction (IGLC) in 1993 and lean construction institutes (LCI) in 1997 further developed the concepts and implementation protocols of LC. Several LC tools and techniques were developed and tested in the construction industry for their efficacy. Resultantly tools like the Last planner system (LPS), just in time (JIT), set-based design (SBD), target value design (TVD), pull approach, building information modeling (BIM), integrated project delivery (IPD), and many more were incorporated in the tools and techniques list of LC for facilitating its implementation. The last two decades have also witnessed some of the successful implementations of the LC that resulted in significant savings in terms of cost, time, and improved productivity (Locatelli et al. 2013; More et al.,2016; Warcup, 2015).

Even though LC has been evolved as a robust theory with strong philosophies and also some successful implementations, the required uptake of LC within the construction industry is very low (Noor et al., 2018; Wandahl, 2014; McGraw Hill 2013, Bashir et al. 2015, Babalola et al., 2018, Stevens, 2014b). Where McGraw-Hill (2013) reported that 48% (out of a sample of 194 in the US) were not familiar with the broad overarching concept of LC in the US, Babolala et al. (2018) found that around 50% of construction firms are not even aware of LC tools and techniques. Similarly, low uptake of LC is also observed in other parts of the world (Wandahl, 2014; Mossman, 2009; Daniel et al. 2017). The major reason attributed towards this low uptake is 1) lack of a robust framework for implementing LC (Arbulu and Zabelle, 2006; Mossman, 2009), 2) poor knowledge (Fearne and Fowler, 2006), 3) lack of cultural adaptivity for lean construction (Shang and Sui Pheng, 2014; Kim and Park, 2006), and 4) faulty or partial implementation of lean tools and techniques (Mossman 2009; Porwal et al., 2010). Resultantly, the construction industry is either remained unaware about LC or, if aware, hesitated in implementing it either due to uncertainties and complexities involved in its concepts or lack of favorable results of the LC implementations (McGraw Hill 2013; Sarhan and Fox, 2013; Simonsen et al., 2014; Warcup, 2015; Santorella, 2017). According to Santorella (2017), 74% of companies that institute lean initiatives in the US have seen little success and the major reason for this low performance is the lack of meaningful adoption of lean culture within the organizational environment.

The state-of-the-art work in identifying the critical success factors (CSFs) for successful implementation of LC has been carried out such as 1) appropriate selection of lean tools and techniques, 2) cultural acceptability, 3) high commitment,4) high empowerment to downstream players, 5) early involvement of key stakeholders and downstream players, 5) standardization and flexibility of/within key processes, 6) increased training, 7) additional resources and many more. However, the dilemma is how to ensure that each of these factors is duly taken care of during the implementation of LC are not well researched in the existing body of literature. This lack of clarity can be a cause of confusion and complications thereby causing new construction companies to refrain from adopting lean construction (Stevens, 2013; Li, 2011; Schweikhart and Dembe, 2009; Green, 1999; Yahya et al., 2016; Ansah and Sorooshian, 2017). There is a need of evaluating the CSFs at the micro level so that lean adopting companies can have clear and practicable strategies to implement LC. The existing LC implementation frameworks are mostly developed using theoretical approaches or from the input of few lean experts thereby making it further hard for the construction industry to implement the existing LC implementation framework. Similarly, the validation process of the existing frameworks is also found out to be less structured and lacking the aspect of practicality (Pearce & Pons, 2019).

To remove confusion and complications within the mindset of the construction industry and facilitate the LC implementation process, an endeavor has been made in this research to formulate robust strategies and frameworks for the successful implementation of LC. The objectives of this research are formulated based on the major research gaps that are preventing the rapid and successful implementation of LC. To achieve the aim of this study, both qualitative and quantitative approaches for recording and analysis of data are adopted and further used for finding answers to the research questions. The outcome of this research will have a huge impact on increasing the uptake of LC along with its successful implementation. Construction companies that have not yet adopted lean practices will be especially benefitted from the outcome of this study as it provides them a complete LC implementation guideline at the project and organizational level that can lead them to rapid initial successes.

1.2. Research Motivation

The performance of the construction industry is not at par with the other industries due to the presence of several wastes, fragmentation in the construction industry, cost/schedule overrun, relatively stagnant productivity, and adversarial relationships with partners. LC, on the other hand, was developed with the potential to overcome the construction industry challenges. The theoretical development and explanation of LC fully conceptualize the weaknesses in the existing construction management approaches. Furthermore, it presented the methods, systems, ways, tools, and techniques that reduce the wastes and inefficiencies in managing the construction, thereby making it very appealing. The last couple of years have also witnessed some of the successful implementations of LC on construction projects that further reinforced the efficacy of LC in controlling malpractices resulting in low performances. The strong theoretical base coupled with some successful lean applications strongly supports LC practices in managing the projects. However, despite its tremendous benefits still, the required uptake of lean construction in the massive construction industry is very low. Identifying the likely shortcomings and then finding practical solutions can help in developing strategies and frameworks for the successful implementation of LC. The wide acceptance of LC is possible if new construction companies start implementing it and able to achieve rapid initial successes. The rapid initial successes will increase the morale and confidence for LC and will help in building a strong case for cultural transformation in favor of lean.

1.3. Problem Statement

An extensive literature review is carried out to identify the major shortcomings and gaps in the existing body of knowledge that barred LC to excel rapidly in the construction industry. The focus remained on identifying the problems that are inadequately researched but at the same time required immediate attention by the lean advocators to promote LC. The literature review results are reported in detail in Chapter 2 as well as separately in Chapters 3-8.

From the literature review and a survey (Chapter 6), it can be concluded that despite significant benefits associated with LC, the uptake of LC in the construction industry is disappointingly slow due to the adoption complexities of LC tools and techniques and convoluted implemented strategies. Specifically, the construction industry lacks effective evaluation criteria, selection framework, and integrated applications of LC principles, tools, and techniques. Similarly, existing LC implementation frameworks are difficult to implement on the projects because mostly these frameworks are developed based on the theories and lack structured development approaches along with a robust validation process. Therefore, there is a strong need for practical validated frameworks that will promote successful LC implementation, which ultimately leads to rapid project success and continuous improvement for the entire construction industry.

Such being-developed frameworks will be expected to address major existing gaps that prevent the construction industry from a successful implementation of LC, as found in the literature and survey mentioned above and briefly discussed below:

1.3.1. Poor Understanding of Lean Construction Tools and Techniques

Several studies have been carried out to identify barriers to the effective implementation of LC. These studies have highlighted the wrong interpretation of lean principles and tools as well as inappropriate/partially implemented tools as one of the key factors towards the failure (Abdullah et al., 2009; Sarhan and Fox, 2013; Bashir et al., 2015; Alarcón et al., 2011; Ayarkwa et al., 2011; Alinaitwe, 2009; McGrawHill, 2013). Currently, a bundle of tools and techniques have been recommended for the implementation of lean philosophy in construction, thereby leaving the choice of selecting the most appropriate tool at the mercy of the constructors. On the other hand, the general understanding of LC tools by the constructors is insufficient to make the right choice.

Although a large number of LC tools exist but this also causes a state of confusion and muddle among the constructors for picking the appropriate tool, which often results in a misperception of the complete lean processes (Stevens, 2014; Li, 2011; Schweikhart and Dembe, 2009; Green, 1999). The contractor who decides in moving towards lean has to spare considerable time in studying all the tools before picking the right tool and a faulty selection of the lean tool during initial phases can prove to be detrimental during the implementation stages (Wandahl, 2014; Bashir, 2013). Various LC implementation ventures have failed to produce the desired results due to incorrect selection and mis-conceptualization of the lean techniques

(Kalsaas et al., 2009, Kim & Park, 2006). The major gaps resulting in poor understanding of lean construction tools and techniques are discussed below:

1.3.1.1. Non-Categorization and comprehensive performance evaluation of LC tools and techniques

It is a common fact that constructor's decision in selecting the most efficient tool is based on the parameters of productivity, time, and cost. The main reason for the lack of clarity for LC tools and techniques is the fact that lean tools are not comprehensively classified and comparatively analyzed within the domains of productivity, time, and cost. All tools are generally grouped under the umbrella of LC but their further classification concerning specific performance parameters like waste, productivity, safety, and quality is scarcely researched. Similarly, the potentials of LC tools and techniques in triggering LC principles and functions is another area requiring further investigation. It would be more beneficial to the constructors if they can compare quantitative benefits and the capabilities of LC tools in achieving LC principles/functions before making a final selection decision. This would help them in selecting the most efficient tool from the complete data set of LC tools.

1.3.1.2. Lack of framework for the selection of lean construction tools and techniques

At present, the general practice of selecting lean tools is based only on performance or LC tool's objectives. However, objectives can be similar among tools and comparative performance can be specific to a process/activity and might not be the same for other processes/activities in construction (Yahya et al., 2016; Kim and Park, 2006). Therefore, other criteria for selecting the right LC tools and techniques should be explored.

Although many researchers have highlighted the importance of selecting the right LC tools and techniques (Sarhan et al., 2019; Ballard et. al., 2007; Mostafa et. al., 2013), but fell short in explaining the methods/strategies for selecting the most appropriate LC tools and techniques. Lack of availability of frameworks for selecting the LC tools and techniques resulted in wrong or partial selection and implementation of LC tools and techniques (Abdullah et al., 2009; Sarhan and Fox, 2013; Bashir et al., 2015; Alarcón et al., 2011; Ayarkwa et al., 2011; Alinaitwe, 2009; McGrawHill, 2013).

Therefore, there is a need of developing a framework that can guide the LC construction companies in selecting the most appropriate LC tools and techniques.

1.3.1.3. Lack of integrated application of LC tools and techniques

Where other lean tools and techniques are mostly derived or adopted from lean production or manufacturing industries, LPS is the only tool specifically designed for implementing LC. Most of the time, the construction companies are only implementing LPS to make their lean journey successful without considering any other LC tools and techniques. However, to fully implement LC principles, it is imperative to ensure the integrated application of LC tools and techniques as each tool targets a particular LC principle. Even LPS alone doesn't have the potentials to implement all the LC principles without being integrated with other tools and techniques. That is the reason, on average 30% of the weekly assignments are not completed even after implementing LPS (Bortolazza & Formoso, 2006). There have been certain challenges and shortcomings identified in the system that are prohibiting LPS to operate fully (Sabek and McCabe, 2018; Fernandez-Solis et al., 2013; Tayeh et a1., 2018; Priven and Sacks, 2016; Vignesh, 2017; Dave et al., 2015) and most of these shortcomings arise due to isolated application of LPS. Integrated application of different tools and techniques is very meagerly researched in the existing literature. Therefore, there is also a need of exploring the potentials and capacity of LPS in fully implementing the LC by integrating it with other Lean tools and techniques.

1.3.2. A Dearth of Standardized Implementable Frameworks of Lean Construction

For the last two decades, the implementation of LC has resulted in many benefits in terms of cost, time, and productivity. However, the successes of LC are mostly in pockets with a limited number of organizations using lean practices (Bashir et al., 2015; Mossman, 2009). Where LC is still struggling for finding ways into the majority of the construction industry, on the other hand, improvements recorded by LC organizations also vary drastically from one organization to another and from project to project. Some organizations have witnessed improvements in the range of 1-20% (CLIP, 2005; Anderson et al., 2012; Conte and Gransberg, 2001; Agbulos et al., 2006) while others also experienced more than 30% of improvements (Locatelli, 2013). These variations reveal the fact that implementation of LC is not yet standardized and every organization is interpreting the implementation process as per their understandings. Resultantly, few organizations that follow lean principles in true spirit can achieve better outcomes than others. The major gaps are discussed below:

1.3.2.1. Lack of practical micro-level evaluation of critical success factors for implementing LC and achieving rapid initial successes

Construction companies need actions that result in immediate benefits. Once the benefits are immediate and evident, the morale and confidence of the project participants in using LC will increase. A good start for LC is equally important as the long-term strategy. The initial positive results coupled with long-term strategic implementation plans would increase the number of lean adopters in the industry. The state of the work has been done in identifying factors that can lead to the successful implementation of LC but fell short in providing a more practical framework to implement them during early construction stages. Identified factors are broad-based and need to be explored at a micro level to inculcate the elements of realism and practicability in LC for new lean adopters. As an example, lean advocator considers both standardization and flexibility as key ingredients for lean, whereas both terminologies contradict each other. Therefore, there is a need to establish the degree of standardization as well as flexibility in managing lean processes and methods to avoid this conflict. Similarly, selection of appropriate LC tools has always been regarded as the key factor for successful implementation of LC (Mostafa, 2013; Pavnaskar et al., 2003; Ward, 2015; Shou et al., 2016), however, the selection criteria are very meagerly reported in the existing literature. Where increasing the awareness of LC is important for increasing the use of LC, there is very little research available that can guide the lean advocators in defining the methods for increasing the awareness for LC. Similarly, further clarifications are needed on other factors also.

Therefore, to increase the initial success rate of LC, it is important to evaluate success factors at the micro/operational level so that realistic implementation of lean tools and techniques can be made possible. Due to little research available in identifying modalities that can lead to immediate successes at the micro/operational level, there is a need to further explore success factors at the micro-level: the level at which the project team operates.

1.3.2.2. Lack of LC implementation frameworks developed using structured approaches

For rapid initial gains, it is imperative to develop robust frameworks/ guidelines/ toolboxes for implementing lean tools and techniques at the project level. Consistent performance would come through the standardized implementation framework which should be easy to comprehend and adaptable during construction. Optimized results would be possible by implementing LC with true spirit and according to the best practices advocated by the lean experts.

Unfortunately, the available lean implementation strategies and frameworks are either based on theories (Koskela, 2000; Swefie, 2013) or expert opinions (Diekmann et al., 2004; EI-Sabek et al., 2018) or the case studies for a single project while focusing on particular activities (Ballard, 2000; Heravi and Rashid, 2018). Although these approaches have helped in establishing a well set of LC principles/subprinciples, there is a lack of a structured approach that can lead the construction industry in implementing these LC principles/factors on projects. Moreover, LC implementation frameworks are very broad-based. At times it is difficult for the construction companies to comprehend and implement the existing models because they are developed at a macro level and don't explain the modalities of implementation. Furthermore, the steps for implementing these strategies especially for new lean adopting companies are scarcely presented in the existing literature.

To fill this gap, there is a dire need of developing a robust and more structured LC implementation framework that can lead the lean practitioners to the complete process of implementation in a sequential and easily understandable way

1.3.2.3. Lack of structured validation of existing LC implementation frameworks

Validation of the developed frameworks/models is an important process for improving authenticity, reliability and determining the degree of applicability of the developed framework on the actual project environment (Richie et al., 2013; Miles and Huberman, 1994). Although many researchers tried to develop the LC implementation framework as discussed in the previous paragraph, very few of the researchers endeavored to validate their frameworks. This lack of validation approach will reduce the confidence of the construction industry in the developed frameworks and will further make it harder for them to implement LC within a project environment. The researchers who tried to validate their frameworks either resorted to an expert opinion by checking the efficacy of their developed framework from the lean experts (EI-Sabek et al., 2018; Ghosh and Heidenreich, 2018) or used simulation techniques (Erikshammar et al., 2013). Other researchers applied their developed framework on single projects to check its efficacy (Swefie, 2013). Similarly, very meager research is available in which frameworks are assessed in terms of their potentials of improving the construction performance outcomes (Al-Aomar, 2012). The extensive literature review indicated that in comparison to other industries, there is a very limited trend of validating the developed LC frameworks using structured approaches. This lack of structured quantitative approaches for validating the LC implementation framework with its effect on overall construction performance is the major hurdle for the construction industry in developing the standardized LC implementation framework. Pearce and Pons (2019) also highlighted that most of the studies related to lean management are qualitative with a lot of subjectivity whereas quantitative analyses are needed to verify and strengthen existing literature and especially confirm the critical factors for lean success.

It has been observed that where a lot of deliberation, care, and robustness is given to developing the LC implementation frameworks, comparatively lesser efforts are carried out for validating the developed frameworks. There is a dire need of in detail and robust validation of the developed LC implementation frameworks with special emphasis on construction industry demands and environments.

1.4. Objective

The goal of this study is to develop and validate frameworks for optimizing the selection and implementation protocols of LC tools and techniques to achieve rapid initial successes, with the following specific objectives:

1. Determine performance-based evaluation and establish a conceptual framework of LC tools and techniques
2. Construct an innovative Integrated LC Tool System
3. Evaluate critical success factors at micro-level for selecting and implementing LC to achieve rapid initial successes, by
4. Develop a robust LC implementation framework for rapid initial successes
5. Validate LC implementation framework using a structured approach

The objectives listed above will be further assessed with a set of research questions, as shown below in Table 1.1

Table 1.1. Research questions for each objective

Objective	Research question
1	• Do all the LC tools be classified within the same performance parameters like cost and schedule control, safety and quality improvement, and productivity enhancement or each tool can be classified differently? • Which LC tool performed better in terms of cost, time, and productivity? • How lean tools help in implementing Lean principles? • What are the different objectives and functionalities of commonly used LC tools and techniques? • Are there any similarities between objectives and functionalities, making the selection of LC tools and techniques difficult and confusing? • How can the construction companies select the most appropriate LC tools and techniques?
2	• What are the shortcomings in existing LPS that are hindering its optimized performance? • How can other LC tools be integrated within LPS to overcome the detrimental effect of its shortcomings? • How can the ILPS be implemented by the construction companies for improved performances?
3	• How much benefit should be expected initially using lean tools and techniques? • How to select construction processes for lean intervention? • How to select LC tools and techniques? • What could be the best project delivery system (PDS) that enables the lean team to implement LC tools and techniques in true spirit? • How much commitment level is expected from field managers, workforce, subcontractors, and suppliers for starting LC? • How much empowerment should be given to field managers, workforce, subcontractors, and suppliers for starting LC? • What could be the best way of imparting lean training to the field managers and workforce? • What kind of support should be provided to project teams for the successful implementation of lean tools by upper management? • What should be the adequate frequency of measuring the performances? • How much standardization and modification are deemed necessary for the successful implementation of LC tools and techniques? • How to increase awareness for LC within the construction industry?
4	• How the critical success factors are related to each other in terms of their influence on others? • What is the order in which these critical factors should be applied for getting the most efficient results? • What are the dependent, independent, or linkage factors within the developed framework?
5	• Will the developed LC implementation framework have the capability of improving construction performances? • How to improve the initially developed LC framework for achieving optimized construction performances? • Are the identified indicators within the framework considered relevant and important? • What are the most important factors that should be adequately addressed for getting better project outcomes?

1.5. Overall Research Methodology

The overall methodology used for this research, as shown in Figure 1.1, includes (1) a systematic literature review (SLR), (2) development of LC tools and techniques selection framework, (3) developing innovated system for integrated implementation of LC tool and techniques, (4) a survey of LC practitioners, (5) identification of critical success factors, (6) validation survey for identifying the relationship between factors, (7) development of LC implementation frameworks, and (8) framework validation survey and analysis.

These steps are briefly discussed below, while more details can be found in each related chapter later.

A preliminary literature review from the reputed and peer-reviewed journals was conducted to identify the gaps within the existing LC implementation process. After identifying the gaps, systematic literature review (SLR) will be carried out consulting case studies, journal/conference papers, industry reports, and academic thesis/dissertations for developing 1) preliminary theoretical framework for selecting LC tools and techniques, and 2) integrated application of LC tools and techniques using LPS platform. The SLR will provide a basis for establishing the context and theoretical basis for conducting further research.

After establishing a strong background, an initial questionnaire survey will be conducted to identify the factors that can result in rapid initial successes. Various statistical analyses will be performed to identify the significant and relative rankings between different factors.

Another round of survey will be conducted to identify the relationships between the factors to identify the factors that help in achieving other factors. McNemar's test will be performed to determine the significant relationships. Interpretative structural modeling (ISM) techniques will be used to develop the initial LC implementation framework.

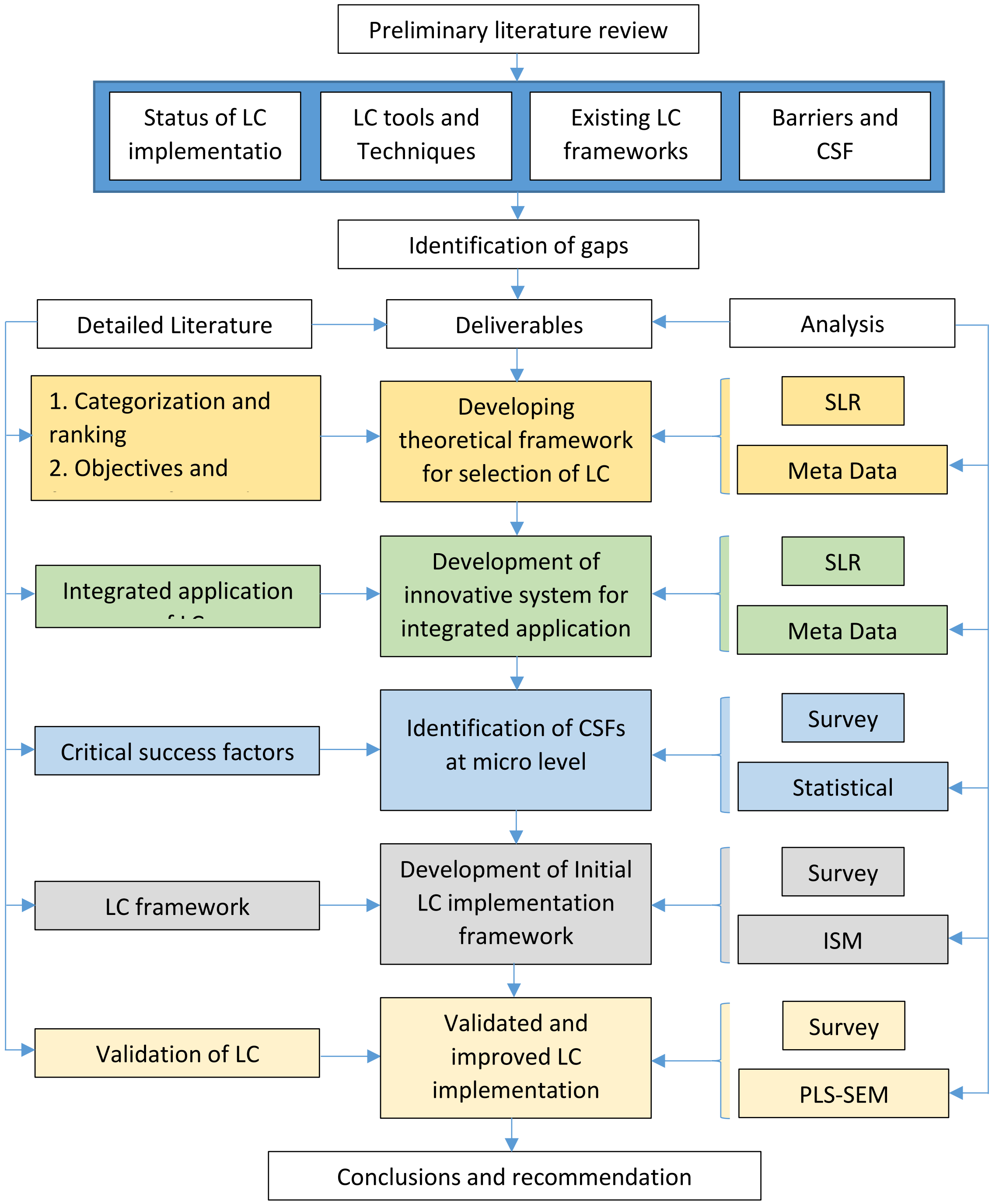

Figure 1.1. Overall research methodology

Finally, the initially developed LC implementation framework will be validated and modified to develop the validated and improved LC implementation framework. The inputs from the LC companies will form the basis of determining the indicators of each of the factors that will be measured against the eight performance parameters of cost, time, quality, safety, relationships, lawsuits, profits, and losses. The partial least square (PLS)-Structural equation modeling (SEM) technique is used to validate and modify the initial LC implementation framework.

1.6. Research Significance

While the present LC literature explains the theory, philosophies, and practical issues along with the application of LC tools and techniques on a limited scale especially involving a specific construction process, this study will further expand the existing body of knowledge by providing a holistic approach to implement the LC at the complete project level. In this study, the lean practitioners will be exclusively approached for identifying the more practical and factual strategies based on their experiences to develop complete guidelines for implementing LC, thereby facilitating the new lean adopters for implementing lean on their projects. Therefore, it can help new lean practitioners in understanding the whole process of selection and implementation of LC tools and techniques. Practically, by developing a robust LC implementation framework, this study would remove complexities and confusions perceived within the mindset of newly lean adopting organizations and will provide a way forward to the construction industry in using lean practices efficiently. Moreover, a complete process for developing and validating the LC implementation framework will be proposed that can be used widely for other research works in the future.

Besides addressing the research gaps, each research objective defined early will also have several more specific outcomes, as listed below:

- Objective 1. Where most of the researchers have contributed to identifying and testing one, two, or in some cases a few more than two LC lean tools and techniques, this study will provide a comprehensive assessment and evaluation of all common tools and techniques in comparison to each other. The outcome of these two objectives will provide a theoretical platform to the construction industry in understanding, evaluating, assessing, and categorizing each of the LC tools relative to others. As a result, lean practitioners will be having a broader window of opportunities in selecting a variety of tools. The conceptual framework that will be developed will guide the construction organizations in selecting the most appropriate LC tool that best matches their organizational and project requirements.

- Objective 2. The development of an integrated platform for implementing LC tools and techniques will provide a necessary bridge between different tools and techniques. The existing LPS is taken as the basic platform for integration. Importantly, this study will increase the body of knowledge by explaining the key functionalities and methodologies involved during the efficient implementation of LPS. It will increase the opportunity for utilizing the LPS to its full potential by integrating it with other tools and techniques. Practically, it will provide the contractors a way forward in implementing different LC tools and techniques simultaneously for improved performances.
- Objectives 3, 4 and 5. Although broad-based factors and theoretical frameworks for implementing LC successfully have been developed, this study will further extend this knowledge by developing strategies at the operational level, the level at which LC tools and techniques have to be practically implemented. The existing broad-based strategies will be further explored at the micro level to

develop LC implementation frameworks. This will help the construction industry in understanding the level of implementing key CSFs at the project level. Developed LC implementation framework will facilitate the construction industry in gaining rapid initial successes which will increase the morale and confidence of the organizational staff in adopting LC.

1.7. Organization of the Dissertation

This dissertation is comprised of nine (9) chapters along with appendices. Except for Chapters 1, 2, and 9, all other chapters are the compilation of the individual journal papers that have either been published or under review and targeting the specific objective of this study. The general organization of the dissertation is as under:

Chapter 1: General Introduction: This chapter summarily explains the background and need for lean construction in the construction industry. The existing problems/gaps during the implementation of lean construction are elaborately discussed. The motivation for undertaking this research and main and sub-objectives are enumerated. The overall methodology for achieving these objectives is explained. The research questions are formulated for each objective for further analysis and finding their answers. The major significances of this research are discussed.

Chapter 2: Literature Review: This chapter starts by examining the existing and forecasted challenges of the construction industry and later on various techniques adopted by the construction industry to overcome these challenges are compared. The contextual background of lean production in general and its application in construction in particular, are examined in a sequential order covering the historical development of definitions, and principles associated with LC along with a detailed description of LC tools and techniques. Available frameworks and success factors for implementing lean construction tools and techniques are also examined. In the end, the present status of lean construction implementation within the construction industry and major reasons for the low uptake of lean construction within the construction industry are discussed.

Chapter 3: Paper 1 - Performance-based evaluation of lean construction tools: The main purpose of this chapter is to evaluate the efficacy of LC tools and techniques in implementing LC. Various LC principles and functions are discussed and further matched with LC tools and techniques to identify the potentials of LC tools and techniques in achieving respective LC principles. Furthermore, LC tools and techniques are categorized based on the performance parameters like productivity, cost, time, safety, and quality. Moreover, LC tools and techniques are also prioritized based on their capabilities of improving the cost (reduction), time (reduction), and productivity. Data from different case studies were critically analyzed and presented in the form of histograms with mean improvements in these three categories.

Chapter 4: Paper 2 - Framework for selection of LC tools based on lean objectives and functionalities: In this chapter, a conceptual framework for selecting LC tools and techniques is developed. The LC tools and techniques are first distinguished based on their objectives and functionalities. A matrix was developed for identifying the functionalities and objectives of each LC tool. In the end, a complete, conceptual framework is developed using the data from the developed matrix and through the extensive review of the literature.

Chapter 5: Paper 3 - Development of Innovative Integrated Last Planner System (ILPS): This chapter highlighted some of the key drawbacks in implementing the LPS. The matrix and framework developed in chapter 4 and the ranking of LC tools from chapter 3, were used as the key inputs for integrating various other LC tools with the LPS to overcome its shortcomings.

Later on, the Integrated model (ILPS) and protocols for implementing various stages of ILPS were discussed.

Chapter 6: Paper 4 - Exploring factors for implementing LC for rapid initial successes in construction. This chapter presented the results, analysis, and strategies for increasing the adoption and successfully selecting and implementing LC tools and techniques through a survey conducted from the experienced lean practitioners. The outcomes of Chapters 3, 4, and 5 are used as the key inputs in developing the questionnaire to find answers to 11 problems/gaps identified. In the end, based on the analysis, key factors for implementing LC for rapid initial successes especially for the new lean adopters will be presented.

Chapter 7: Paper 5 - Development of Interpretative Structural Modeling (ISM) based Lean Construction Implementation Framework: In this chapter, relationships between various factors (identified in chapter 6) will be identified to assess the influential power of one factor on the other. The factors identified in chapter 6 are further improved with the existing literature with an effort to include all critical factors required for developing the initial LC implementation framework. The step-by-step implementation process of all these factors will be analyzed using structured analysis means to develop a robust initial LC implementation framework using ISM. Furthermore, the factors are further classified based on their driving and dependence power into dependent, independent, and linkage factors.

Chapter 8: Paper 6 - Validation of Lean Construction Implementation Framework Using Partial Least Square – Structural Equation Modeling (PLS-SEM): In this chapter, the factors/subfactors identified in chapter 6 and the initial LC implementation framework developed in chapter 7 are validated through the inputs from the LC companies who are undertaking LC projects using PLS-SEM. The initially developed LC framework will be further modified based on the reliability and validity of the factors, indicators, and paths within the framework. Finally, a validated and improved LC implementation framework will be developed.

Chapter 9: Conclusions and Recommendations: Where in the individual chapter's specific conclusions relative to that chapter are presented, in this chapter the overall conclusions, implications/contributions of this research effort, and future recommendations will be discussed.

2. LITERATURE REVIEW

2.1. Existing Challenges in the Construction Industry

Construction projects are always considered to be highly uncertain and volatile as projects are undertaken in dissimilar environments involving numerous specialty teams working together to achieve the goals of the construction (Sinesilassie et al., 2018). This uncertainty leads to the production of enormous wastes both in the product and processes which at times are considered to be inherent in the construction projects. According to Babalola et al. (2019), the construction industry is exposed to numerous non-value-adding activities that have become the major source of waste generation. According to Koskela (1993), non-value-adding activities like waiting, rework, inspection, overproduction, large inventories, and moving are major contributors to the generation of lots of waste. The Construction Industry Institute conducted a detailed evaluation of the construction projects and concluded that the contribution of non-value-added effort or waste in construction projects, is at an average of 50% (Diekmann et al. 2004). Similarly, Mossman (2009) also concluded that 55-65% of construction efforts are wasted and have a detrimental effect on construction productivity. The presence of such a huge amount of waste is a major factor of low performance and inefficiencies in the construction industry (Aziz et al., 2013). According to the author, the construction industry in the United Kingdom is experiencing up to 30% of rework, 40-60% labor efficiency, and at least 10% material wastage. Moreover, wastage of time has increased to the tune of 57% in the construction industry (Aziz et al., 2013). Similarly, Love et al. (2018a, 2018b), after analyzing 346 construction projects in Australia, revealed reworks events that accounted for 34% of the total cost and the main contributors of reworks were found to be owners (50%) and contractors (43%) (Love et al. 2018 b). Apart from inefficiencies, construction claims are also increasing in the construction industry due to change orders, adversarial relationships, constructability issues, contract administration issues, unrealistic schedule/cost estimates, natural occurrences, and resource availability issues (Aslam et al., 2019; Navigate construction forum, 2012). According to the research perspective issued by Navigate construction forum (2012), the value of the construction claims in 2012 reached up to $ 32.2 Million globally thereby causing an additional burden on the construction economy.

Because of wastes/non-value-added activities, the construction industry is experiencing 1) time and cost overrun (Aslam et al., 2019; Yap and Skitmore, 2018; Sarhan et al. 2017; Hussin et al., 2013), 2) low-profit margins (Sarhan et al. 2017) and 3) productivity issues (Sarhan et al. 2017; Mossman, 2009) on most of its projects. Similarly, according to Aslam et al. (2019), the cost can be increased by 40% if projects are not managed well and design changes are not reduced considerably. Similarly, other researchers have also identified the cost and schedule overrun issues associated with construction projects (Yap and Skitmore, 2018; Moura et al., 2007; Tafazzoli and Shrestha, 2017). According to Hussin et al. (2013), the construction industry is experiencing the chronic problems of schedule delays and cost overrun, and almost 70 % of construction projects are delayed and 14% have to bear the cost overrun issues. A study conducted by Construction user’s roundtable (CURT) in 2017 revealed that only 9% (out of 28) of companies are achieving a high level of excellence in total project performance.

The construction industry is also a major contributor to environmental issues. According to EPA (2018), the construction industry in the US is responsible for producing approximately 548 million tons of waste. Egan's report (1998) also confirmed that almost 30% of construction reworks and 10% of materials are wasted on the majority of construction projects in the UK. This 10% of the material waste is also causing some severe environmental issues.

According to the report published by CLMA (2016), construction productivity is not progressing like the other industries. The report shows a clear and distinct marginal decline of construction productivity in comparison to other industries based on the labor hours worked in the industry.

In a study conducted by Diekmann et al., (2004) for Construction Industry Institute, it was found that where the waste of time is 12% in the manufacturing industry, the construction contributes to wastage of labor time by 57%. This implies that the laborers are consuming just 50% of the time in delivering the value-added outcomes in construction and the rest of the time is simply a waste. This has reduced the productivity of construction to almost half. According to Stevens (2012), despite advances in professionalism, methods, technology, and human resources, still, the productivity in construction has not improved and even lower than it was in 1997. In a more recent study, Matt Stevens calculated the US construction industry's labor productivity from 1993 to 2013 in a white paper for his management research, advice, and education firm (Stevens, 2014a). Stevens likewise found that except for a productivity surge in 2008 and 2009, the construction industry's productivity is in decline, lower now than it was in 1993. According to the author, the major reason for this lack of productivity is attributed to the misalignment of goals of different stakeholders where the project owner focuses on production, and contractors need job productivity to finish early. Lack of communication between the designers and builders is the biggest obstacle causing constructability issues and a decrease in productivity.

According to the World Economic Forum (2017), the lower performances, complexities, and uncertainties related to infrastructure projects exposed the problems of traditional project delivery and management systems. Considering the widespread increase in construction projects, the construction industry should adopt and develop innovative project management practices and techniques that should meet all the existing and future challenges of the construction industries.

Many researchers have criticized the traditional project management approach of design - bid – build because of its lack of collaboration and communication, promotion of adverse relationship, neglecting both value maximization and waste minimization, no consideration to the optimized flow of processes and information, non-involvement of downstream players, lack of flexibility and strict compliance (Koskela and Howell, 2002; World Economic Forum, 2017; Stevens, 2012; Aziz et al., 2013; Ballard et al., 2007). According to Koskela (1993), the traditional project management approaches only emphasize the conversion activities (activities which are to be performed: typically work breakdown structure) without realizing the presence of tremendous non-value-adding activities (required for binding the conversion activities). Where much of the effort is exerted in increasing the efficiency of conversion activities, very little or almost none of the effort in reducing or eliminating the non-value adding activities done in the traditional approach. Resultantly, the constructors have very little control over the flow processes due to the expansion of non-value activities and in the end, the output value is reduced considerably.

In summary, it can be concluded that currently, the construction industry is facing some chronic problems that have resulted in cost and time overruns, and productivity issues. The problems are a result of tremendous wastes both in construction processes and material as well as many managerial issues inbred in the construction industry. The construction industry is in the continuous hunt for improving its performances by adopting innovative management approaches to improve professional management practices.

2.2. Measures to Overcome Challenges

To overcome the challenges, the construction industry is striving hard in finding out the ways and methods to improve construction performances. According to Muhammad et al. (2013), the adverse effects of issues like insufficient quality, low productivity, poor coordination, and high cost, normally associated with the construction, can be reduced using better management practices and using the latest technologies. To improve the efficiency of construction projects, the construction industry is trying to develop innovative project management philosophy which can reduce the inefficiencies within the construction and target the specific challenges of construction. Project delivery methods like design-build (DB), Total quality management (TQM), Agile construction, and construction manager at risk (CM@risk) are incorporated to increase the collaboration and coordination between different construction stakeholders. Similarly, new technological developments like the use of 3D computer-aided drawing (CADs) and Building information modeling (BIM) for improving visualization and rapid generation of the construction plan and design are also in use in construction. Although DB and CM@ risk approach managed to reduce the constructability issue, its focus always remained on achieving the transformation goal of construction products and have little to pursue the value or flow goals that are the major causes of increased wasteful activities (Koskela et al. 2002). Similarly, elements of continuous improvement, quality assurance, the involvement of downstream players, identification of non-value-adding activities are not explicitly described in these approaches (Aziz et al. 2013; Becker et al.,2011). Moreover, the use of CAD has also not successfully reduced the change orders due to design errors (Aziz et al., 2003). The comparisons of different commonly used management and project delivery techniques are discussed in table 2.1. The comparison is based on the influence level of different management/delivery approaches in reducing wastes (Koskela, 1992; Koskela et al., 2002; Aziz et al., 2013; Becker et al., 2011, World Economic Forum, 2017; Ballard et al., 2007; Noori, 2019; Iqbal, 2015; Straçusser, 2015).

Table 2.1. Comparison of different management approaches and delivery system

Management/ delivery approaches / **Factor for reducing waste**	**Design Bid**	**Total Quality Management**	**BIM/CAD**	**Lean approach**	**Agile**
Reduce uncertainty	M	H	M	H	L
Cordial Relationship	M	H	N	H	H
Involving downstream players	L	H	N	H	H
Compatibility of design with construction	H	M	H	H	H
Long term relation	L	M	-	H	L
Customers Satisfaction	M	H	H	H	H
Flow considerations	L	M	M	H	M
Effort in reducing the non-value adding activities	L	M	H	H	M
Continuous Improvement	L	H	H	H	M
Collaboration	M	H	M	H	M
Inbuilt quality and safety	N	H	M	M	L

N – No, L – Low, M – Medium, H – High

It can be viewed that lean approaches once applied can have a greater impact on reducing most of the causes of wastes. Since 1990, the construction industry is trying to find out the breakthrough in improving its productivity by utilizing the lean production philosophy coupled with technological developments.

2.3. Lean Production

The concept of lean production was first originated in Japan in the 1950s with the name “Toyota Production System” (TPS) as Toyota Motors pioneered in building the concepts (Koskela, 1992; Aziz et al., 2013; Muhammad et al., 2013). After World War II, the Japanese manufacturing Industry suffered huge setbacks due to a limited supply of raw materials and inadequate space for inventory (Diekmann et al., 2004 from the book written by Womack et al. 1990). Keeping this in view, the main focuses of the TPS are the elimination of inventories, reducing the set-up times, autonomation, collaboration, delivering quality products instantly, meeting the customers' demands, and maintaining the flow (Kim 2002). The Post-World War scenario fostered a perfect environment for the TPS to incorporate approaches like JIT and zero inventory with aim of improving the flow, value and eliminating wastes during the production process (Koskela, 1993). Later on, based on the instructions from the quality champion W. Edwards Deming, Japan altered the way quality aspects were viewed. Deming introduced them to the TQM system for developing a culture in which quality led the production design. At that time, the TQM concepts like continuous improvement, people/employee empowerment, managing the quality proactively by conceiving the defects/errors prior seemed to be new to Japan. However, they successfully adopted the TQM and further improved it with total quality control (TQC). They started to develop multi-skilled teams working collaboratively to find the root causes of the defects. Resultantly, the quality improved dramatically. The concepts of concurrent engineering (CE) and product design were also incorporated within the TPS, thereby making it a robust production management philosophy that increased the efficiency of Toyota car motors to many folds. Some of the examples of how TPS amalgamated different aspects in its theory are: the concepts like zero inventories, pull approach, and delivering the products instantly were derived from JIT, quality assurance, and continuous improvement adopted from TQM, and simultaneous production and designing were extracted from CE.

Initially, the idea of TPS was practiced, developed, and refined by Industrial engineers, however, in the 1980s, a wave of books explaining the theory and wider presentation of this approach was explored in detail. In 1996, Womack and Jones explained the TPS in their book "Lean Thinking" and identified the fundamental principles of lean thinking as

- Specifying value by-product from the customers' point of view

- Identification of the value stream (value-added and non-value adding activities)
- Using a pull logistic approach and producing what is required at the right time
- Pursuing perfection through continuous improvements and refinement
- Improving the flow process by removing non-value-adding activities

Later on, in 1990, the name lean production was first used by John Krafcik in International Motor Vehicle Program (IMVP) and described the core functions of lean production as producing the maximum by using less of everything.

According to Diekmann et al. (2004), apart from the manufacturing industry, lean principles started making their way in other industries as well. The lean production theory and techniques were modified and expanded over the decades depending on the industry's requirements to make quality products. The software, aerospace, air travel, and shipbuilding industries put on extensive efforts for applying lean principles to improve profitability, quality and reduce waste.

2.4. Incorporation of Lean Production in Construction

With the core concepts of reducing the wastes, improving the value and flow processes, and improving the relationships between different parties, Lauri Koskela provided a guideline of using the basic principles of lean production to optimize construction processes and improving its performances (Koskela, 1993). Koskela in 1992, initiated lean production in the construction industry and formulated a production management paradigm for conceptualizing production in three complementary ways, namely (1) Transformation; (2) Flow; and (3) Value generation (TFV). According to Koskela et al. (2002), the inadequacy in conventional construction management is due to its non-reliance on TFV framework. In the traditional approaches of construction management like Design Bid Build (DBB) and DB, the project activities are further broken down, and later on, activities are further interconnected based on their logical relationships through a critical path diagram (CPM). The whole effort in managing the construction projects is exercised through central control and further measured using schedule and cost benchmarks. In the whole process, management of workflow and creation and delivery of value is never focused upon, resulting in some serious failures. Lean production and TFV theory have led to the birth of LC as a discipline that incorporates the transformation-dominated contemporary construction management by inculcating the aspects of value and flow into the system. Since 1990, the construction industry is trying to use lean principles for improving its productivity, quality, and performance. Apart from Lauri Koskela, many other researchers and industrial evaluations of construction performances have recommended the use of lean principles in construction to improve its performances and productivity. Glenn Ballard and Gregory Howell did significant attempts in introducing lean production in construction using the name LC. Series of articles were published that emphasized the role of using lean within the construction (Ballard and Howell, 1993 and 2004; Howell and Ballard (1994a and 1994b). Later on, John Egan published a complete report namely “Rethinking Construction (Famously known as The Egan Report)” in the United Kingdom in 1997 and criticized the construction industry as being underachieving with a lot of wasteful and inherited inefficient practices thereby necessitating dramatic improvements effort to change from its traditional approach (Egan, 1998). The report applies the lessons of manufacturing revolutions to the construction industry and suggested methods that closely relate to the lean production theory. More recently, the reports published by the World economic forum, (2017) and CLMA (2016) further emphasized the use of lean construction for overcoming its challenges. At present, the “Lean theory” and “lean applications” for construction design, procurement, and production functions have received significant attention in many quarters around the world.

2.4.1. Historical Development of Lean Construction

The roots of lean construction go back to the early 1990s when Koskela introduced a lean production system to overcome challenges of construction by applying the tripartite view of production as TFV. Based on the realization of tremendous wastes that existed in the construction industry, lean production tools like JIT, TQM, Kanban (KAN), and TQC were considered to be the essential elements that should be considered in construction (Koskela 1992; Abdelhamid and Salem, 2005). In 1993, the IGLC was formed to streamline the procedures, practices, tools, and theoretical/practical introduction of lean production in construction. During that period implementation of lean construction started at a very minimal scale mostly on an experimental basis for developing lean production tools derived from manufacturing into the construction industry. Resultantly, in 1994, a very comprehensive and state-of-the-art tool "Last planner system" (LPS) was developed by Ballard (1994) to meet the construction requirements and bringing reliability to the planning function. The massive need for applying lean production tools was realized once the Egan report was published in the United Kingdom in 1998. With the formation of the LCI in 1997, the construction industry found a central platform to practice, improve, and integrate the idea of lean into construction. With the development of the Last planner delivery system (LPDS) by Ballard (2000), the construction industry seemed to be set in implementing the lean within a complete construction environment (design – construction).

However, in the first few years, the focus remained on developing the concept of LC, identifying the differences between the manufacturing and construction industry, applicability, and identification of lean production tools for construction, and developing the frameworks for implementing LC. Later on, Koskela and Howell (2002) emphasized the importance of the flow aspect that should be given more attention during the planning and construction phase. The main focus remained on maximizing the value and minimizing the waste in the construction (Bertelsen 2004). The guiding principles of lean construction were formulated in more detail by the construction industry institute (Diekmann et al 2004; Ballard et al.,2001).

Based on the guiding principles, different lean construction tools were identified and frequently tested in construction projects from 2000 to date. The results from the case studies, practical implementations of lean construction were made public, and seeing the remarkable improved performances, many construction firms started implemented lean design and construction. With time, LC adopted new and innovative approaches like BIM/Virtual design and construction (VDC) (Khanzode et al., 2006; Sacks et al. 2010), integrated project delivery (IPD) (Matthews and Howell, 2005), prefabrication (PREFAB) (Bjornfot and Sarden 2004; Jaillon, & Poon, 2009) and modular construction (MOD) (Bertelsen, 2005) to facilitate its implementation and meet its principles. More recently the use of the internet of things (IoT) is being explored to further automatize the LC processes (Dave et al. 2016). Digitalization of LC tools like Digital Kanban boards (Liu and Shi, 2017) and the use of the immersive medium of virtual reality are further making their way into the tool list of LC. The historical development of LC is also shown in figure 2.1.

Over 30 years, LC has experienced some significant successes after being implemented. However still, it is an emerging trend that has to be refined so that more and more construction companies can easily adopt and implement it. It is a matter of fact and agreed by several researchers that lc has the potential to overcome the challenges being faced by the construction industry. Presently, more research is underway in developing robust implementation frameworks to facilitate the potential lean users for lean implementation.

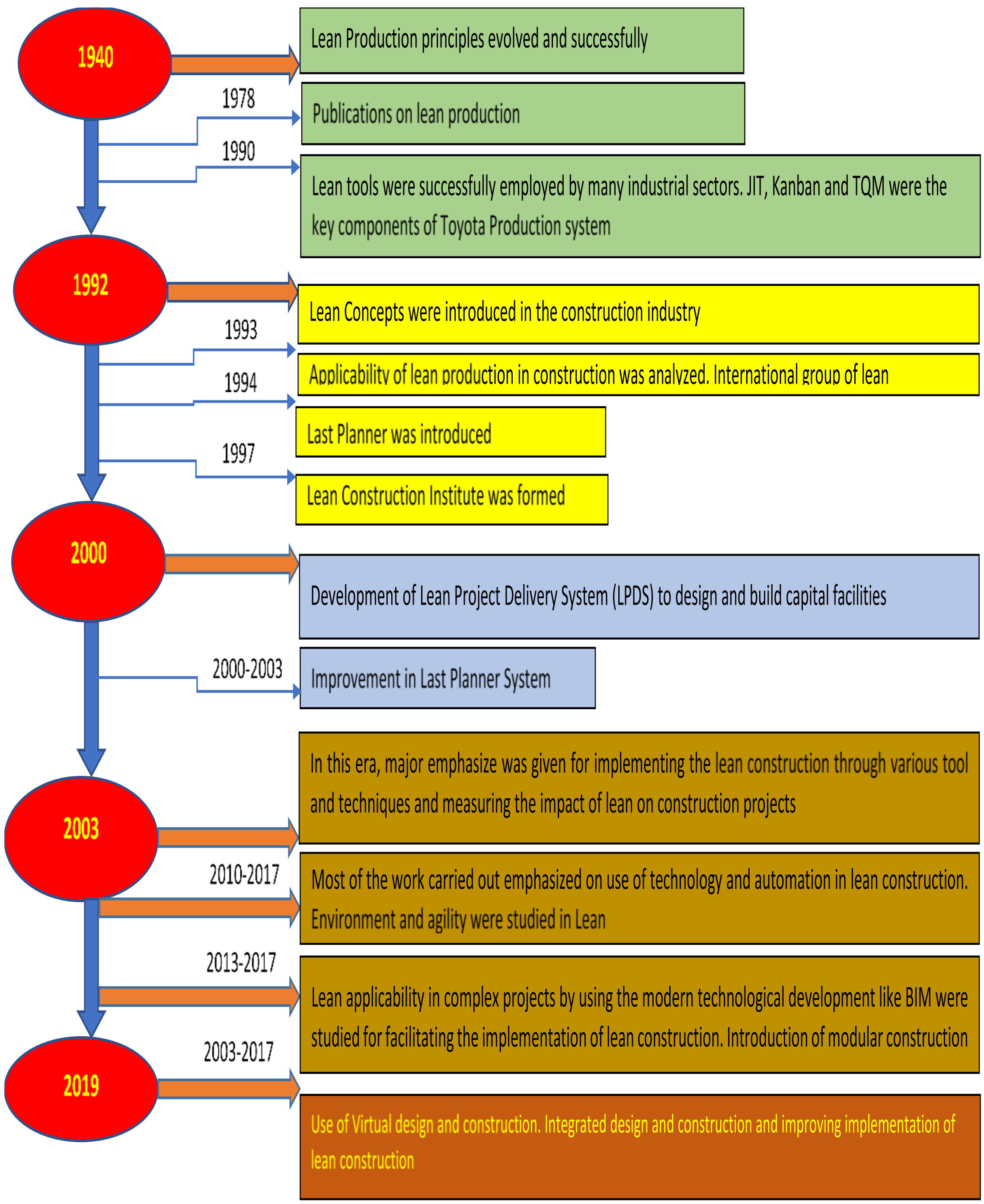

Figure 2.1. Historical development of lean construction

2.4.2. What is Lean Construction?

Initially, the concept of LC was started for improving the workflow, meeting the customer's requirements most efficiently, and removing the waste from the construction process/materials. The inspiration for applying LC came from lean production, however, with the growing interest and users of LC, the definition of LC assumed various transformations and extensions (Mossman, 2018). According to the author, with the widespread implementation of LC around the world, varieties of definitions of LC exist to include practices emerging from within the communities. Few of the authenticated definitions of LC definitions frequently cited by the researchers are shown below.

According to Howell (1999), "*Lean construction results from the application of a new form of production management to construction. Essential features of lean construction include a clear set of objectives for the delivery process, aimed at maximizing performance for the customer at the project level, concurrent design of product and process, and the application of production control throughout the life of the product from design to delivery.*

A simpler definition of LC was later on presented by Koskela et al. (2002) as "*a new way of designing the production systems by minimizing the waste of time, material and effort for generating the maximum value".*

According to Diekman et al (2004), LC was defined as "*the continuous process of eliminating waste, meeting or exceeding all customer requirements, focusing on the entire value stream, and pursuing perfection in the execution of a constructed project."*

More specifically Abdelhamid (2013) further extended the definition of LC as "*A holistic facility design & delivery philosophy with an overarching aim of maximizing value to all stakeholders through systematic, synergistic & continuous improvements in contractual* *arrangements, product design, construction process design & methods selection, the supply chain and the workflow reliability of site operations*."

According to Mossman (2018), lean" is *a practical collection of theories, principles, axioms, techniques and ways of thinking that together and severally can help individuals and teams improve the processes and systems within which they work".*

According to the AGC of America lean forum*, "Lean Construction is based on the holistic pursuit of continuous improvements aimed at minimizing costs and maximizing value on a construction project: planning, design, construction, activation, operations, maintenance, salvaging, and recycling".*

LCI defines LC as "*a respect- and relationship-oriented production management-based approach to project delivery—a new and transformational way to design and build capital facilities".*

From these definitions it can be seen that researchers have tried to highlight five important aspects within LC definition: (1) it's a new form of production management, (2) aims, and objective of LC like waste reduction, maximizing value, meeting customers' requirements, workflow reliability, (3) A synergy of different philosophies, techniques/methods (4) Respect for people, and (5) Pursuing perfection through continuous improvement. Most of the researchers have tried to include these five terms in their definitions independently. These five aspects were also mentioned frequently in a detailed analysis carried out by Mossman (2018) in providing the guidelines for developing the LC definition.

For the sake of this study, a certain modified form of LC definition is developed to cover all these five aspects as

"Lean construction is a new way of production management which synergistically integrates different theories, principles, and techniques for reducing wastes, maximizing value, meeting customer's requirements by reducing workflow variabilities and non-value adding activities in a collaborative, respectful and people-focused environment."

2.4.3. Lean Construction Principles

LC principles are mostly derived from the principles of lean production**.** Womack and Jones (1996), Koskela (1992), Liker (2004), and MacInnes (2002) have significant contributions in identifying the principles of lean production based on the theoretical concepts.

Based on the lean production principles, major contributions in developing LC principles were formulated by researchers like Diekmann et al. (2004), Sacks et al. (2010), and Ballard et al. (2001). The detailed principles are shown in table 2.2.

Table 2.2. Lean construction principles

Lean construction principles	**Diekmann et al. (2004)**	**Sacks et al. (2010)**	**Ballard et. al. (2001)**
Customer Focus			
Meet the requirements of the customer	x	x	x
Define value from the viewpoint of the customer (project)	x	x	x
Use flexible resources and adaptive planning	x	x	x
Cross-train crew members to provide flexibility	x	x	x
Use target costing and value engineering	x		
Consider all options		x	
Ensure requirement flow-down		x	
Verify and validate		x	
Culture/People			
Provide training at every level	x		x
Encourage employee empowerment	x		
Ensure management commitment	x		
Work with subcontractors and suppliers to regularize processes and supply chains	x		x
Cultivate an extended network of partners		x	
Decide by consensus		x	
Use multiskilled teams		x	
Workplace Organization/ Standardization			
Encourage workplace organization and use of the 5S's	x		
Implement error-proofing devices	x		x
Provide visual management devices	x	x	x
Create defined work processes for repetitive tasks	x	x	x
Create logistic, material movement, and storage plans that adapt to changes in workplace configuration	x		
Go and see		x	
Waste Elimination Part I (Process Optimization)			
Minimize double handling and worker and equipment movement	x		x
Balance crews, synchronize flows	x	x	x
Remove material constraints, use kitting, reduce input variation	x		
Reduce difficult setups and changeovers	x	x	x
Reduce scrap	x		x
Use TPM	x		
Visualize production process		x	
Use only reliable technology		x	
Waste Elimination, Part II (Supply Chain)			
Institute JIT delivery, supply chain management	x	x	x
Waste Elimination, Part III (Production Scheduling)			
Use production planning and detailed crew instructions, predictable task times	x		x
Implement the last planner/reliable production scheduling/short interval production scheduling/ Pull approach	x	x	x
Practice last responsible moment/pull scheduling	x		x
Use small batch sizes, minimize WIP	x	x	x
Use decoupling linkages, understand buffer size and location	x		x

Table 2.2. Lean construction principles (continued)

Lean construction principles	**Diekmann et al. 2004**	**Sacks et al. 2010**	**Ballard and Koskela et. al. 2001**
Use parallel processing		x	
Waste Elimination, Part IV (Product Optimization)			
Reduce parts count, use standardized parts	x	x	x
Use pre-assembly and prefabrication	x		x
Use preproduction engineering and constructability analysis	x		x
Visualize production methods		x	
Simultaneous design of product and process			x
Continuous Improvement and Built-In Quality			
Prepare for organizational learning and root cause analysis	x	x	
Develop and use metrics to measure performance; use stretch targets	x		
Create a standard response to defects	x		
Encourage employees to develop a sense of responsibility for the quality	x		

It can be seen from Table 2.2 that the main principles of LC are directed to 1) maximize value by meeting the customers' requirement, 2) reducing the waste through process/production optimization and maintaining the flow, 3) improving standardization of processes and workplace organization, 4) involving and empowering the employees, 5) creating a culture that has the capability of achieving the perfection through continues improvement and 6) developing a mindset for generating the quality product. Most other researchers have used almost similar LC principles in evaluating the conformance of LC within their projects/institutions (Ballard et al, 2007, Tezel and Nielsen, 2013; Aslam, 2013; Young et al., 2016).

2.5. Lean Construction Tools and Techniques

Implementation of LC as a philosophy emphasizes the use of different tools and techniques mostly adopted from the manufacturing industry. Ballard (1994) introduced the *Last Planner System (LPS)* as the most formidable technique in achieving the goals of LC. The LPS emphasizes the role and contribution of the last planner in planning where the last planner is a person who is responsible for the completion of its production unit/individual task at the operational level (Aziz and Hafez 2013). Two important tools used in the LPS are the pull approach and percent plan complete (PPC). Where the pull approach is explained later in this section, PPC is the measurement method to evaluate the percentage of tasks completed over the week (tasks completed in a week/tasks planned in that week). Continuous improvement is achieved by measuring, analyzing, and recommending suitable actions to improve the PPC.

Visual Management (VM) is a tool for improving both vertical and horizontal communication to control the processes and provide transparency in terms of achieving the goals within the target set by the planners. It is usually achieved by displaying different sign postings showing progress charts, cost and schedule updates, weekly targets, and safety vision, and many others. In some cases, the 3D and 4D drawings displayed for specific activity can be more beneficial for the workforce to visualize the methods for efficient completion (Tan et al., 2003; Valente et al., 2017). *Daily huddle meetings (DHMs)* provide the necessary platform in which all team members can share their views, work in harmony for the eradication of problems being faced daily through their experiences. It serves as a motivational platform for the workers as well as helps in improving the work processes (Ballard and Zabelle, 2000). *First Run Studies (FRS)* is used to reform the critical works to improve the work processes by redesigning and streamlining the different tasks involved. Video files, photos, and graphics are commonly used in which the first run of few selected operations are examined in detail for suggesting the refined or alternate ways of doing things more efficiently (Salem et al., 2005; Salem et al., 2006). Plan Do Check Act (PDCA) cycle is used to develop the FRS. “Plan” means selection and analysis of respective work process through the people involved, “Do” means to try out the idea on the field as a first run, “Check” refers to measuring the outcome and redesigning the shortcomings. During “Analysis” all team members are again gathered for communicating the improved method along with the performance standards required to achieve. *5S* is a tool used for reducing wasteful activities especially related to material management by utilizing five levels of housekeeping as Sort, Straighten, Shine, Standardize, sustain (Abdelhamid and Salem, 2005; Ajay and Sridhar, 2016). “Sort” refers to the separation of needed tools/materials and removing the undesired tools/materials. “Straighten” is the arrangement of tools/materials in an organized manner. “Shine” means to clean the places kept for tools/materials. “Standardize” refers to maintain the 3S previously discussed. “Sustain” is to develop the habit of conforming to the rules. It is used to economize the workspace and also helps in reducing the lead time. *Fail-Safe for quality and safety (FSQS)* is a tool used for preventing defective parts from flowing into the system by early detection. In construction, it aims at stopping certain processes once some malfunctioning is observed. It is achieved by either using *Poka Yoka (PY)* devices or detailing certain people to look for and report that malfunctions immediately. It can be extending to safety by early detection of hazards as well (Abdelhamid and Salem 2005, Salem et al. 2005). *Six Sigma (SS)* is used for the reduction of process and production variabilities by utilizing a statistical approach in identifying and eradicating the defects in the processes. It eliminates the root cause of defects and increases the efficiency of production planning (Abdelhamid, 2003; Beary and Abdelhamid, 2006; Han et al., 2008). There are two approaches used to perform SS applications on the projects namely DMAIC and DFSS. Define, Measure, Analyze, Improve and Control (DMAIC) is a recommended approach for an already established process requiring improvements. Define for six Sigma (DFSS) is an approach recommended for newly established procedures. *Kanban* (KAN) is a lean approach developed by the automotive industry to pull materials through the production system on just in time basis. This is an important tool used in LC for pulling the material/products at the right time to reduce the wastes of storage, waiting, overproduction, etc.

Pulling of material is functionalized by using the KAN cards displaying the type of material, the quantity used, quantity required, and location along with dates (Arbulu et al., 2003; Jang and Kim, 2007; Burgos and Costa, 2012). *Just in Time (JIT)* is a concept used in LC for improving the material flow and reducing material/product wastes due to storage, overproduction, and handling. It is an effective tool for managing the inventory and uses the KAN system to make the flow continues. The main concept of JIT is the delivery of the material at the right quantity, at the right time and location (Ballard and Howell, 1995; Bamana et al., 2017; Polat and Arditi, 2005). *Kaizen (KAIZ)* is a tool used for the continuous improvement of the complete system. It helps in improving the process and eliminating waste by analyzing the specific aspects of the tasks in harmony with the outputs from different multidisciplinary teams. Normally fishbone diagrams, Pareto charts, 5 whys, PDCA cycles are used for analysis purposes (Shang and Sui Pheng, 2014). *Concurrent Engineering (CE)* is parallel execution of both design and construction by involving all the project stakeholders until the completion of the project. Multidisciplinary teams are grouped for performing parallel tasks to achieve improved functionality, quality, and production. In lean, it assumes the primary importance once all the stakeholders are involved in the project at the early stages of the project design to minimize future conflicts (Anumba et al., 2002). To reduce the demand variabilities of the products, *Prefabrication/ Modular Construction (PREFAB/MOD)* is a rapidly growing technique that has resulted in a tremendous reduction of lead times and complexities in the production system. It involves the prefabrication and preassembling of certain components of construction at places away from construction sites thereby transporting the material to the site by using the JIT approach (Ballard and Arbulu, 2004; Bjornfot and Sarden, 2006). Similar to FSQS, *Poka Yoka (PY)* devices are used for early detection of defects by signaling anything wrong in advance to stop the production line until the faults are corrected. This will ensure that no malfunction component enters into production line which can damage the complete line in the future (Tommelein, 2008). Another tool used in lean environments for improving the flow by reducing the constraints is the *Theory of Constraints (TOC)*. In this tool, constraints are determined in the flow of value-adding work that is hindering the production system (Carneiro et al., 2009; Santos et al., 2012). The constraints are then minimized through collaboration resulting in the development of a new process that will determine the rate of production in the future.

LC also emphasizes the establishment of standardized processes for repetitive activities to reduce the uncertainties in the execution of the respective processes. The activities are optimized through continuous analysis. *The standardized processes (SP)* help in providing the stability in processes execution and maintaining continuous flow (Aapaoja and Haapasalo, 2014).

The hallmark of the lean construction philosophy revolves around the collaboration and early involvement of all key project stakeholders so that visualization can be improved and further conflicts are eradicated. *Integrated Project Delivery (IPD)* is the most recent inclusion of project delivery techniques in the LC philosophy for providing optimized efficiency within the projects. It emphasizes the elements of collaboration and trust among all the parties by binding them into a relationship in which pains and gains are shared among all (Matthews and Howell, 2005; Khanzode et al., 2005). It utilizes tools like set-based design and concurrent engineering for making an efficient integrated supply. *Set-based design (SBD)* helps in preventing conflicts within design and construction by developing multiple design alternatives in collaboration with those who have to execute the respective task (Parrish et al., 2008). Alternatives are discussed, analyzed, and optimized by the teams for optimal solutions. It helps in avoiding rework and promotes institutional learning.

To stabilize the cost of the final project within the desired limit, lean philosophy advocates the implementation of the *target value design (TVD)*. It is more of a cost-predicting tool in which the Client's value is given the prime importance in setting the cost of the final project (Do et al., 2014). After establishing the cost, the design and planning are carried out to achieve the best possible product within the targeted cost already set. It also enforces the concept of value engineering in determining the best possible value within the constraint of the cost.

The main focus of LC is always on the reduction of wastes by removing or diminishing the effects of non-value-added activities within the complete production system. Segregation of non-value added activities which are not contributing anything in the processes is carried out by using the *value stream mapping (VSM)* in which all the process are further analyzed by breaking them into smaller components with details of the value-added activities and non-value added activities (Desai and Shelat, 2014; Pasqualini and Zawislak 2005). The non-value-added activities that are considered to be deemed necessary are optimized to reduce their effect on the production system. The current state of executing the processes is identified and after the removal of all non-value-added activities, the future state is visualized which refines the processes with minimum wastes.

Another very important tool for simplifying the implementation of LC is the use of visualization tools like *BIM* (Sacks et al. 2010). With the advent of BIM technology, the visualization process is effectively utilized as BIM provides a link between the design and construction by duly incorporating the aspects of cost, time, quality, and safety of the project. Incorporation of BIM at the early stages of design in collaboration with all the key stakeholders involved in the construction provides a platform for rapidly implementing various concepts of LC. BIM provides an excellent platform to visualize the compatibility of the construction with the design even before the start of the construction.

In summary, many tools and techniques can facilitate the implementation of lean construction during various stages of construction. Although LPS, TVD, SBD, JIT, VDC, VM, TOC, KAIZ, SP, SS, IPD, TQM, and CE are various lean implementation techniques having their independent tools, most of the lean researchers have also considered them as an independent tool. As an example, pull approach, reverse phase, lookahead, and weekly scheduling are common and inherent tools used in LPS. KAN or 5S or can be used as one of the tools for ensuring the smooth implementation of JIT. BIM either can be used independently or as a tool for virtual design and construction (VDC). The name tools and techniques are commonly and interchangeably used for every method that facilitates the LC implementation process. In this dissertation, tools and techniques mean, all those tools, techniques, and systems that can be employed independently to facilitate lean implementation.

2.6. Benefits of Lean Construction

The main benefits of using LC are (1) to reduce wasteful practices, (2) value addition, and (3) optimization of the construction processes. It will help the owners in completing their projects to the best of their expectations and requirements, facilitates architects/engineers in developing the plans that are constructible, understandable, and later on meet the least number of change orders. It can facilitate constructors in efficiently planning and utilizing the resources by minimizing/removing the non-value-adding activities/wastes from their practices/materials and improving productivity. According to Diekmann et al. (2004), LC practices have the potential to reduce essentially non-value adding time and minimizing wasted time. Reducing waste and non-value-adding time will improve construction productivity. According to Warcup (2015), large productivity improvements can be achieved by optimizing existing processes, for instance, could reduce completion times by 30% and cut costs by 15%. In the end, the final product can be made within the budget and time that best meets the customer's requirement. The lean theory explicitly explains the procedures, methods, and protocols that can help the project participants to overcome all the challenges that lead to low construction performance.

The theory can only be reliable if it is successfully implemented by the users. Over the period, the construction industry has experienced some successful implementations of LC. A very detailed survey carried out by McGraw Hill (2013) found that apart from schedule and cost savings, significant improvements in increasing the overall competitiveness were observed by the lean users. Moreover, it was also found that the construction firms that have used lean practices have attained better quality during the projects. Agbulos et al. (2006), Mao and Zhang (2008), and Locatelli et al. (2013) observed the increase in productivity by using LC techniques in managing the projects. Whereas, others, experienced time and cost savings due to LC (Conte and Gransberg, 2001; More et al., 2016; CLIP, 2006). According to Ballard et al. (2007), PPC was improved from 62% to 84% and the overall cost of the project was reduced by 6.4% using LC practices, in a tunneling project. Similarly, Locatelli et al. (2013) reported an increase in productivity ranging from 5 to 50 % in 19 different projects undertaken using the lean philosophies. More et al. (2016) explored LC efficacy in residential projects and found a reduction in the project schedule by 25%. Dallasega et al. (2016) observed labor-saving of 8% compared to the initial estimate once LC practices like LPS and pull approach were applied in an expansion of hospital project. According to Erol et al., (2017), the application of LC can result in a reduction of approximately 10% of the total duration of the project and with a significant impact in reducing the variability in time duration. Ballard (2008) reported two case studies in which considerable reduction in project cost and time was observed by applying the lean project delivery approach. In one of the case studies, the project was completed 3.5 months ahead of schedule with a cost that was 14.6% below the target cost. In another case, the target cost was reduced from the benchmark cost by 14.1%, however, the project was even completed at a cost that was less than 5.4% of the target cost. Alarcon et al. (2005), analyzed over 100 projects to check the efficacy of LC in Chile. The author reported an improved performance within a range of 7% - 48% along with improved reliability of planning and PPC. According to Nowotarski et al. (2016), the use of LC practices helped in avoiding substantial costs due to efficiently assessing the risks and finding solutions. Dodge Data Analytics conducted a study from the inputs of 162 owners to demonstrate that lean intensive projects are 3 times more likely to be completed ahead of schedule and 2 times more likely to be completed under budget. Moreover, the study further demonstrated that projects with the best performances were following the lean methods (Mace, 2016/LCI-Dodge data-analytic)

Apart from the performance benefits, many LC firms have observed intangible advantages like improved customer satisfaction (McGraw Hill, 2013, Aziz and Hafeez, 2013; Babalola et al., 2019) and improved relationship between partners (Young et al., 2016; Mesa et al., 2019) and better safety performances (Wu et al., 2019; Moaveni et al., 2019, Howell et al., 2017).

Besides many researchers have highlighted the efficacy of LC individually, there are many well-renowned forums like the World economic forum (2017), Association of general contractors (AGC), and Project management institutes (PMI) that are strong proponents of using LC at construction projects. Egan's report (1998) has further highlighted the use of lean philosophies to overcome the wastes and inefficiencies in the construction industry. According to World Economic Forum (2017), the construction industry needs a better adaptation of present innovative solutions that can be applied at larger scales and has the potential of providing new ways of collaborating, sharing information, and reducing the non-value adding / wasteful practices. The forum suggested the use of lean techniques in improving existing construction practices. Other data collection and analytic forums like Statista, Dodge, and analytics and McGraw-Hill performed the studies and emphasized using LC to manage the construction projects (McGraw Hill, 2013; Statista, 2019, b; Mace 2016/LCI- Dodge and analytics 2016).

2.7. Presently Available Factors Leading to Successful Lean Construction Implementation

To implement LC successfully, Ballard and Kim (2007) presented 14-step implementation guidelines for launching a lean journey through inputs from the lean companies, and further suggested 11 recommendations for successfully implementing it on capital projects. Ballard and Kim (2007) identified that selection of right partners, engaging downstream players, target costing, set-based design, encouragement and confidence to lean teams, pull production, in build quality and safety, just in time procurements, first-run studies and computer modeling plays an important role for successful implementation of lean construction. 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. Salem et al. (2006) conducted a case study to evaluate the implementation of six lean tools (LPS, FSQS, 5S, DHM, FRS, Increased visualization) based on the lean assessment model. The assessment tool provided the guidelines for assessing and modifying the lean tools as per the results. Gao and Low (2014) presented the new framework for implementing LC based on the 14 principles of Lean production. The author provided the guidelines for implementing each principle in construction by applying different strategies along with the application of different lean tools and techniques.

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

Ballard et al. (2007) conducted interview sessions with different companies practicing LC and according to them, commitment, leadership, cultural and behavioral change are major critical factors for successful implementation of the LC. However, enhanced training and compatible contractual relationships can also impact positively in implementing LC. The early involvement of contractors or even subcontractors during the design and planning stage can be an effective start to the lean initiative.

Mostafa et al. (2013) conducted a literature review and provided a framework for the successful implementation of lean concepts in the manufacturing industry. According to the authors, resistance to lean improvement can be overcome through effective lean-related education and training programs. Understanding the lean tools and techniques will remove the inadequate application and ineffectiveness during their implementation. Similarly reviewing and analyzing the records of lean implementation will help in removing inefficiencies from the lean implementation procedures in the future. Assessing the outcome of lean tools has been continuously referred to as a key factor for successful implementation (Mostafa et al. 2013, Ward

2015, Ayarkwa et al. 2011). Lessons learned from the past implementation must be recorded after due analysis of the results. It will benefit in refining the LC practices and helps in implementing the lean as a long-term strategy.

Cano et al. (2015) carried out a structural analysis using a crossed-impact matrix in determining the barriers and critical success factors for LC implementation. Apart from identifying the 10 most critical success factors, the author believes that the success of LC depends on trustworthy and longtime relationships with the employees and the publication of the results. Simonsen et al. (2014) and Shou et al. (2016) stressed the true alignment of the lean tools concerning the objective of the processes. The selection of lean tools should be based on their compatibility with the construction process. According to Pavnaskar et al. (2003), the wrong appliance of lean tools will completely derail the whole lean-based initiative. A wrong selection of tools is due to the insufficient understanding of the lean tools and their implementation methodologies. Ward (2015) conducted a detailed evaluation of factors leading to the successful implementation of LC through interview sessions and came up with 13 critical factors. According to the author, construction firms that are newer to lean initiatives must utilize the services of the right facilitators for understanding and implementing lean practices. Similarly, companies shouldn’t be relying on one or two lean tools rather look forward to incorporating more tools. Pavnaskar et al.'s (2003) conclusion of using more than one tool is based on the statement that not all lean tools can solve the same problem and not all problems can be solved by a single tool. The selection of construction processes for lean improvement is another area that needs to be effectively monitored. As highlighted by Narayanamurthy and Gurumurthy (2014), the selection of process plays a key role in the successful implementation of lean concepts. Based on the literature review, the authors presented a framework for selecting the processes by considering seven factors that directly impact process selection. Significant factors include 1) unbiasedness in the selection of process, 2) ease to manage, 3) affordable, 4) acceptable to all, and 5) compatible with the lean tools. Lovatt and Shercliff (1998) also presented a similar model for selecting processes during engineering design. Empowerment to employees along with incentives is also considered as the key success factor in implementing LC practices. This will reduce the resistance to change by the employees and increase their motivation for effective implementation (Bashir et al., 2015; Kawish, 2017; Ayarkwa et al., 2011).

These factors found from the literature above are listed without ranking in Table 2.3. In summary, the major factors that are leading successful implementation are in a great variety, from project team commitment, tools selected, to early involvement and collaboration among project participants, as well as training and others. However, existing research and practice did not identify the level of implementation success of those factors; therefore, more investigation is necessary for this field.

Table 2.3. Summary-successful lean implementation factors

Factors	**References**
People Focused	
Top-level of commitment from all project teams, partners, and management	Enshassi et al. 2019; Warcup, 2015; Ayarkwa, 2011
Empowering employees for taking lean initiatives	Bashir et al., 2015; Kawish, 2017; Shang and Sui Pheng, 2014
Strong cultural and behavioral acceptance for lean	Sarhan, 2011; Ballard et al. 2007
Early involvement of all key project stakeholders	Kawish, 2017; Shang and Sui Pheng, 2014
Providing enough incentives for lean teams	Sarhan, 2011; Kawish, 2017; Shang, 2014; Ballard and Kim, 2007
Lean tools and techniques	
Correct selection and implementation of lean tools and techniques	Mostafa, 2013; Pavnaskar et al., 2003; Wards, 2015; Shou et al., 2016
Compatibility of lean tools with construction processes	Narayanamurthy and Gurumurthy (2014)
Appropriate selection of construction processes for lean intervention	Narayanamurthy and Gurumurthy, 2014; Lovatt and Shercliff, 1998
Relational	
Use of compatible contractual relationships/project delivery system	Nesensohn et al., 2012; McGraw-Hill, 2013
Establishing trustworthy partners	Nesensohn et al., 2012; Kawish, 2017; Shang and Sui Pheng, 2014; Cano et al., 2015; Ballard and kim, 2007
Increased level of collaboration across the board and teamwork	McGraw-Hill, 2013
Educational	
Provision of adequate opportunities for training and understanding lean tools and techniques	Mostafa et al., 2013; Sarhan, 2011; Shang and Sui Pheng, 2014; Enshassi et al., 2019; Kawish, 2017; Ayarkwa, 2011; Wards, 2015; Kanafani, 2015
Implementation and continuous improvement	
Use of latest information technologies like BIM for improving visualization and transparency in information sharing	McGraw-Hill, 2013; Sacks et al., 2010
Gradual implementation of lean	Kim and Park, 2006; Bashir et al., 2015; McGraw-Hill, 2013
Provision of adequate resources from the top management	Cano et al., 2015; Wards, 2015
Assessing lean outcomes and analysis for continuous improvement	Enshassi et al., 2019; Ayarkwa, 2011; Mostafa, 2013
Awareness	
Publication and presenting lean results in massive construction forums	Sarhan, 2011; Bashir et al., 2015

2.8. Present Status of Adoption of Lean Construction in the Construction Industry

Even though the theory of LC amicably supports the increased performance along with some successful implementations, the required boom for using LC by the massive construction industry is very sparse (Noor et al., 2018; Babalola et al., 2018; Bashir et al., 2015; Wandahl, 2014). According to McGrawHill (2013), out of a sample of 194, 48% were still not familiar with the broad overarching concepts of LC, even though 37% of the representatives were active members of the LCI. Similarly, 51% of the representatives have not used LC either because of unfamiliarity (22%) or even familiarity (29%) of lean concepts. Similarly, Balabola et al. (2018) found that although the awareness for LC is increasing, still around 50% (out of a data sample of 446) are not even aware of LC. Additionally, more than 50% have not used any of the LC techniques. According to Alves et al. (2012), presently the low rate of adoption of LC within the construction industry is because the industry practitioners are finding it difficult to fully diffuse the theoretical concepts into practice. The author emphasized the role of academia to bridge the gap of making the lean a more practical approach to engaging people in a more meaningful experience. Stevens (2014b) further highlighted that because LC has incorporated a large number of lean tools and techniques, thereby increasing the complexity of implementing LC for the construction industrial practitioners. Resultantly, the uptake of LC is low and not to the level as emphasized by the lean advocates. Stevens (2014b) further recommended that only those lean tools and techniques should be worked upon that are aligned well with the construction industry like the LPS, JIT, VM, and others.

As per Wandahl (2014), the rate of adoption of LC in the Danish construction industry seemed to be extremely low with only 6% (sample size 485) of the sampled respondents were using LC. Moreover, the author found that only 23% of the respondents were knowing Stevens

(2014). Similarly, in the UK Construction industry, the uptake of Stevens (2014b) is low as pointed by many researchers (Bashir et al., 2015; Mossman, 2009; Daniel et al., 2017). In a study conducted in the UK, only 14.7% (out of 55 samples) of the respondents used 70% of the Stevens (2014) techniques on their projects (Daniel et al. 2017). Ankomah et al. (2015) after surveying in Ghana stated that 90% of the respondents are not aware of LC practices like LPS, KAN, KAIZ, and 5S.

In summary, it can be said that the uptake of LC is low among the construction industry all over the world. LC could not excel as rapidly as envisaged initially Considering the potential of using LC as discussed in the above sections, there is a need to understand the barriers that are preventing the construction industry from using the LC techniques and then suggesting the measures that can help the construction industry in overcoming these barriers to increase its adaptation.

2.9. Why Lean not Taking Off

Although, LC organizations are working hard in introducing LC to the general construction industry through seminars, presentations, congress, and conference forums, sufficient awareness level for lean is not achieved (McGraw Hill, 2013; Wandahl, 2014; Bashir et al., 2015). Several reasons can be associated with this low rate of adoption of lean concepts in construction ranging from lesser understanding and poor implementation of lean tools to cultural/behavioral issues. Mossman (2009) explained 17 reasons why lean has not taken off in the construction industry. The major reasons included fragmented nature of construction, 1) the involvement of many sub/specialty contractors, 2) long term change and development, 3) resistance to change if companies are making profit through existing management techniques, 4) less time available for preparations, 5) limited knowledge and skills for lean. Arbulu and Zabelle

(2006) presented two major challenges that hamper the successful implementation of LC as (1) a lack of understanding about the lean and (2) lack of a distinctive framework for making the lean transformation happen. According to the author, the current approach to implementation of LC is wide and shallow because of which only pockets of excellence have been seen in construction. According to Fearne and Fowler (2006), most of the time, lean efforts failed because of the poor understandings of lean concepts. Resultantly, lean tools are either applied partly or wrongly that effected the performance negatively. The failures to achieve initial successes have also resulted in declined adoption of LC as it affects the morale and confidence of the project teams in favor of LC.

According to Johansen et al (2004), the construction industry has the inherent problem of maintaining the historic trends which puts a barrier on adopting the new management trends. Similarly, the dense dependence on other parties to seek self-optimization negatively supports the ideologies of LC. Presently, the industry is more skewed towards making profits instead of project optimization. This entails that the existing culture in the construction industry doesn't support lean in one way or the other. It is necessary to change the prevalent culture and mindset of the construction industry that should commensurate with the lean culture. Cultural changes are deemed necessary for the construction firms to adopt LC as a long-term strategy. According to Santorela (2017), 74% of companies that institute lean initiatives in the USA have seen little success and the major reason for these low performances is the lack of meaningful adoption of lean culture within the organizational environment. According to the author, the major barrier in achieving the successful implementation of LC is the lack of providing enough opportunities like empowerment and encouragement to the employees for adopting lean culture.

Lack of adequate awareness has been identified as one of the top barriers to adopting LC by many researchers (Sarhan and Fox, 2013; Simonsen et al., 2014; Jørgensen and Emmitt, 2008). Similarly, others have identified fear of failures or uncertainties associated with LC preventing the Construction industry from adopting Lean practices (Abdullah et al.,2009; Mossman, 2009; Warcup, 2015). Many lean practitioners have identified wrong or partial implementation (Mossman, 2009; Porwal et al., 2010) and lack of cultural acceptance for lean (Shang and Sui Pheng, 2014; Kim and Park, 2006) as main barriers which can result in failures of lean effort. Other researchers have also highlighted that the LC implementation process is very complex because of the amalgamation of many ideas and techniques that are increasing the confusion in implementing the lean in its true form (Green, 1999). Moreover, the implementation process is very slow and takes time to show positive results (Mossman, 2009; Carman et al., 2014; Fearne and Flower, 2006). Finally, the constructors are finding difficulties in achieving the rapid initial successes, as a result, the motivation level of the employees and management is not increasing in favor of the LC (Aziz and Hafez, 2013).

2.10. Summary of the Chapter

The detailed literature review as explained in this chapter further confirms that the problem/gaps identified and explained in chapter 1 are valid and must be explored to find solutions. With the rapid growth in the construction sector, it is expected that the construction industry has to oversee many challenges like shortage of skilled manpower, availability of materials and space, and shortage of funds. However, the dilemma is that along with the upcoming challenges likely to be encountered due to growth, there are still many inherent shortcomings within the existing construction practices like cost, time and productivity issues, environmental and sustainability problems, and adverse relationships. As a result, construction wastes are continuously increasing thereby reducing the construction performances. The existing construction management practices need to be improved to cope with the challenges otherwise there will be a further decline in construction productivity. LC developed from Lean production theories have already started to emerge as the robust philosophy with the potentials of improving the construction performances. LC as a philosophy has been explained in detail in the existing literature concerning its impact on reducing the construction challenges and also some of the successful implementations of LC further provided a strong basis for using the LC. LC principles and factors have been developed and further used in formulating the LC frameworks for implementing the LC. Similarly, many tools and techniques have been identified that can facilitate the implementation process of LC. However, despite all the theoretical explanations along with some successful implementations, the required uptake of LC within the massive construction industry is not very encouraging. Moreover, the construction industry is still struggling in implementing the LC due to a lack of understanding about LC and its tools and techniques, lack of robust framework for selecting the LC tools and techniques, lack of detailed and structured LC implementation framework and so many other barriers as discussed in this chapter.

It must be noted here that some of the information discussed in this chapter is also partially repeated in the upcoming chapters marked as red fonts. This is because of a fact that the coming chapters are compiled based on the individual papers covering each of the objectives and the contents of the papers in this dissertation are kept the same as those published/submitted in the respective journals.

3. PAPER 1: PERFORMANCE-BASED EVALUATION OF LEAN CONSTRUCTION TOOLS[1]

3.1. Abstract

The main purpose of this study is to acquaint the construction industry regarding the efficient utilization of lean tools and systems for successfully implementing lean principles and increasing the adoption rate of lean construction (LC). Lean principles and their corresponding functions are identified based on the theoretical explanation of LC philosophy in the literature. After developing the necessary relationship between principles and lean functions, the lean tools are further mapped with the relevant lean principles. To improve the uptake of LC, the benefits associated with each lean tool and system are reported by going through a systematic literature review and case studies. As a result of the performance-based evaluation, it was found out that almost every tool is contributing to impact the cost, time, and productivity but with different magnitudes. The majority of tools can improve performance by more than 10%. To implement all lean principles on a single project, a combination of tools has to be applied as not a single tool is found that can have the capability of implementing all the principles and functions. The outcome of this study has further added to the existing body of knowledge as it provided a detailed evaluation of how lean tools and systems can facilitate the implementation of LC principles in the performance of lean functions and how the implementation of lean tools and systems can impact the construction projects within the parameters of cost, time and productivity.

[1] The material in this chapter was co-authored by Mughees Aslam, Zhili (Jerry) Gao, & Gary Smith and under review in journal of Engineering, Construction and Architectural Management. Mughees Aslam had primary responsibility of conducting the systematic literature review and performing meta data analysis. Mughees Aslam was the primary developer of the conclusions that are advanced here. Mughees Aslam also drafted and revised all versions of this chapter. Zhili (Jerry) Gao & Gary Smith guided the study process, directed the framework of the paper and checked the data analysis as well as proofreading.

Keywords: Lean Construction, Lean tools, and system, Lean principles, Lean functions, Performance, Benefits

3.2. Introduction

Lean construction (LC) philosophy was introduced for improving the performance of the construction industry that was suffering from the dilemma of low productivity, cost, and schedule overruns as compared to other industries (Koskela, 1992; Aziz and Hafiz, 2013; Abdelhamid and Salem, 2005). The theory of LC further got the intention of the construction stakeholders after its successful implementation on some of the projects with very encouraging results in terms of productivity along with cost and schedule controls (Agbulos et al., 2006; Mao and Zhang, 2008; Locatelli et al., 2013; More et al., 2016).

Despite the fact, LC has been evolved as a robust theory with strong philosophies and also some successful implementations, the required uptake of LC within the construction industry is very low (Wandahl, 2014; McGraw Hill, 2013; Bashir et al., 2015, Bababola et al., 2018; Steven, 2014). According to Santorela (2017), 74% of companies that institute lean initiatives in the US have seen little success and also there is a lot of variation in the reported successes of LC implementations. Some organizations have witnessed improvements in the range of 1-20% (CLIP, 2006; Conte and Gransberg, 2001; Agbulous et al., 2006) while others also experienced more than 30% of improvements (Mao and Zhang, 2008; Locatelli, 2013). These variations reveal the fact that implementation of LC is not yet standardized and every organization is interpreting the implementation process as per their understandings. Resultantly, few organizations that follow lean principles in true spirit can achieve better outcomes than others.

To implement LC principles in true form, researchers have recommended many tools and systems that can facilitate the implementation of LC. These tools/techniques and systems have been frequently tested in construction and their results can be used as an effective way to motivate the construction industry in using LC. Inspired by the benefits of lean tools and systems, the construction industry can move towards implementing LC thereby increasing its adoption rate. Apart from motivating the construction industry, the effective implementation of lean principles on construction projects can be facilitated by using lean tools and systems. These tools and systems are specifically developed to target certain principles and objectives of LC and help in implementing the LC principles because their functionalities truly align with the LC functions (Ballard and Tommelein, 2016; Aslam et al., 2020a). Hence, LC tools and techniques can augment LC in two ways: 1) facilitating the construction firms in implementing lean principles, and 2) realizing the benefits of lean tools and systems, the uptake of LC can be increased.

However, the general understanding of the LC tools by the constructors in terms of their efficacy in implementing LC principles is not adequately explored. This results in a state of confusion and muddles among the constructors in deciding among the appropriate tool and often results in the misconception of the whole LC process (Stevens, 2014b; Li, 2011; Schweikhart and Dembe 2009; Green, 1999). There is a need for more empirical evaluation of LC tools based on the performance parameters that will benefit constructors in making the appropriate choice of the lean tool.

In this paper, an effort has been made in first classifying LC tools and systems based on their effectiveness in implementing the LC principles and functions. The classified tools are further evaluated based on their impact on performance parameters such as productivity, cost, and time. This research will provide a way forward to the construction contractors, in deciding their approach for the successful implementation of LC principles and further controlling the time and cost overrun issues along with productivity developments. The outcomes of this study will provide a new paradigm for constructors in making more concrete decisions for selecting the lean tools which can enhance their construction efficiency and help them in implementing the LC principles.

3.3. The Emergence of Lean Construction

Construction projects are always considered to be highly uncertain and volatile because they are undertaken in unfamiliar environments involving numerous specialty teams, mostly met the first time, working together to achieve goals of construction. This uncertainty leads to the production of enormous wastes both in the product and processes which at times are considered to be inherent in the construction projects. These wastes have not only resulted in cost and schedule overruns but also are the major source of declined productivity.

Over the past 40 years, the construction industry is striving hard for increasing its performance by utilizing different technologies and management philosophies. For example, by the rapid development of Computer-Aided Design (CAD) technology, the efficiency of drawings is improved but this development could not reduce design errors or change orders thereby making no substantial performance improvements that should optimize the construction process to reduce cost (Love et al., 2000). Similarly, design/Build (D/B) projects endeavored to reduce design errors and rework but could not improve the performance of construction projects due to many process variabilities (Becker et al., 2011).

Koskela in 1992, initiated lean production in the construction industry and formulated a production management paradigm for conceptualizing production in three complementary ways, namely (1) Transformation; (2) Flow; and (3) Value generation (TFV) (Koskela 1992). This tripartite view of production has led to the birth of LC as a discipline that incorporates transformation-dominated contemporary construction management. Several successful experiences have been witnessed after the implementation of the LC in projects. Locatelli et al. (2013) reported an increase in productivity ranging from 5 to 50 % in 19 different projects undertaken using the lean philosophies. More et al. (2016) explored LC efficacy in residential projects and found a reduction in the project schedule by 25%.

Agbulous et al. (2006) observed an increase in productivity ranging from 5 to 17% in crew-based operations for a drainage project by using computer simulation techniques and then validating the results on the ground. Because of the implementation of LC, percent plan completion (PPC) was improved from 62% to 84% by using the lean approach for a specialty contractor working in a tunneling project (Ballard et al., 2007).

3.4. Motivations for the Study

Since the inception of LC in 1992 and even with a good number of lean implementation successes in individual projects, still, the construction industry is not able to utilize the full benefits of LC. The major reason behind this lapse is the slow rate of adaptation as well as the ineffective implementation of LC by the construction firms (Stevens, 2014b; CLMA, 2016). To evaluate the slow rate of adaptability and ineffective implementation, several studies have been carried out to identify barriers to the effective implementation of LC in the industry. The major barriers identified are lack of knowledge about LC principles, inadequate implementation of LC, lack of managerial/Government level commitments towards lean, and use of inappropriate/partially implemented tools (Johansen et al., 2002; Bashir et al., 2010; Porwal et al., 2010; Sarhan and Fox 2012; Alarcón et al., 2011; Ayarkwa et al., 2011; Alinaitwe, 2009;

McGrawHill, 2013; Simonsen et al., 2014). According to Gehbauer et al. (2017), the biggest obstacles to lean transformation are unwillingness to change until forced, lack of institutional support, and the presence of corruption culture especially in underdeveloped countries which prevent the companies to follow the lean principles of transparency, customer value, alignment of interests, etc. Another obstacle to lean transformation is the general myth that lean transformation is a gradual process and construction firms have to wait for witnessing the significant successes/benefits. Construction firms find difficulties in achieving the rapid initial successes, as a result, the motivation level of the employees and management is not increasing in favor of LC (Aziz and Hafez, 2013).

To implement the LC philosophy, many tools, and systems are developed with a focus to minimize waste, improve workflow and increase value to the product (Ballard and Zabelle, 2000; Aziz and Hafez, 2013; Salem et al., 2005; Ansah and Sorooshian, 2017). Where several tools have been recommended, the dilemma is that which lean tool can best be utilized in implementing the principles of LC, is an area that is inadequately researched. Moreover, the use of lean tools in removing the obstacles of lean transformation also needs to be explored at organizational and project levels.

It is a common fact that the constructor's decision in using LC practices is largely tested and based on its impact on cost, time, and productivity. There is a great potential in increasing the uptake of LC if benefits associated with lean tools and systems are explored and made available to the construction industry in the form of different case studies. For the construction industry which is desperately looking forward to improving performances, this comparative analysis between lean tools can act as the main motivation for implementing LC. Presently, the benefits of individual lean tools are reported by different researchers but very few studies provide comparative data in which the benefits of all tools are presented. Ansah and Sorooshain (2017) tried to rank the 40 lean tools based on the criterion of project delays by using the interviewing technique from 11 experts of the industry and recommended CE as the most effective tool for controlling the project delays. Similarly, Salem et al. (2005) established a more detailed assessment of LC tools and compared six tools among themselves. As per Salem et al. (2005), the implementation of the LPS and DHMs caused a maximum increase in PPC in comparison to others.

Another problem is that mostly the tools are tested individually on projects or activities and measured for their impact on cost, time, and productivity (Stewart and Spencer 2006; Jang and Kim 2007; Pasqualini and Zawislak, 2005). Due to this individuality reporting of the benefits of the lean tools, the bulk of the construction industry could not fully access the benefits of all tools. Therefore, a comprehensive study explaining the benefits of all tools is necessary as it will provide a platform for the construction industry to realize the benefits of LC and resultantly will increase the uptake of LC.

The goal of this study is to identify efficient tools to increase the uptake of LC. The main objectives of this study are:

- Identifying lean tools that can be used as an effective method to implement the LC principle in the performance of functions
- Exploring the benefits of lean tools within the parameter of cost, time, and productivity.

3.5. Research Methodology

An extensive literature review is carried out in evaluating the performance of commonly used LC tools and systems in implementing LC principles through different conceptual journal papers and case studies. Moreover, the research is further extended in identifying the impacts of LC tools and systems based on the parameters of cost, time, and productivity. The majority of case studies are accessed from multi-sources such as the International group of LC (IGLC), American Association of civil engineers (ASCE), Science direct, and Elsevier. To achieve the objectives of this study, a qualitative and quantitative approach is used by extracting the data from the literature.

Qualitative analysis is carried out in three stages. In stage one, LC principles and their corresponding functions are identified based on the theoretical explanation of LC philosophy in the literature. In stage two, the relationship between LC principles and relevant lean functions is established to summarize the impact of LC principles in the performance of lean functions. In stage three, the lean tools and systems are further mapped with the relevant lean principles corresponding to the performance of lean functions. The outcome of this analysis will provide the capability of each tool and system in implementing lean principles and achieving lean functions.

A total of 112 research papers were referred to for understanding the lean tools and systems concerning LC principles and functions. The data was further analyzed qualitatively with the number of studies carried out for assessing the individual lean tool impact on the performance criteria of productivity, waste continuous improvement, safety, and quality. The number of studies for a respective lean tool in each area is summed up to further classify them within the fields of productivity, waste, continuous improvement, safety, and quality. The results will establish the most preferred and highly researched tools along with the area of improvement.

To report the benefits of lean tools and techniques, quantitative data regarding the cost, time, and productivity for each LC tool is collected from 143 case studies and further analyzed based on their mean impact. The outcomes of each lean tool as specified in case studies are converted into percentage change for standardization and comparison. Finally, LC tools are ranked based on the mean scores in all the categories of cost, time, and productivity. The Schematic view of the complete research methodology is shown in figure 3.1.

Most of the research on lean tools measures the Percent plan complete (PPC) for estimating the productivity of the lean tools whereas other studies only measured productivity as per its standard definition. This research utilizes the percentage increase or decrease in either labor productivity or PPC with the logic that both PPC and labor productivity are highly correlated (Liu et al. Ibbs 2010). However independent studies on PPC as workflow variation and labor productivity could yield a distinct result in both these fields.

3.5.1. Parameters of the Study

For this research, the impact of each LC tool on cost, time, and productivity is assessed for developing an efficient decision-making framework for the selection of the most appropriate lean tool. The reason for selecting these parameters are as under:

3.5.1.1. Cost and schedule

Generally, the success of a construction project is visualized in terms of economic benefits it offers to major stakeholders such as Contractors, Owners, Consultants, and customers. Major contributory factors in determining the economic benefits are cost and schedule adherence, safety compliances, and quality assurances so that costumer can utilize the benefits of the final products in the best possible way. However, for the sake of this research, only cost and time are considered because these two parameters have a direct impact in the minds of the constructors for making a prompt decision in going towards the lean especially in the early stages. Once the lean philosophy has to be accepted within the minds by considering the tangible benefits it offers in terms of cost and time, further explorations in terms of safety, quality, value, and continuous improvement can be made easy and, in the end, complete lean culture can be enforced. Another important aspect of grounding the decision on cost and time evaluations is the basis of most of the contracts in the construction industry which have the overall goal of cost and schedule compliances.

3.5.1.2. Productivity

As per the Project Management Institution, productivity in construction is often defined as the total output per labor hour. The output is generally taken as weight, volume, or length and the input resource is usually in cost of labor or man-hours. Because of the diverse nature of construction, a single index for the entire industry is neither meaningful nor reliable hence each project normally evaluated its productivity by using the basic definition of any output per labor hr. This is one of the basic measurement parameters used in determining the efficiency of the construction project. In most of the lean studies, the Percent Plan Complete is measured in terms of activities executed in a week divided by activities planned in the same week (Ballard, 2008; Ballard and Zabelle, 2000). Labor productivity was found to be positively correlated with the lean measurement tool of Percent Plan Complete (PPC), as a measure of the workflow (Liu et al., 2010). For this study, the data for productivity from the research studies were taken in the form of percentage change of either PPC or labor productivity. Productivity in construction is one of the leading contributors to ensure the timely and cost-effective completion of the projects and have a significant effect on the overall performance of the project.

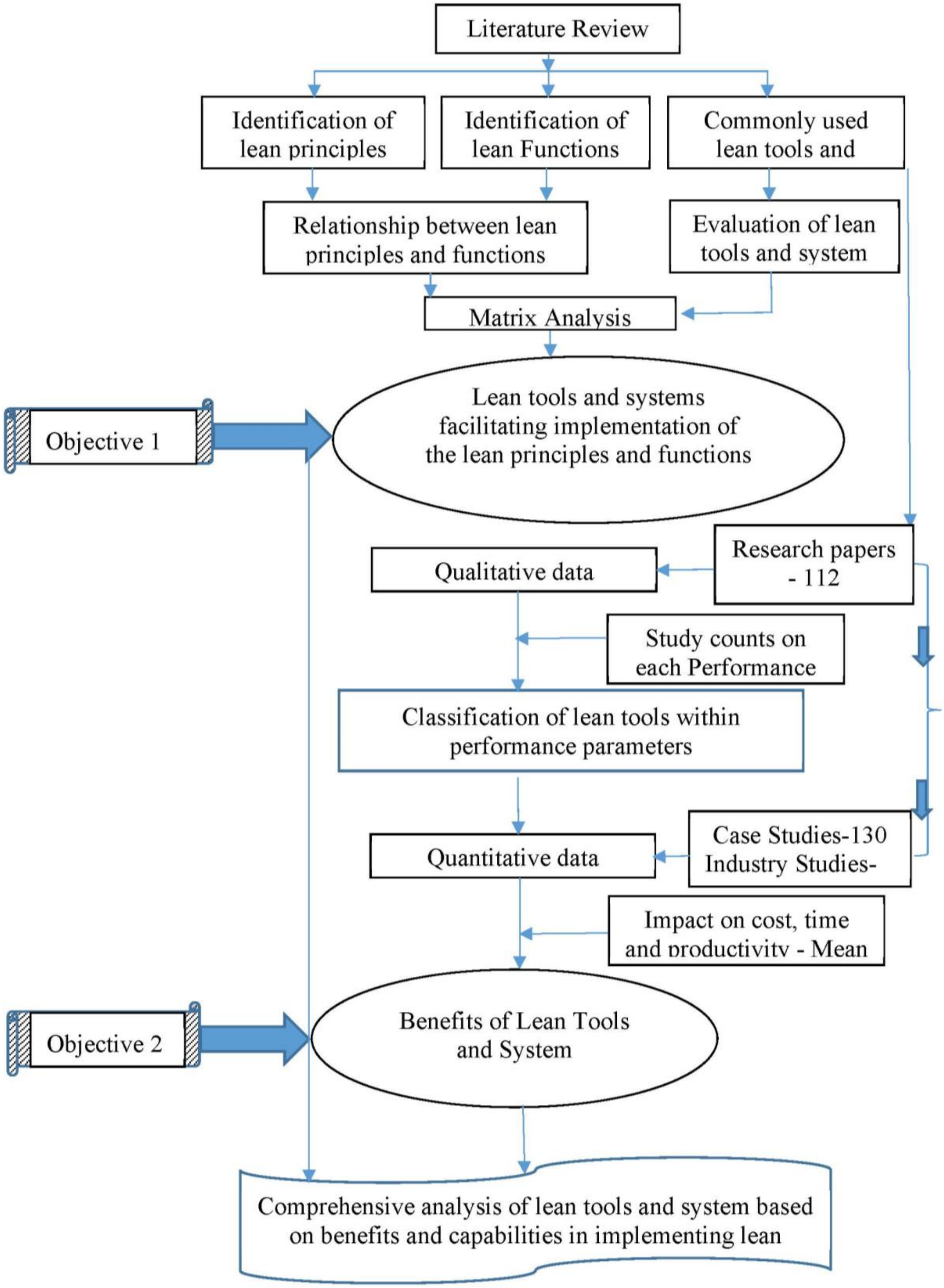

Figure 3.1. Research methodology for chapter 3

3.6. Lean Construction Principles and Functions

Based on the lean production principles (Womack and James 1996, Liker 2004), major contributions in developing LC principles were formulated by researchers such as Diekmann et al. (2004), Sacks et al. (2010), and Koskela (1992,2000). Koskela (1992) enumerated 12 principles of LC and further decomposed these principles within the three views of transformation, flow, and value (Koskela, 2000). Later on, significant work was carried out by the construction industry institute (2004) to constitute the principles of LC (Diekmann et al., 2004). Accordingly, five main and 16 sub principals of LC were formulated. Sacks et al. (2010) further enlisted the LC principles for further integrating these principles with building information modeling (BIM) functionalities. After going through the literature, the main LC principles are as follow:

- Reducing the share of non-value adding activities - A
- Reducing cycle times - B
- Reduce variability - C
- Increase flexibility - D
- Increase transparency-E
- Increase output value through systematic consideration of customer requirements - F
- Ensure requirement flow down - G
- Use visual management - H
- Build continuous improvement into the process - I
- People involvement - J
- 11.Organizational commitment - K

- Organizational learning - L
- JIT delivery - M
- Optimize work content, optimize production system, optimize production schedules - N
- Standardization - O
- Benchmark - P

Functions are the proper work of the system. As an example, the functions of the last planner system are extensively explored by Ballard and Tommelein (2016), and recommended several functions from specifying what tasks should be done when and by whom, to planning again and again, to learning from plan failures. Moreover, the authors highlighted the importance of other functions such as a focus on making work-ready, workflow reliability selection criteria for tasks, system transparency, and measurement of system performance.

The major contributions in identifying the lean principles and functions are carried out by researchers such as Koskela (1992, 2000), Ballard and Tommelein (2016), Sacks et al (2010), Mano et al. (2019), and Diekmann et al. (2004). Based on the efforts of researchers, the relationship between lean principles and functions is developed by identifying which lean function contributes to which lean principle and as shown in table 3.1.

Table 3.1. Lean principles Vs lean functionalities

S/No	Lean Functions	Lean Principles
	Making release of work between specialists reliable	B, C
	Learning from plan failures	L, I, N
	Specifying what tasks should be done when and by whom in each phase/milestones /activity	B, J, N
	Selecting tasks for daily and weekly work plans—deciding what work to do next	B, N
	Making scheduled tasks ready to be performed	B, C, N
	Recording data and Analysis_ Measuring planning system performance	I, L, P, O
	Making visible the current and future state of the project	E, H
	Re-plan as necessary to adjust the plan to the realities of the unfolding future.	C, N
	Identifying criteria for selection of tasks ready to be performed near term work plans	B, C,
	Develop long term relationships	J, N
	Manufacturing the material away from the construction site	B, C
	Reduce set up and changeover times	D, B
	Identification of Repetitive processes	O
	Brainstorming for identifying non-value adding activities and minimizing their effects	A, N
	Removing conflicts in design and construction collaborate	A, B, C
	Daily involvement of crew	J, N, G
	Ensure that every stakeholder have mutual goals	K, J, A
	Plans made with the collaboration of all parties involved in the construction	J, C
	Simultaneously designing and construction	N, B
	Develop multiskilled teams	D, B 2010)
	Develop and use metrics to measure performance; use stretch targets	I, P, O, L
	Reduction in inventory	M, B, C
	Provide employee empowerment	J
	Reduce batch sizes	M, B, D
	Visual Signs, presentations	H, N, E
	Breakdown of the complete project into phases /milestones /activities	B, C
	Decide by consensus, consider all options	J, N, G, k, C, D
	Define value from the viewpoint of the customer (project)	F, G
	Use target costing and value engineering	F
	Minimum storage of material at the site	M, B
	Minimum movement of materials and manpower	M, B
	Arranging the stores and material based on priority and ease in discovery	B, C, N, M
	Pull Approach and reverse planning	B, C
	Documenting the processes, methodologies, and planning	O
	Increased visualization of the project using soft wares	H, G, F, E
	Utilizing technology for rapid generation of different options and plans	B, H, N, O, D
	Improve communication among partners	C, K, J
	Developing an early warning system for indicating the malfunctions and defects	C, B
	Risk Assessment	C
	Conduct root cause analysis	B, N, C
	Parallel production	B, C
	Maintain workable backlog; a backlog of ready work (tasks ready to be executed)	B, C
	Schedule Buffer	B, N, C
	Reveal and remove constraints on planned tasks	C
	Cultivate an extended network of partners	J, N
	Getting quality right, the first time (reduce product variability)	C, N
	PDCA	N, I, L
	Focus on concept selection	F

To further summarize, out of 48 lean functions identified, the bulk of the lean functions directly contribute to principles such as reducing lead time, reducing variabilities, and optimizing work content and production system/schedule as 22, 21, and 17 respectively. The contribution of other functions to respective lean principles is shown in figure 3.2.

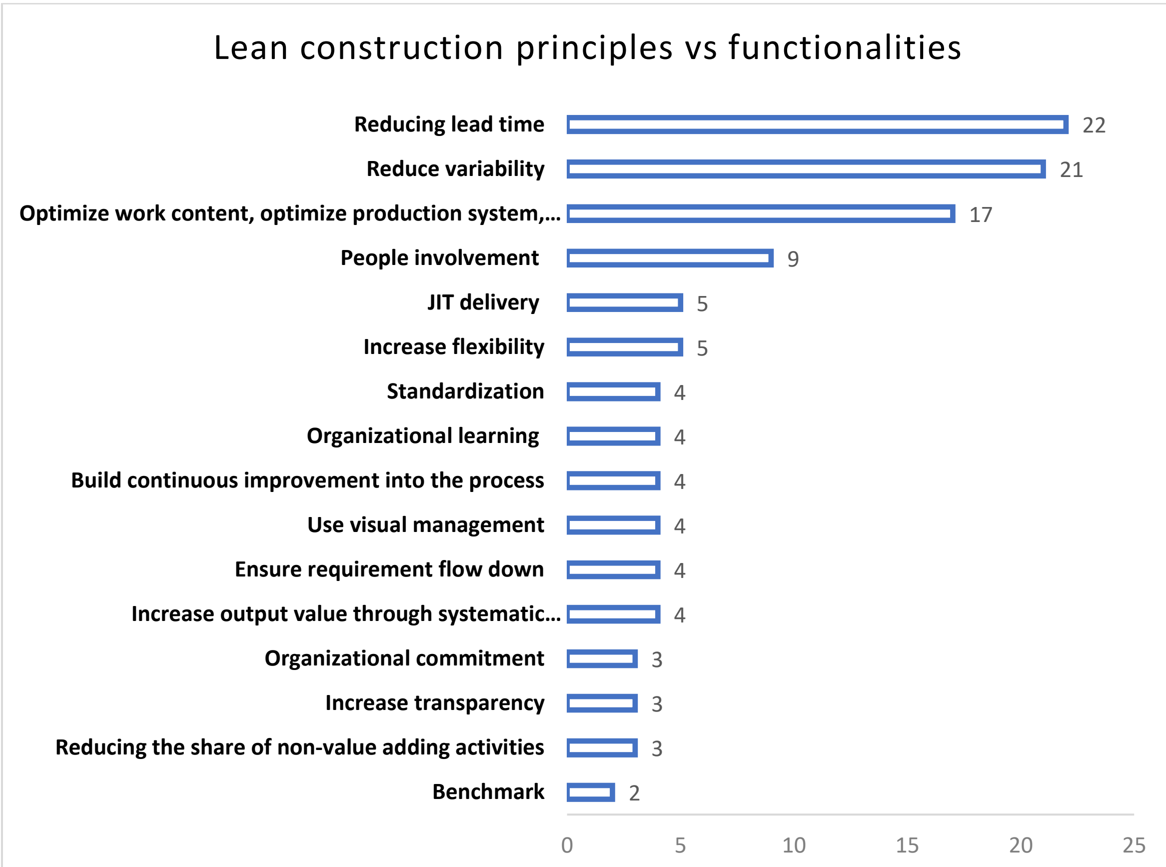

Figure 3.2. LC principles leading to lean functions

3.7. Contributions of Lean Tools and Systems in Implementing Lean Construction Principles and Achieving Lean Functions

Several lean tools and systems have been recommended and frequently tested in the construction industry in the performance of lean functions and to implement LC principles. The tools and systems range from systems such as the last planner system (LPS) which occurs within the target delivery as a system for project planning and control to root cause analysis tools such as Poka yoka (PY), 5 Whys, Fail-Safe for quality and safety (FSQS), to tools for risk and constraint analysis such as the theory of constraints (TOC) and Failure effect Mode Analysis (FEMA). Other tools such as Kaizen (KAIZ) for continues improvement, set-based and target value design (SBD/TVD) and building information modeling (BIM) for adding value and improving visualization, Kanban (KAN), and 5S for efficiently implementing the principles of Just in time (JIT) were also made part of LC toolboxes for implementing LC. Moreover, the project delivery systems such as integrated project delivery system (IPDS) for increasing collaboration in which each partner should strive for achieving the common goals along with concurrent engineering (CE) for simultaneous design and construction were included. Other tools such as value stream mapping (VSM), prefabrication/Modular (PF/MOD), line of balance (L of B), first-run studies (FRS), and A3 have also commonly used tools for implementing few principles of LC.

Despite the use and recommendation of so many tools, the studies that comprehensively explain the competitiveness of lean tools and systems in implementing the lean principles for performing the lean function is inadequately researched. For the efficient application of LC, a detailed investigation must be carried out to classify the lean tools and techniques in achieving lean principles. In this study, the lean tools and systems were further mapped based on their efficacy in implementing lean principles in the performance of lean functions. A matrix was developed as shown in table 3.2 in which each tool and system and the lean principles were further mapped along with the lean functions. The developed matrix will provide the necessary information that which tool and system are capable of implementing which LC principle in the performance of lean functions. The cell contents in the matrix contribute to the serial numbers of the corresponding lean functions as shown in table 3.1. To shorten the contents of the matrix, the integral tools of the LPS such as reverse phase, master, lookahead, and weekly planning along with measurement tools are not shown with the understanding that the functions of LPS duly cater for all these tools.

From the matrix, it can be seen that tools and systems have the capability of implementing LC principles and functions of LC. As an example, LPS can contribute to performing the nine (9) lean functions each for ensuring implementation of LC principles such as reduce lead/cycle time and reducing variabilities respectively. Similarly, tools such as VSM and SBD/TVD target two (2) lean functions in implementing the LC principle of meeting the customers' value respectively. However, it can be seen that many tools don't offer valuable contributions to achieving certain principles of LC. Where LPS doesn't offer much in implementing the principles of organizational commitment and just in time delivery, the tools for root cause analysis are not contributing to the principle of reducing the share of non-value adding activities. The detailed evaluation of each tool can be seen in table 3.2.

In summary, it can be seen in figure 3.3 that LPS has the capability of performing 26 lean functions and implementing 13 lean principles that make LPS the most demanding system for implementing LC. Similarly, tools such as BIM, SBD/TVD, FRS have the capability of implementing more than 10 LC principles. Almost all the lean tools and systems have the capability of implementing certain lean principles in the performance of the lean function. It is a matter of organizational capabilities that influence the selection of the tool or system in achieving relevant lean principles. The outcome of this study will provide a general guideline for the construction firms to select a tool or system for facilitating the LC implementation to its true spirit.

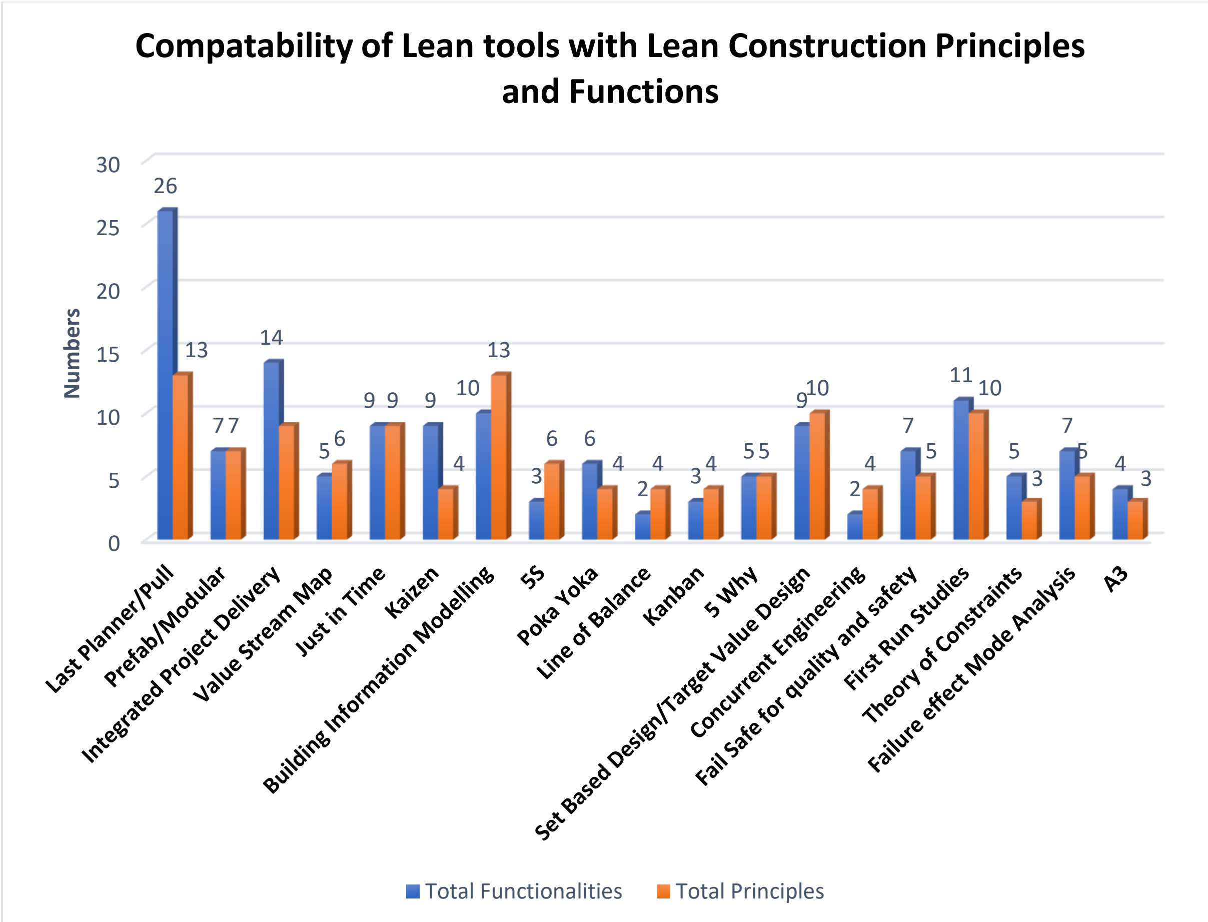

Figure 3.3. Lean tools to implement lean principles and functions

Table 3.2. Matrix analysis for lean tools, principles and function

		Lean Principles															
Lean Tools and System	**Abbr**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**
Last Planner/Pull	LPS		*1,3,4, 5,9, 26, 33, 42 43	1,5,8,9 ,26 18,33, 42, 43	27, 20	37 , 7	28,29	28	7, 25	2,6, 21, 47	3,10, 23		2,6		2,3,4, 5,8,1 0, 43, 47	21	6, 21
Prefab/ Modular	PF /Mod	14	1,3, 11, 12	1,11, 22	12, 24									24	3	13	
Integrated Project Delivery system	IPDS	15, 17, 14	15, 19	15, 18		37 , 7	28, 29	16	7		10,16 , 17, 18, 45	17			16,19 , 45		
Value Stream Map	VSM	14	26	26			28, 29	28			27						
Just in Time	JIT		22, 30,31, 32,33	32,33		37				2,21	23		2, 21	22, 30, 31,32	32		21
Kaizen	KAIZ			8, 18, 27						2,6, 21, 47						13, 21	21
Building Information Modelling	BIM	14, 15	15, 19, 36	37, 15	36	37 , 7, 35	35	35	35, 36	21	37	37			36,19	36	
5S	5S		32, 12	32	12	25								32	32		
Poka Yoka	PY		38	38, 40						2, 6, 21					40		
Line of Balance	L Of B		41	41						21							21
Kanban	KAN		32, 31			25			25					32, 31			
5 Why	5 Why		38	38, 40						2, 6, 21					40		21
Set-Based Design/Target Value Design	SBD/ TVD	14, 15	19, 15	15	12, 36	37 ,7	48, 29	27			27	37			27,19 , 36		

Table 3.2. Matrix analysis for lean tools, principles and function (continued)

		Lean Principles															
Lean Tools and System	**Abbr**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**
Concurrent Engineering	CE		19	37								37			19		
Fail-Safe for quality and safety	FSQS		38	38,40, 39, 46						2, 6, 21					46, 40		21
First Run Studies	FRS		5	5,8, 18, 27					25	2, 6, 21, 47	37, 27	27	2, 6, 47		5, 8, 47	34	21
Theory of Constraints	TOC	14	43	8, 39, 44,43, 46											8, 43		
Failure effect Analysis	FEMA		38	38,40, 39						2, 6, 21					46, 40		21
A3	A3									2, 6, 21			2, 6, 21			34	

* Cell contents contain the serial numbers of the lean function as given in table 1

3.8. Classification of Lean Tools Respecting Performance Parameters

Widespread research has already been carried out in establishing the well-defined lean tools and systems that can be used in construction. The researchers who have done remarkable efforts in identifying LC tools include.

In this study, the categorization of lean tools is carried out based on their impact in five areas that are productivity, waste reduction, continuous improvement, safety, and quality improvements. A total of 19 LC tools and systems are identified that are impacting these five areas and extensively researched for their applicability in construction. The number of studies in evaluating the respective lean tools and systems within the parameters of productivity, waste, continuous improvement, safety, and quality respectively is summarized in figure 3.4. It can be seen that the most recurrent evaluation of LC tools is based on the parameters of productivity and waste reduction with 66 and 64 counts respectively and the least common parameters are safety and quality with 16 and 29 counts. This shows that researchers are keener in applying LC tools for the improvements in areas of productivity and waste management. The improvement in productivity is desired in the construction industry whereas waste reduction will in turn results in controlling the cost and schedule overruns.

As seen in figure 3.4, almost every tool except FEMA is developed to enhance productivity with varying counts of research studies. Similarly, in the area of waste reduction, all the tools except FSQS and FEMA are causing varying degrees of impact levels. The degree of influence by each of the lean tools within areas of continuous improvement, safety, and quality can also be visualized from figure 3.4. It can be seen that LPS is the only tool that can be classified within categories of productivity, safety, quality, and waste as being considerably tested for its efficacy in these areas. PF/Mod can be effectively used for waste reduction along with tools such as LPS IPD VSM, JIT, and BIM. BIM and KAIZ can better be classified under the area of continuous improvement. The comparative level of each LC tool is shown in figure 3.4.

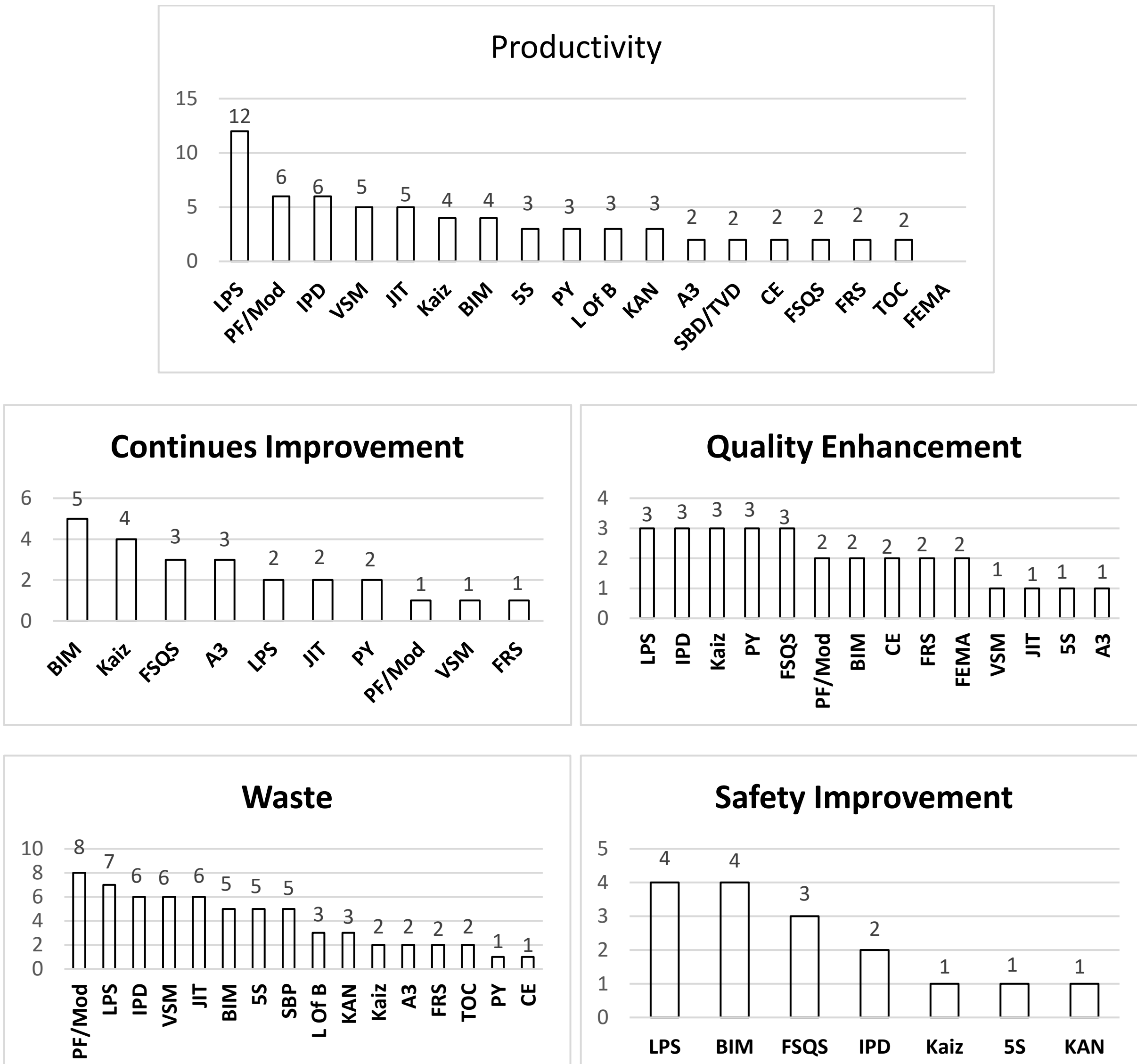

Figure 3.4. Classification of lean tools with an improvement area

3.9. Performance-Based Evaluation of Lean Tools and Systems

As explained earlier, to convince the constructors in moving towards lean, the incentives or benefits offered by each tool in a distinct measurable form need to be evaluated and documented so that every LC tool is assessed based on its merit. The data is collected from the outcome of different case studies used to evaluate the impact of LC tools on the aspect of cost, time, and productivity.

50 case studies were conducted to evaluate the cost impacts whereas a total of 47 and 46 case studies were conducted to measure the impact on time and productivity by each tool and system respectively. This indicates that researchers and key stakeholders are more eager in measuring the cost, schedule, and productivity impacts of each tool to visualize the monetary and scheduled benefits of LC tools. Figure 3.5 shows the highest number of case studies conducted for the evaluation of the impact of LPS and BIM whereas limited or no study for the evaluation of tools such as FSQS and FEMA was found within the specific domains of cost, time, and productivity. The tools such as PF/MOD, IPD, BIM, and JIT are also evaluated extensively for finding their respective impacts on the cost, time, and productivity.

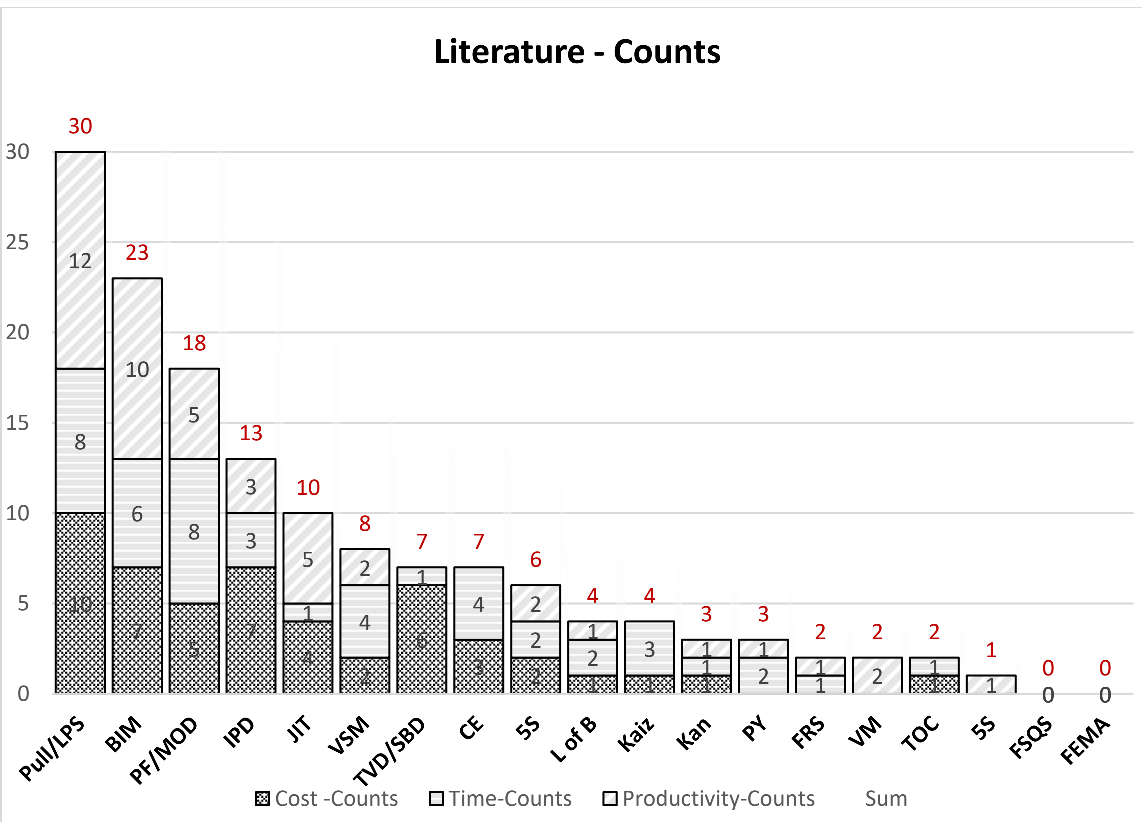

Figure 3.5. Number of studies for cost, time, and productivity

3.9.1. Impact on Cost Control

The results as displayed in figure 3.6 indicates that CE, LPS, and FRS have resulted in more than 30% of cost-saving whereas JIT and KAN resulted in the lowest cost reduction in the range of 7.5% to 5% respectively. However, tools such as FSQS and FEMA are not tested in the fields. However, it can be seen that almost all the tools and systems have some degree of impact on reducing the cost of the projects. The majority of the tools are successful in reducing the cost by more than 10%.

3.9.2. Impact on Productivity

JIT, KAN, VSM, and FRS are considered to be the most productivity enhancement tools. Their implementations on the projects have increased productivity by more than 50% as shown in figure 3.7. All the tools which are tested in the field for evaluating the impact on productivity improvement have been able to improve productivity by 10%.

3.9.3. Impact on Time

TVD/SBD, BIM, and LPS are considered to be the most time-efficient tools as these tools were able to reduce the schedule by more than 40% as shown in figure 3.8. TVD/SBD and BIM are more design-related lean tools that are commonly used during the design phase of the construction and then further developed to reduce the conflicts between construction and design. This means that timely and corrective changes during the design phase can reduce the time considerably. PF/MOD, Kaiz, and TOC are the other tools that can reduce time by 30%. Almost all the tools except CE and PY can reduce the time by greater than 10%.

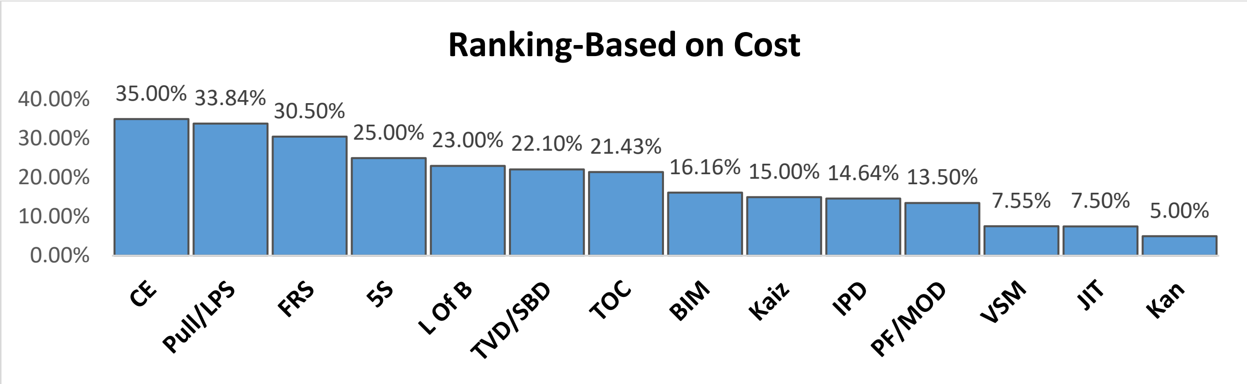

Figure 3.6. Ranked lean tools based on cost mean (%)

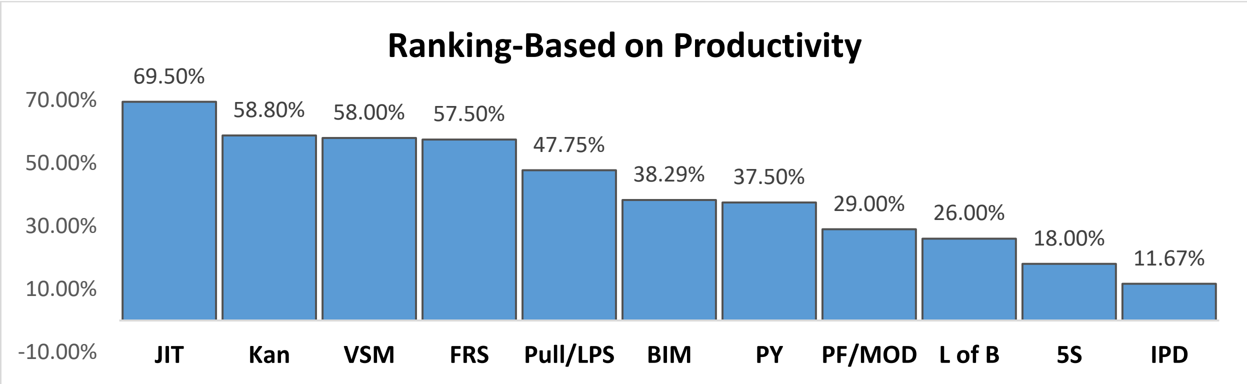

Figure 3.7. Ranked lean tools based on productivity mean (%)

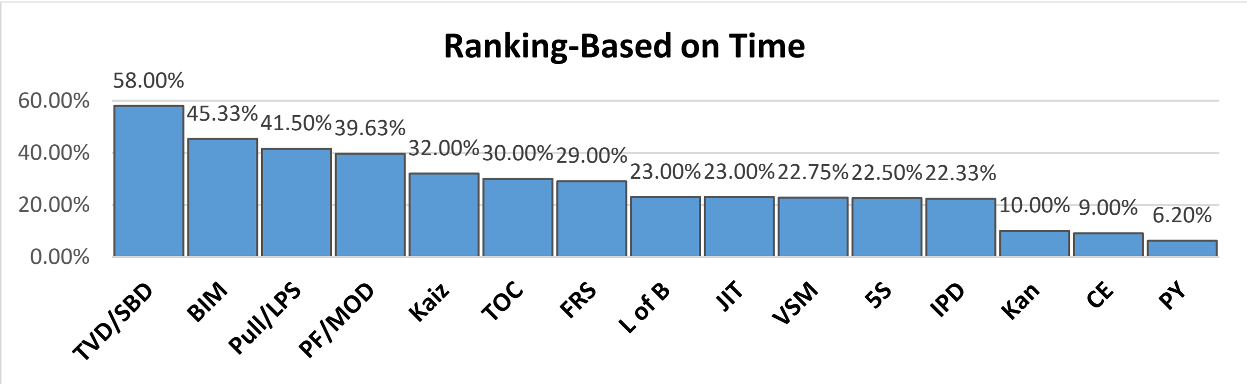

Figure 3.8. Ranked lean tools based on time mean (%)

3.10. Findings and Discussions

This study is carried out for a detailed evaluation of each lean tool and system in support of implementing lean principles to perform the LC functions and further increasing the uptake of LC by reporting the benefits of LC tools and systems. A total of 19 lean tools have been identified which are contributing in some form or the other in improving the performance of construction projects based on the aspects of productivity enhancement, waste reduction, improving quality and safety, and establishing a continuous improvement environment. More studies are carried out in determining the efficacy of LC in improving productivity and waste reduction in construction projects as compared to safety, quality, and continuous improvement. This implies that the construction industry is more eager in determining the impact of LC tools and systems on parameters such as cost, time, and productivity as compared to their impact on other parameters such as quality and safety.

Evaluation of lean tools and systems was carried out to classify the contributions of each tool and system in implementing the LC principles in the performance of lean functions. As a result, 16 LC principles are further mapped with the identified lean tools and systems to classify lean tools or systems within their respective LC principle. LPS is the system that can facilitate the implementation of 13 lean principles and able to achieve 26 lean functions. Similarly, other lean tools such as BIM, FRS, JIT, KAIZ, SBD have the capability of facilitating approximately 10 lean principles.

Furthermore, the ability of lean tools and techniques in performing lean functions was also assessed by comparing each tool and system with 48 identified lean functions that are required from the LC project. The bulk of the lean functions are based on the 4 major principles of LC as reducing lead time, reducing variabilities, optimizing work content and production system, and people involvement. There are specific lean functions that are based on certain principles of LC. As an example, principles of increasing output value through meeting customers requirement is used in performing lean functions of defining value from the viewpoint of the customer (project), use target costing and value engineering, and focus on concept selection. LPS, BIM, SBD/TVD, and FRS are the tools that facilitate performing 10 or more lean functions. JIT and IPD can facilitate the performance of 9 lean functions. Almost every tool and system have the capability of implementing a certain principle of LC and performance of certain lean functions.

As a result of performance-based evaluation in terms of cost, time, and productivity for every lean tool and system is carried out and reported in this study. Almost every tool is contributing to impacting the cost, time, and productivity in construction projects but the magnitude of impact differs among the tools. Mostly all the tools can improve the performance in terms of cost, time, and productivity by more than 10%. Few tools such as LPS, Pull/LPS, FRS, BIM, 5S, VSM, PF/MOD, JIT, and TVD/SBD have the capability of improving the overall construction performance by more than 25%. There are tools such as CE, FRS, and 5S, and systems such as LPS which has resulted in a cost-saving of more than 20%. Similarly, significant time savings were observed on projects where lean tools were used. It was found out the majority of lean tools were able to reduce the project schedule by more than 20%. Several tools are found that have the capability of improving construction productivity by more than 40% such as JIT, KAN, VSM, FRS, and LPS.

To implement LC in its true spirit, effort should be made in implementing all lean principles so that every lean function can be performed. However, it can be observed that not a single tool or system is available that can implement all the LC principles or that can help in performing all the lean functions. Therefore, lean practitioners must implement LC by combining lean tools or systems rather than relying on one or two tools. This will facilitate the construction firms in the full implementation of the LC and achievement of better and rapid benefits.

3.11. Conclusion

LC successfully emerged as a philosophy for bringing improvement in construction processes by removing the wastes and adding value to the product. However, the uptake of LC is very low within the construction industry considering its complex implementation strategies and lack of rapid initial successes. To facilitate the implementation of LC principles and increase the uptake of LC, different lean tools and systems have been identified and analyzed in this study based on their capabilities to implement LC principles in the performance of lean functions and to check their impact on cost, time and productivity. It is found out that almost all the lean tools and systems can facilitate in implementing a certain lean principle and performing specific functions. The results of this comparative theoretical and performance-based evaluation of lean tools and systems indicate that there is a lot of potential in improving construction performance by using lean tools and systems. Since lean tools and systems are the ways and methods to implement LC, realizing the significant benefits of these tools and systems along with the capability of each tool to implement lean principles in the performance of lean functions, there is a strong chance that the uptake of LC will be increased. In this competitive world, construction firms are more interested in implementing those methods on their projects which can buy them with rapid benefits, and using the lean tools and systems for implementing LC can provide them with this competitive advantage among others. The obstacles to lean transformation such as complexities in implementing lean principles, strong resistance to change and lack of rapid successes can be overcome if construction firms start realizing the benefits associated with lean tools and systems which in turn increase the uptake of LC. Practically, this novel study will help construction companies in realizing the benefits that can be achieved by using LC and further provide a way forward to the construction industry in implementing LC principles by using lean tools and systems. The outcome of this study has further added to the existing body of knowledge as it provided a detailed evaluation of how lean tools and systems can facilitate the implementation of LC principles in the performance of lean functions and how the implementation of lean tools and systems can impact the construction projects within the parameters of cost, time and productivity.

4. PAPER 2: FRAMEWORK FOR SELECTION OF LC TOOLS BASED ON LEAN OBJECTIVES AND FUNCTIONALITIES[2]

4.1. Abstract

Lean construction (LC) has been used as the potential project management philosophy to overcome some productivity and waste issues and addressing challenges of the construction industry. Furthermore, to facilitate LC implementation, different lean tools have been developed for LC. Presently, the initial selection of lean tools is predominantly objective-based with little consideration to its conformity with the construction methodology. This research aims at bringing clarity within the mindset of constructors in selecting the most appropriate tool during the initial selection phase. An extensive literature review is carried out in identifying the objectives and functionalities of each LC tool. The results indicate that many tools have almost similar objectives but different functionalities thereby making the selection criteria sensitive to the functionalities of the lean tools. The functionalities of lean tools have to be consistent with the respective construction processes for the successful implementation of LC. Finally, a framework has been proposed for selecting the most appropriate lean tools. The major contribution of this study is to improve the decision-making capability of the constructors in selecting the most appropriate tool that works in consistency with the construction.

Keywords: LC tools, Objectives, Functionalities, Similarities, Application Methodologies

[2] The material in this chapter was co-authored by Mughees Aslam, Zhili (Jerry) Gao, & Gary Smith and published in International Journal of Construction Management. Mughees Aslam had primary responsibility of conducting the systematic literature review and performing meta data analysis. Mughees Aslam was the primary developer of the conclusions that are advanced here. Mughees Aslam also drafted and revised all versions of this chapter. Zhili (Jerry) Gao & Gary Smith guided the study process, directed the framework of the paper and checked the data analysis as well as proofreading.

4.2. Introduction

The construction industry remained under the focus for its low performance in terms of productivity, cost, schedule, and quality issues (CLMA 2016, Aslam et al. 2019, Philips-Ryder et al., 2013). It has been established by many researchers that most of the construction projects are facing the dilemma of cost and time overruns as well as productivity for long (Al-Momani, 2000; Aljohani et al., 2017; Dozzi & AbouRizk, 1993). Construction Industry is striving hard in overcoming these issues by considering both the aspects of construction management as well as technology (Arefazar et al., 2019; Zhang et al., 2018). In response, lean construction (LC) has been emerged as an effective management philosophy with the objective of waste reduction, controlling variation within construction, maintaining flow, value generation, improving safety and quality of the construction products (Ballard, 1993). The successful implementation of LC has further reinforced the superiority of LC over the typical/traditional management philosophy (Agbulous et al., 2006; Locatelli et al., 2013; More et al., 2016). LC philosophy has been augmented by the adoption of different application techniques to facilitate implementation. The tools and techniques are mostly originated from manufacturing companies like Toyota Motors and Motorola and further modified for their practicability in construction (Koskela, 1992; Abdelhamid, 2003). Few tools have been extensively measured for impact in the construction industry and have the capability of improving the construction performance by one way or the other (Abdelhamid, 2003; Ballard et al., 2007; Ballard & Howell, 1995; Muhammad et al., 2013, Salem et al., 2005; Sacks et al., 2003; Sacks et al., 2010; Matthews & Howell, 2005).

With the rapid induction of a large number of lean tools applicable to the construction, constructors find it difficult to select the most suitable tool for their requirements (Green 1999, Stevens 2013). The importance of the selection of the right tool is key for the success of LC

(Ansah & Sorooshian 2017, Stevens 2013, Salem et al. 2006). Various LC implementation ventures have failed to produce the desired results due to incorrect selection and mis-conceptualization of the lean techniques (Kalsaas et al. 2009, Kim & Park 2006). Wrong interpretation and compatibility issues of lean techniques with construction are considered to be one of the major reasons for such failures (Porwal et al., 2010; Ahiakwo et al., 2013; Cerveró-Romero et al., 2013). Due to the paucity of time, constructors may not be spending considerable time in selecting the right tool. As a result, the initial decision regarding a tool is made in urgency with a focus on its objective only. Whereas, the dilemma is that many tools have the same broad outcome objective but impacts differently because of their compatibility with the specific construction process. As an example, the tools like Just in Time (JIT) and 5S (sort, set in order, shine, standardize and sustain) have the same objectives of reducing variabilities in material and information management but has to be used differently during construction. JIT is more compatible in managing the material available at the right time whereas 5S is more applicable to the storage of materials. Presently, very limited research is carried out in providing a platform to constructors for selecting the right tool based on its compatibility with the construction. The non-existence of such a platform results in the selection of tools that may not work with the construction processes. There is a need to characterize the LC tools based on their objectives and application methodologies to make the implementation process successful.

This is a novel study that describes the similarities between the tools based on their objectives and functionalities thereby facilitating the decision-making in selecting the appropriate tool at the initial stages. The characterization of LC tools based on the functionalities will further facilitate the constructors in selecting the most appropriate tool that would work in full harmony with the construction methodologies. The main focus of this study is to provide guidelines to the constructors for the initial selection of lean tools.

4.3. Challenges for the Construction Industry

Construction projects are always considered to be highly uncertain and volatile because of the nature of the work as projects are undertaken in dissimilar environments involving numerous specialty teams working together to achieve the goals of the construction (Sinesilassie et al. 2018). This uncertainty leads to the production of enormous wastes both in the product and processes which at times are considered to be inherent in the construction projects. These wastes have not only resulted in cost and schedule overruns (Stevens 2013, Al-Momani 2000, Aljohani et al. 2017, Dozzi and AbouRizk 1993) but are also the major source of declined productivity as shown in figure 4.1 (CLMA-2016). Figure 4.1 shows a clear and distinct marginal declination of construction productivity in comparison to other industries based on the labor hours worked in the industry. Other industries are blossoming with high production and reduced labor hours whereas productivity of the construction is almost stagnant, even in some cases lower than the productivity in 1950.

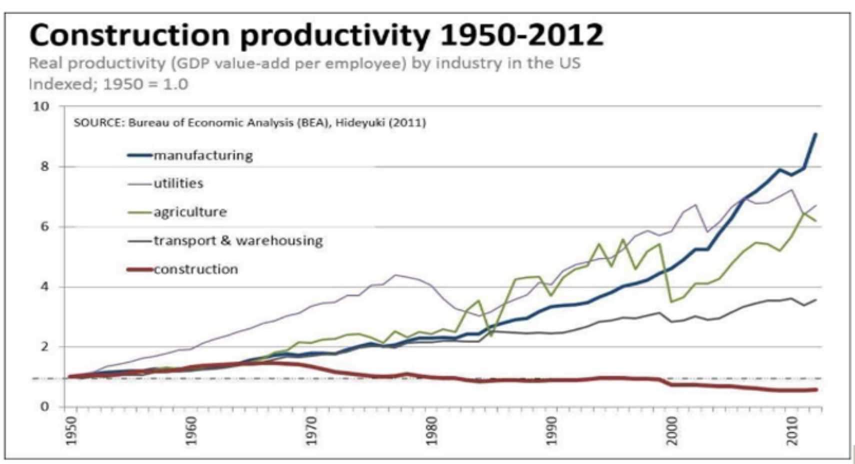

Figure 4.1. Declining trend in construction productivity, LLC (CLMA-2016)

4.4. Lean Construction as a Philosophy

The concept of LC was introduced by Lauri Koskela by presenting the construction as a production unit where production was conceptualized under the three complementary ways as transformation, flow, and value (Koskela 1992). According to Koskela (1992), the successful transformation requires, maintenance of flow within the processes and the deliverance of the product that meets customer satisfaction. With the basic introduction floated, the subsequent years witnessed some of the core developments in the field of LC, standardized under the umbrella of Lean Construction Institutes (LCI) in 1997. Diekmann et al. (2004) have summarized the five principles of LC as customer focus, culture/people, continuous improvement, workplace standardization, and waste elimination. The main focus of LC remains on eliminating the waste and delivering the product that best meets the customers' satisfaction. According to Ballard et al. (2007), LC helps in developing the system within the organizations that assure continuous improvement by learning from the past. LC has always accentuated the role of the collaboration within all the project team by giving significant importance to the persons involved at the bottom tiers.

The successful implementation of LC influenced the construction industry in moving towards the lean for improving performance. The major motivation for using LC practices is because of successful experiences witnessed by the lean practitioners and reported in the literature. Agbulos et al. 2006, Mao and Zhang 2008 and Locatelli et al. 2013 observed an increase in productivity by using LC techniques in managing the projects. Whereas, others, experienced time and cost savings due to LC (Conte and Gransberg 2001, More et al. 2016, Anderson and Amdahl 2012, CLIP 2006). According to Ballard et al. (2007), the percent plan completion (PPC) was improved from 62% to 84% and the overall cost of the project was reduced by 6.4% using LC practices, in a tunneling project. Similarly, Locatelli et al. (2013) reported an increase in productivity ranging from 5 to 50 % in 19 different projects undertaken using the lean philosophies. More et al. (2016) explored lean construction efficacy in residential projects and found a reduction in the project schedule by 25%. Dallasega et al. (2016) observed labor-saving of 8% compared to the initial estimate once LC practices like LPS and pull approach were applied in an expansion of hospital project.

Despite the benefits experienced, still, the required uptake of LC is very sparse within the construction industry (McGrawHill, 2013; Bashir et al., 2015; Wandahl, 2014). Fragmented nature of construction, lack of collaboration and coordination between various stakeholders, complexities involved in implementing lean tools, and lack of understanding about lean tools are some of the key factors preventing the LC to perform to its full potentials (Bashir et al.2015; Mossman, 2009, Wandahl, 2014). LC can only excel in the construction industry if such methods and strategies are devised which can be easily understood and implemented by duly aligning with the lean construction principles.

4.5. Sequential Development of Lean Tools and Techniques in Construction

To materialize the implementation of LC philosophy in a more systematic manner, different tools have been developed over time. Glenn Ballard pioneered the last planner system (LPS) in 1993. LPS can overcome the variabilities within construction by considering planning and collaboration as the key elements in achieving the goals of LC (Ballard, 1993). A variety of other tools have been identified, implemented, and tested for their efficacy in the field. The emphasis on using these tools in LC has been advocated by different researchers in different eras. A list of major LC tools that have been discussed extensively in the literature is shown in table 4.1.

Table 4.1. List of major LC tools

S/No	LC Tools	Abbreviation	Major Developments Since
1.	Last Planner System	LPS	1993, (Ballard, 1993)
2.	Pull approach	PULL	1995, (Ballard & Howell, 1995)
3.	Just In Time	JIT	1995, (Ballard & Howell, 1995)
4.	Concurrent Engineering	CE	1998, (Ballard & Koskela, 1998)
5.	Poka Yoka	PY	1999, (Santos & Powell, 1999)
6.	Daily Huddle Meeting	DHM	2000, (Ballard & Zabelle, 2000)
7.	Set-Based Design	SBD	2000, (Ballard & Zabelle, 2000)
8.	Visual Management	VM	2003, (Tan et al., 2003)
9.	First Run Studies	FRS	2003, (Muhammad et al., 2013)
10.	Kanban	KAN	2003, (Arbulu et al., 2003)
11.	Line of Balance	L of B	2003, (Kankainen & Seppänen, 2003)
12.	Six Sigma	SS	2003, (Abdelhamid, 2003)
13.	Prefabrication/Modular	PF/MOD	2004, (Ballard & Arbulu, 2004)
14.	Fail-Safe for quality and safety	FSQS	2004, (Diekmann et al., 2004)
15.	Integrated Project Delivery	IPD	2005, (Matthews & Howell, 2005)
16.	Building Information Modelling	BIM	2003, (Sacks et al., 2003)
17.	Value Stream Mapping	VSM	2005, (Pasqualini & Zawislak, 2005)
18.	5S	5S	2005, (Salem et al., 2005)
19.	Theory of Constraints	TOC	2005, (Salem et al., 2005)
20.	Target Value Design	TVD	2006, (Jørgensen, 2006)
21.	Standardized Process	SP	2006, (Gallardo et al., 2006)
22.	Kaizen	KAIZ	2011, (Nahmens & Ikuma, 2011)
23.	Failure Mode and Effect Analysis	FMEA	2013, (Wehbe & Hamzeh, 2013)

4.6. Problem Statement and Research Objectives

Over time, several lean tools have been added to facilitate lean implementation. Although, a large number of LC tools extended the window of opportunity for constructors, but also confusing regarding which tool to be selected (Green 1999, Stevens 2014). The major cause of the confusion is the lack of a robust framework for selecting tools causing failures to the lean initiatives (Yahya et al. 2016, Ansah and Sorooshian 2017). The contractor who decides in moving towards lean has to spare considerable time in studying all the tools before picking the right tool. A wrong selection of the lean tool during the initial phases can prove to be detrimental during the implementation stages (Wandahl 2014).

At present, the general practice of selecting the lean tools is based only on performance or LC tool's objectives. However, objectives can be similar among tools while comparative performance can be specific to a process/activity and might not work for other processes/activities in construction (Yahya et al. 2016, Kim and Park, 2006). Construction activities are hugely affected by specific project environments, economic conditions, and manpower required to execute this work. Hence, every construction activity needs to be managed with different types of lean tools which should be carefully selected. Because of the functionality differences, compatibility between lean tools with construction processes/activities has to be carefully checked (Pearce and Pons 2013). In construction, some of the processes can be planning, design, construction, material and equipment management, quality assurance, safety, site keeping, and the relationship between parties. Each process needs a peculiar and distinct execution methodology. If functionalities of the selected tool are not in congruence with the construction process, results can be damaging.

Researchers, on one side, have significantly contributed in categorizing LC tools based on the performance (Ansah & Sorooshian 2017, Salem et al. 2005) but, on the other side, very meager research has been carried out in developing the framework for the initial selection of lean tools. Although the framework for implementing LC as a whole is developed (Alarcon et al. 2011, Ballard et al 2007, Mostafa et al. 2013), these frameworks are broad-based and fell short in defining the guidelines for selecting the most appropriate lean tool. There is a need to characterize the lean tools based on the objectives and functionalities so that the adopters of the LC philosophy have a better understanding of picking the right tool. By using appropriate and proper tools to the delivery process of a construction project, LC will provide more significant gains to the organization (Marhani et al. 2018)

To fill the gap, the following objectives are set for this study:

- Distinguish between LC tools based on lean objectives and respective functionalities,
- Develop conceptual framework in selecting the most appropriate lean tool and techniques

4.7. Methodology

To achieve the objectives of this study, an extensive literature review was carried out. Database of Science direct, American Society of Civil Engineers (ASCE), International Group of Lean Construction (IGLC), and Taylors and Francis online were used as the main source for selecting the research papers relevant for this study. However, to improve the data, google scholar was also used as the secondary resource. To align the objectives of individual tools with the LC, 12 (twelve) objectives of LC are considered and enumerated as; reducing variabilities in planning, design, and processes, maintaining a continuous flow of materials and work, better visualization, customer focus, defect analysis and control, improving working procedures, continues improvement, safety culture and improvement in communication between the stakeholders (Ballard et al 2007, Salem et al., 2005; AbdelHamid, 2008). Keywords were established related to each objective of this research and used as the main method of searching the requisite research paper for respective tools. Identification of requisite papers was made in three stages. In stage one, all relevant papers were listed down based on the titles and abstract without going into the details of the papers. In stage two, the introduction and conclusion were made the basis for the retention of the papers. The last stage comprised the final selection of papers based on the complete context. After filtration, a total of 106 papers are selected for distinguishing lean tools within the context of objectives and functionalities.

The complete scheme of this study is presented in figure 4.2. LC tools will be classified into respective objective and functionalities groups. The analysis will be based on relative research paper counts to decide the classification of lean tools in the respective groups. The objective and functionalities of each tool will be presented in the form of metrics that can serve as a baseline in selecting the lean tools. Using the objectivity metrics, the organization can select lean tools for achieving specific lean principles and by using the functionality metrics, compatibility of the lean tool with the construction process can be ensured. Based on the lean principles and functionalities of lean tools with construction processes, tools will be initially selected. After the initial selection of lean tools, further factors like comparative performance measures, training, level of acceptance, behavioral and level of preparedness for the selected tools can be evaluated for final inclusion or exclusion of the selected tool. In the end, the framework for selecting the most appropriate tool will be presented.

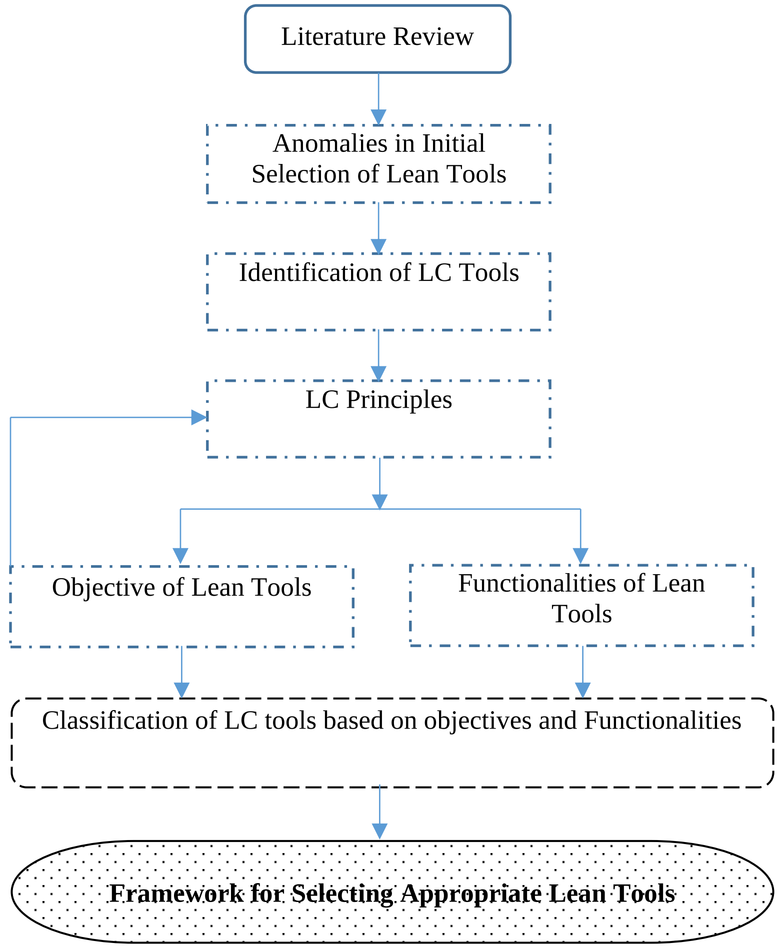

Figure 4.2. Scheme of the study for chapter 4

4.8. Anomalies in Selection of Lean Construction Tools and its Effect

Typically, most of the construction literature focused on determining the procedures for applying lean manufacturing tools in construction projects with little effort in providing direction on selecting the most appropriate tool (Yahya et al. 2016, Ansah and Sorooshian 2017). Frameworks for implementing tools like LPS, VSM, JIT, KAN, BIM, and IPD have been studied previously (Ballard et al., 2007; Salem et al., 2005; Desai & Shelar, 2014; O'Connor & Swain, 2013) but for others tools, very little information is available. LC practitioners are possibly biased towards certain sets of tools for implementation, thereby, totally neglecting the other tools that can have the potentials of performing better. Selection bias occurs when LC tools are prematurely chosen by only relying on objectives and without assessing the compatibility of lean tools with the construction processes. Resultantly, the whole LC process would be derailed because of the mis-conceptualization (Kalsaas et al., 2009; Wandahl, 2014; Stevens, 2014). For a construction firm endeavoring to move towards lean, the selection of construction tools based only on the objectives might not produce the results desired. In reality, each LC tool has been developed to target a specific process of construction. For example, JIT is for improving the supply chain of the construction project rather than scheduling, LPS is more closely related to the planning and execution aspect of the project rather than quality or design and VSM is more focused on reducing the non-value adding activities within the processes. IPD, SBD, and CE can only work in a special type of project delivery environment. The selection of LC tools should be based on their objectives and functionalities to facilitate better management of specific construction processes.

4.9. Analysis Based on Lean Objectives and Functionalities of Lean Tools

From the literature review, the list of objectives and functionalities for respective LC tools are summarized in Appendix A. LC never advocates the use of a standard set of tools because of its philosophy to achieve the best results. However, to provide the complete framework for implementing LC's objective, it is necessary to distinguish between different tools based on the objectives as well as functionalities.

4.9.1. Classification Based on Lean Objectives

Based on the data set, LC tools are further classified to their objectives. From table 4.2, it can be seen that combined twenty-two (22) tools have almost twelve (12) lean objectives overall. Table 4.2 was developed to summarize the objectives of each LC tool which explains the number of LC tools having the same objectives.

Out of the total twelve (12) objectives, LPS and VSM target seven (7) objectives followed by PF and BIM which are targeting the six (6) objectives. LPS has been identified as being in conformance with LC, thereby targeting the greatest number of objectives. Whereas tools like FSQS, KAN, and PY are targeting two objectives. The overall summary of the lean tools along with the number of objectives is given in figure 4.3.

Reducing process variabilities is the objective targeted by most tools. Nineteen (19) out of twenty-two (22) (or 86%) tools have the objective of reducing process variabilities. This suggests that researchers and companies implementing teams are keeners in reducing the process variability within the construction to control the waste. Similarly, the objective of improving the workflow, one of the major principles of LC, is targeted by thirteen (13) (or 59%) of the LC tools. 41% or Nine (9) tools have the objectives of reducing design and planning variabilities. Similarly, the percentages of the lean tools targeting the objectives are given in figure 4.4.

4.9.2. Classification Based on Functionalities of Lean Tools

Objectives of LC tools are broadly based with an emphasis on the overall reduction of waste, improvement inflow of materials and work, continuous improvement, and value generation. However, each lean tool has been designed to target a specific lean objective but with different functionalities. The application methodologies of LC tools are formulated based on the specific construction process and hence employ different techniques to implement. As an example, 86% of the tools have the same objective of reduce process variabilities but differ substantially in respective functionalities. The last planner system (LPS) removes the planning and process variabilities during planning sessions in the form of the reverse phase, look ahead, and weekly planning involving key project participants. BIM tries to remove the planning and process variabilities concerning the design and further integrating the schedule with 3D visualization of the construction project. Six Sigma (SS) removes the process variability by measuring variability through a quantitative set of observations and then performing statistical analysis for removing the defects within the processes. Integrated project delivery (IPD) utilizes the concept of collaboration among all the project participants by binding them in a relationship in which all profits/losses are shared and the product is designed and constructed simultaneously. Functionalities of all LC tools are identified and presented in the form of metrics in table 4.4.

LPS is the only tool that assures planning using scheduling techniques and involving the last planners. It ensures the involvement of downstream players like a foreman, inspectors, etc in the planning phase to remove process variabilities as well. Since the hallmark of LC is collaboration and involvement of people, therefore, most of the tools resort to the methodologies of collaboration and people involvement. Few tools have specific methodologies like the use of 3D and 4D (BIM), manufacturing components away from the site (PF), use of cards for material delivery (KAN), and arranging the materials and tools (5S).

Apart from objectives, there are also similarities between the application methodologies of LC tools. As an example, data recording and analysis is the general application methodology used by LPS, SS, KAIZ, TVD, VSM, and FMEA. Further exploration of this general methodology reveals that the techniques of data collection and analysis are different among the tools. LPS measures the Percent Plan Complete (PPC) for performing the deviation analysis whereas SS measures the number of defects and performs complete statistical analysis for necessary corrections. KAIZ uses the data of project performances /defects within construction processes and plans for corrective actions in a collaborative manner. TVD utilizes the data of cost-effectiveness on similar projects to establish the cost. VSM measures the data in the form of value-adding and non-value-adding activities for eliminating the wastes. Similarly, other general methodologies that are common in lean tools can further be explored in detail to understand the complete application procedure. A better understanding of the LC tool's functionalities/application methodologies will result in a better selection of lean tools.

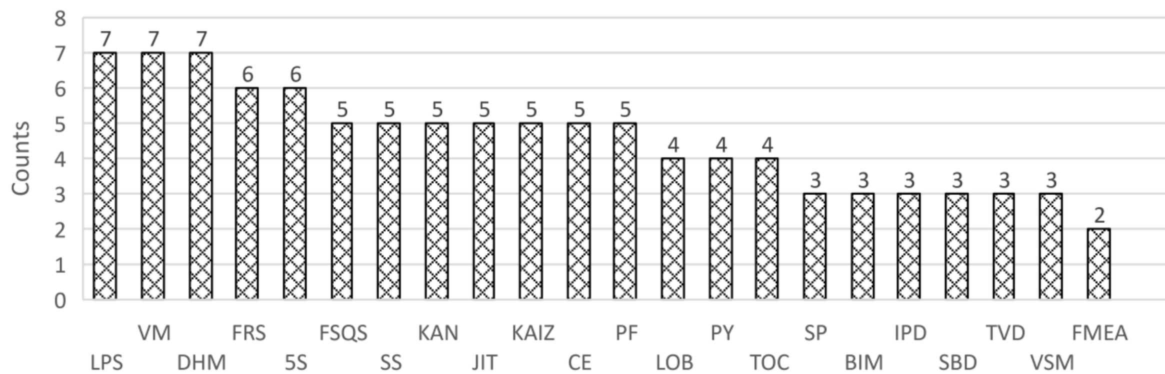

Figure 4.3. Number of objectives targeted by individual tools

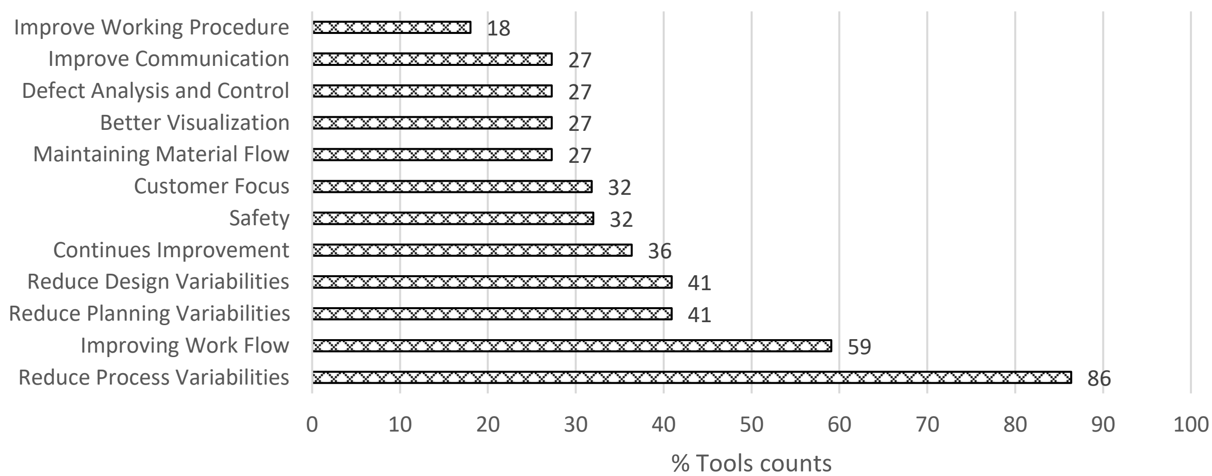

Figure 4.4. Percentage (%) of tools targeting objectives

Table 4.2. LC tools Vs lean objectives

Lean Tools / Objectives	LPS	VM	DHM	FRS	5S	FSQS	SS	KAN	JIT	KAIZ	CE	PF	LOB	PY	TOC	SP	BIM	IPD	SBD	TVD	VSM	FMEA
Reduce Planning Variabilities	*								*			*			*		*	*		*		*
Reduce Design Variabilities		*									*	*			*		*	*	*	*		
Reduce Process Variabilities	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*			*	*
Maintaining Material Flow					*			*	*				*		*						*	
Continues Improvements	*	*	*	*	*		*			*						*						
Better Visualization	*	*		*								*				*	*				*	
Customer Focus	*						*				*	*					*			*	*	
Improving workflow	*		*	*					*	*	*	*	*	*	*			*	*		*	
Defect analysis and control						*	*			*									*		*	*
Improve communication	*	*															*	*	*			
Improving working procedures		*	*	*	*							*										
Improves Safety	*	*			*	*		*		*				*		*						*

Table 4.3. Functionalities of tools based on application methodology

Methodology \ Tools	LPS	VM	DHM	FRS	5S	FSQS	SS	KAN	JIT	KAIZ	CE	PF	LOB	PY	TOC	SP	BIM	IPD	SBD	TVD	VSM	FMEA
Master Phase Scheduling	*																					
Reverse Phase Schedule	*																					
Look ahead Schedule	*																					
Weekly Schedule	*																					
Recording data and Analysis	*						*			*										*	*	*
Constraint Analysis	*									*			*		*							*
Pull Approach	*							*	*			*						*				
Visual Signs		*		*	*					*												
Root cause analysis				*		*	*			*					*							*
Removing conflicts in design and construction											*						*	*	*	*		
Material management								*	*													
Risk Assessment						*									*					*		*
Inventory Control									*													
Reduce Complexities	*		*	*		*	*		*	*	*		*		*	*		*	*		*	*
Transparency	*	*		*				*	*	*			*			*		*	*		*	
People Involvement	*	*	*	*			*		*					*	*	*	*	*	*	*	*	*
Lesson Learnt	*	*	*	*			*		*	*				*				*	*			
Schedule Buffer	*														*							
Value Engineering											*						*	*		*		
Considering alternate solutions				*									*				*	*	*			
Collaboration	*		*	*			*		*	*	*				*	*	*	*	*	*		
Simultaneously designing and construction											*							*				
Standardizing the processes and material									*			*				*	*	*	*			
Manufacturing the material away from the construction site												*										

Table 4.3. Functionalities of tools based on application methodology (continued)

Tools / Methodology	LPS	VM	DHM	FRS	5S	FSQS	SS	KAN	JIT	KAIZ	CE	PF	LOB	PY	TOC	SP	BIM	IPD	SBD	TVD	VSM	FMEA
Identification and minimizing effect of non-value adding activities										*											*	
Use of signs for smooth delivery of materials								*														
Defect identification and analysis										*				*@			*					*
Safety Analysis and mitigation measures				*						*				*@	*		*					*
Early Warning system		*				*								*								
Daily involvement of crew			*																			
Arranging the stores and material using 5S					*																	
Design the new process				*													*					
Identification of Repetitive processes	*															*						
Increased visualization of a project using soft wares																	*					

@ Identification only

Table 4.3. Functionalities of tools based on application methodology (continued)

Tools / Methodology	LPS	VM	DHM	FRS	5S	FSQS	SS	KAN	JIT	KAIZ	CE	PF	LOB	PY	TOC	SP	BIM	IPD	SBD	TVD	VSM	FMEA
Master Phase Scheduling	*																					
Reverse Phase Schedule	*																					
Look ahead Schedule	*																					
Weekly Schedule	*																					
Recording data and Analysis	*						*			*										*	*	*
Constraint Analysis	*									*			*		*							*
Pull Approach	*							*	*			*						*				
Visual Signs		*		*	*					*												
Root cause analysis				*		*	*			*					*							*
Removing conflicts in design and construction											*						*	*	*	*		
Material management								*	*													
Risk Assessment						*									*					*		*
Inventory Control									*													
Reduce Complexities	*		*	*		*	*		*	*	*		*		*	*		*	*		*	*
Transparency	*	*		*				*	*	*			*			*		*	*		*	
People Involvement	*	*	*	*			*		*					*	*	*	*	*	*	*	*	*
Lesson Learnt	*	*	*	*			*		*	*				*				*	*			
Schedule Buffer	*														*							
Value Engineering											*						*	*		*		
Considering alternate solutions				*									*				*	*	*			
Collaboration	*		*	*			*		*	*	*				*	*	*	*	*	*		
Simultaneously designing and construction											*							*				
Standardizing the processes and material									*			*				*	*	*	*			
Manufacturing the material away from the construction site												*										

Table 4.3. Functionalities of tools based on application methodology (continued)

Tools / Methodology	LPS	VM	DHM	FRS	5S	FSQS	SS	KAN	JIT	KAIZ	CE	PF	LOB	PY	TOC	SP	BIM	IPD	SBD	TVD	VSM	FMEA
Identification and minimizing effect of non-value adding activities										*											*	
Use of signs for smooth delivery of materials								*														
Defect identification and analysis										*				*@			*					*
Safety Analysis and mitigation measures				*						*				*@	*		*					*
Early Warning system		*				*								*								
Daily involvement of crew			*																			
Arranging the stores and material using 5S					*																	
Design the new process				*													*					
Identification of Repetitive processes	*															*						
Increased visualization of a project using soft wares																	*					

4.10. Proposed Framework for Selecting Most Appropriate Lean Tools

Determination of objectives and functionalities will provide a way forward to the constructors in identifying tools that are fully compatible with their construction environments and duly aligned with LC principles. Because of the number of tools having the same objectives and functionalities, there is a need to further refine the selection process. The sequence of actions required for selecting the initial tools is presented in figure 4.5 and explained below:

4.10.1. Identification of Specific Construction Process/Activity

Before deciding on the use of lean tools, the first step is to identify the processes and activities that require lean intervention. Narayanamurthy and Gurumurthy (2014) presented a framework for selecting the processes by considering seven factors that directly impact the process selection. Significant factors include the current status of managing the process (efficient/inefficient), ease in managing, ability to impact cost and time, affordability, acceptability, level of training, and compatibility with the tools (Narayanamurthy and Gurumurthy 2014, Lovatt and Shercliff 1998). These factors will help the decision-makers in selecting the lean tools that fully align with the organization's goals and project environments. For new lean users, it would be easy to select few processes, manage them using lean tools, and develop expertise before the full implementation of LC in all processes (Bashir et al 2015, Sarhan 2011).

4.10.2. Identifying the Construction Methodology of Process/Activity

After identifying the processes, the second step is to understand the construction methodology of these processes/activities that best fit within the organizational environments. Lovatt and Shercliff (1998) explained the necessity of understanding the whole process during the design phase, for identifying the tools to manage them. As an example, the material supply chain process must be clearly defined based on the contract details and specifications. The methodology for the selection of vendors, modes/ routes for transporting the material, and stocking requirements that support the installation processes have to be clearly understood.

4.10.3. Identifying the Lean Construction Principle

The decision-makers should have significant knowledge about the LC principles to find its most compatible LC tools and techniques. The identification of LC principles will provide a way forward to the decision-makers in selecting the lean tools. The objectives of the lean tools should be aligned with the LC principles.

4.10.4. Selection of Lean Construction Tools

As explained earlier, the decision-makers should be looking for lean tools that fully align with the LC principles and are compatible with the construction processes/activities. Out of all the lean tools available (as explained in table 4.1 also), organizations should shortlist all the lean tools that have lean-based objectives duly aligned with organizational goals and compatible with the construction process. Table 4.2 and Table 4.3 will provide basic guidelines for shortlisting the lean tools. However, still, there can be several tools having the same objectives and functionalities and needs to be filtered for determining the most appropriate tool. One of the most fascinating factors compelling the constructors to use lean is the benefits in terms of time and cost that can be envisaged using lean practices. Tools that offer comparatively better time and cost benefits can be picked for further analysis. Companies can track the outputs of different tools either from their database or using lean forums like LC Institutes (LCI).

4.10.5. Acceptability Among Users

Cultural acceptance of the selected tools must be sought from lean teams who have to implement respective tools on the project. Cultural acceptance has been highlighted as the key factor for the successful implementation of LC (Ballard et al., 2007; Kawish, 2017; Warcup, 2015). The long-term sustainability of lean depends on the cultural changes inbuilt within any organization for accepting and further implementing lean practices.

4.10.6. Training Level

The level of training required for the selected tools can also be a key factor during the decision process (Ayarkwa et al., 2011; Shang and Sui Pheng., 2014). All key stakeholders including subcontractors and employees need to be trained and should have the required theoretical understanding and knowledge of implementing lean tools and techniques on the projects. Appropriate training sessions can be arranged for project teams for developing the required skills for implementing the selected lean tool.

4.10.7. Lean Tool Implementation

Once lean tools are finalized, plans for their implementation must be formulated in collaboration with all key project participants especially downstream players. The finalized lean tools must be implemented with full commitment and belief from all management tiers. The top management should provide adequate support in making the lean implementation process successful.

4.10.8. Follow Up

The results must be continuously monitored, evaluated, and documented for further refining the selection and implementation procedure. In case of unfavorable results, anomalies can either be a wrong selection of tools or wrongly implemented plans. Either way, the selection and implementation of lean tools will be optimized to achieve the best possible results.

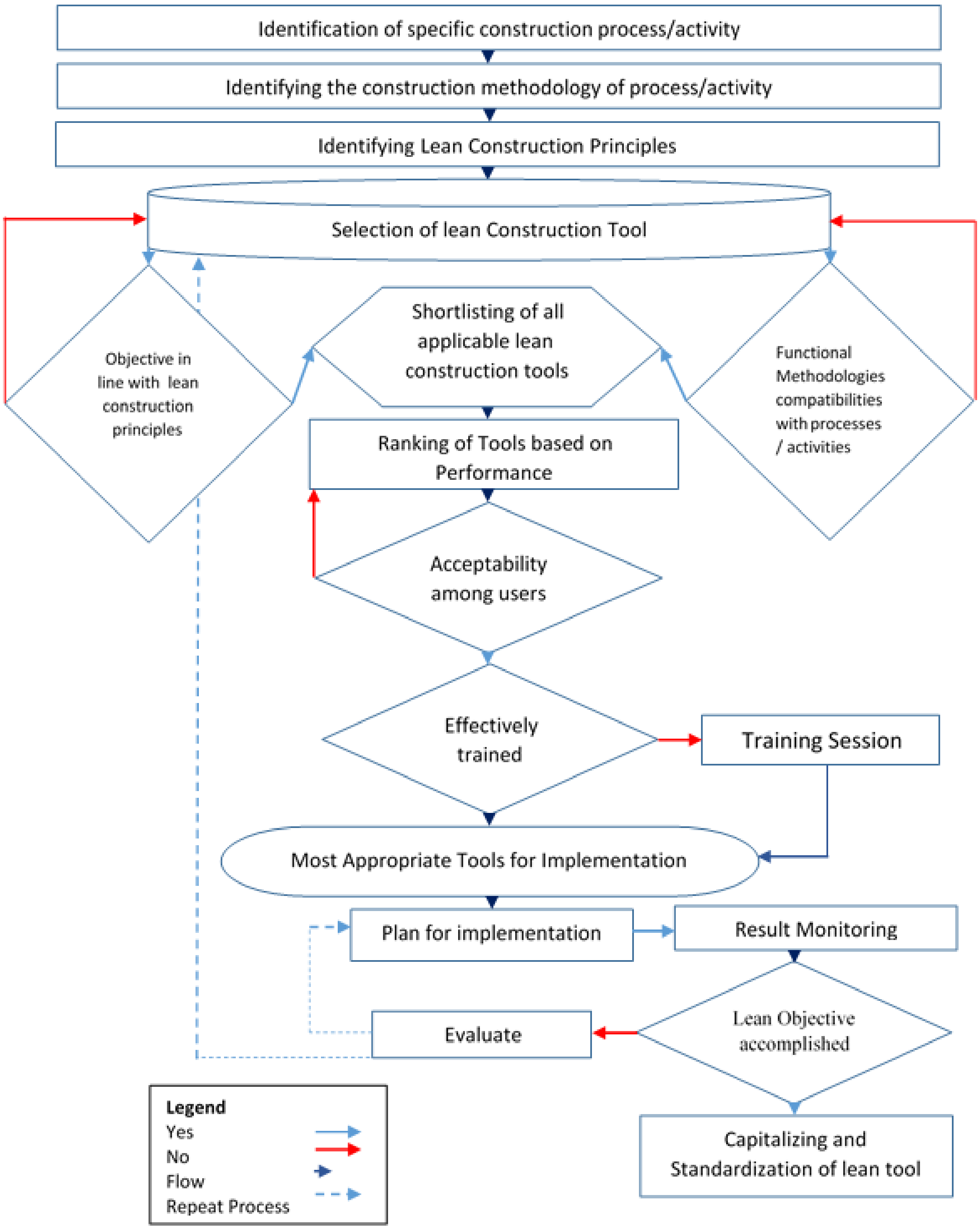

Figure 4.5. Proposed framework for selecting the most appropriate lean tools

4.11. Discussion

Many tools are targeting the same objectives which on one side causes a state of confusion for deciding the best tool for their utilization but on the other hand, it increases the opportunity for selecting a tool targeted capability. LC considers construction as a production unit that has to undergo certain phases from the inception of the project to project closeout. Hence, one tool cannot sufficiently address LC as few tools only target a specific process of construction. Table 4.2 demonstrated the fact that different lean tools have different areas to focus upon. There is not a single tool that can be employed on construction projects to achieve all the principles of LC. For an organization to be called truly lean, it is mandatory to use a combination of lean tools for covering all lean principles. For example, JIT and KAN focus on material management rather than reducing design variability. Similarly, tools like TVD and SBD are focused on design variability. TOC, FMEA, and PY have similar objectives and implementation methodologies. LPS is the only tool for targeting the maximum number of objectives within the framework of LC. However, the use of LPS in reducing design variability and material management has to be further explored and validated. Most of the LC tools are principally developed for reducing the process variability considered to be the most detrimental to construction. Similarly, it can be seen that many of the tools have similar lean objectives. Where the objectives are similar, the decision to select a tool depends on its compatibility with the construction processes and prevalent project environments. To establish the fact, it is necessary to explore functionalities of each tool based on their application methodologies which can be checked further for alignment with the construction processes/activities.

In further exploring the functionalities of each tool, it can be seen from table 4.3 that reverse phase planning, look ahead planning and weekly planning are the hallmarks of LPS which makes LPS a superior tool for planning project activities by duly involving all stakeholders and employees. However, LPS does not contribute much to root cause analysis, removing conflicts in design and construction, material management, risk assessments, improving working procedures, and inventory controls. In a journey towards lean, effort should be made to achieve all the principles of LC. The choice of lean tool should not be restricted to one or two, rather the decision should be based on considering the complete construction process. This may require selecting and implementing several tools to achieve the improvements desired across a range of construction processes.

The objectives and functionalities are essential considerations for initially selecting LC tools. It should be kept in mind that both must be consulted and should not be considered as independent entities. After the initial selection of lean tools, further factors like comparative performance measures (Sarhan, 2011; Shang and Sui Pheng, 2014; Enshassi et al. 2019), level of acceptance (Warcup, 2015), behavioral and level of preparedness for the selected tools (Sarhan and fox 2013) can be evaluated for final inclusion or exclusion of the selected tool. The proposed framework as presented in Figures 4.5 by duly incorporating all likely factors, can provide a way forward to constructors for appropriate selection and implementation of tools. The appropriate selection of lean tools will facilitate the lean implementation and constructors will be able to find rapid immediate successes. Rapid immediate successes will boost the morale of the company in delivering the projects using the lean way. This will result in the elimination of many wasteful practices and will make the construction industry more productive. This framework can further be refined by including other factors like cultural, behavioral, and commitment so that lean effort should last long and sustainable.

4.12. Conclusions

The development of LC philosophy has given rise to several tools for facilitating implementation and improving the performance of the construction industry. LC philosophy is not dependent on a set of standard tools. It is up to the organization that wants to implement the LC, to decide which LC tools they need and choose tools to achieve the objectives of LC efficiently. Relying on only one or two tools for moving towards the lean, is not what the lean philosophy intends. It advocates a holistic thinking process in which the system keeps on improving itself. The decision about the initial selection of the lean tool is the first step in moving towards lean followed by consideration of other factors like the acceptability of lean tool within the organization, preparedness for implementation, and training required. With the development of so many LC tools, the initial selection criteria for picking the right tool should be objective-based with due consideration to its functionalities. Aligning the application methods of lean tools with the type of construction is traditionally given very little importance during initial selection. At times, this has resulted in the wrong selection of tools. The purpose of this paper is to facilitate the constructors in deciding to select the right tool by describing the similarities between different LC tools based on their objectives and functionalities and further suggesting the ways of selecting the best tool and techniques. Theoretically, the outcome of this study will add to the existing body of knowledge as it presented the detailed evaluation of objectives and functionalities of different tools along with a framework for selecting the appropriate lean tools. Objectives and functionalities of lean tools can be easily understood and employed. Practically, the outcome of this study will facilitate constructors in selecting tools that fully align with lean principles and project requirements and will be sustainable in the future also. Although, this a novel study in which a hypothetical framework is developed for selecting the lean tools initially, however, the validation/refining of the framework can be carried out as a future study through case studies or using the empirical approach. This research can be a good start point for many researchers in exploring the techniques for selecting the most appropriate lean tools that can help lean practitioners in successfully implementing the LC.

5. PAPER 3: DEVELOPMENT OF INNOVATIVE INTEGRATED LAST PLANNER SYSTEM (ILPS)[3]

5.1. Abstract

The last planner system (LPS) has been recognized as one of the most formidable tools for implementing lean construction (LC) and improving construction productivity. The last 25 years have witnessed the sequential development of LPS but still, the construction industry is unable to utilize its full potentials. However, it was reported that the users of LPS are only able to achieve 70% of their weekly assignments with a lot of potentials to perform better. Considering it a complete LC tool, LPS is mostly implemented in isolation thereby exposing many areas that are being overlooked and couldn't be managed well. An effort has been made in this study in developing strategies to overcome LPS implementation challenges by integrating LPS with other available lean tools and techniques. A systematic literature review is carried out, followed by conceptual development of findings and theories into a robust integrated LPS implementation model. Thirteen (13) major shortcomings in implementing LPS and sixteen (16) lean tools to overcome shortcomings are identified. Presently LPS is managed as a single entity whereas due to its vast diversity, all of its stages should be managed independently. To manage LPS stages independently, in this study, lean tools are integrated within LPS stages to develop the innovative integrated LPS system (ILPS). Additionally, a guideline for sequential amalgamation of LPS with the lean tools at different stages is presented to smoothen the ILPS implementation process. The ILPS will facilitate the construction industry in utilizing the LPS to

[3] The material in this chapter was co-authored by Mughees Aslam, Zhili (Jerry) Gao, & Gary Smith and published in International Journal of Civil Engineering. Mughees Aslam had primary responsibility of conducting the systematic literature review and performing matrix and meta data analysis. Mughees Aslam was the primary developer of the model and wrote conclusions that are advanced here. Mughees Aslam also drafted and revised all versions of this chapter. Zhili (Jerry) Gao & Gary Smith guided the study process, directed the framework of the paper and checked the data analysis as well as proofreading.

its full potentials. This newly developed ILPS will help the lean practitioners in increasing construction productivity and reducing the cost and time overruns.

Keywords: Integrated Last planner system (ILPS), Lean tools and techniques, shortcomings, look-ahead planning, constraint analysis, visualization

5.2. Introduction

The last planner system (LPS) has been considered as the most common tool in implementing the lean construction (LC) philosophy due to its wide range of benefits offered especially in the areas of productivity as well as cost and schedule controls (Sabek & McCabe, 2018; Brittle et al., 2018; Fernandez-Solis, 2013; Priven & Sacks, 2015; Ballard, 2008; Vignesh, 2017). The most significant benefits of LPS are reduction in project variabilities, improving and maintaining the smooth flow by exposing the wastes, promoting the culture of collaboration and trust among all the project stakeholders, and developing a culture that pursues continuous improvement. The successful implementation of LPS has further reinforced the conceptual ideas of LC for achieving the anticipated outcome (Vignesh, 2017; Gao & Low, 2014; Daniel et al., 2019; Ballard et al., 2007).

Apart from the successful implementation of the LPS, there have been certain challenges and shortcomings identified in the system that are causing hindrances in getting the optimized benefits. Many researchers believe that LPS is not being utilized to the best of its capabilities due to certain inherent shortcomings in it [(Sabek & McCabe, 2018; Fernandez-Solis, 2013; Priven & Sacks, 2015; Vignesh, 2017; Tayeh et al., 2018; Perez & Ghosh, 2018, Abdelhamid, 2003; Alarcón et al., 2011; Lindhard, 2013; Dave et al., 2015; Khanh & Kim, 2016). 1) Lack of visualization capabilities (Ahiakwo et al., 2013), 2) non-compatibility with project delivery methods (Fuemana & Puolitaival, 2013), 3) underutilized lookahead planning (Priven & Sacks, 2015; Vignesh, 2017), 4) nonperformance of constraint analysis (Fernandez-Solis, 2013) and 5) lack of considerations to continuous maintenance of flow (Lindhard & Wandahl, 2013) are few of the common shortcoming identified in existing LPS. Although LPS has resulted in improved percent plan completion (PPC) on projects, still lean practitioners are unable to complete more than 70% of weekly assignments even after implementing LPS (Bortolazza & Formoso, 2006)

Although the state-of-the-art frameworks and implementing strategies are available to remove inefficiencies in existing LPS however, these frameworks lack the operational aspects of LPS. Most of the LPS implementation frameworks are broad-based and target only the macro aspects of the project and organization (Sabek & McCabe, 2018; Perez & Ghosh, 2018; Lagos et al., 2019; Zaeri et al., 2017). Whereas, implementation strategies that specifically facilitate the implementation of various stages of the LPS are meagerly explored (Khanh & Kim, 2016; Aboseif & Khallaf, 2020; Abusalem, 2018). Additionally, implementing strategies and shortcomings are explored in isolation from each other and lacks the necessary linkages between each other (Fernandez-Solis, 2013; Vignesh, 2017; Aboseif & Khallaf, 2020; Ebbs et al., 2018). This isolation in identifying shortcomings/barriers and implementation strategies of LPS makes the implementation process difficult and complicated.

This paper outlines major shortcomings in the LPS through an extensive literature review to develop implementation guidelines that can increase the efficiency of the existing LPS by incorporating the new LC tools. The existing practices of LPS can be augmented by introducing tools and techniques that are compatible with LPS and have the capabilities of reinforcing the LPS implementation process. After integration with other lean tools and techniques and targeting the required shortcoming, an effort will be made to develop an integrated last planner system (ILPS) model. This is a novel study in which the shortcomings in LPS are removed by utilizing the benefits of other tools in a sequenced and phased manner and implementation guidelines for implementing each ILPS stage will be formulated. This research will benefit the contractors, owners, and clients in developing a more rational approach for implementing LPS under the umbrella of LC philosophy.

5.3. Lean Construction and Last Planner System

Koskela introduced concepts of lean philosophy in construction by presenting the construction as a production unit where production was conceptualized under the three complementary ways as transformation, flow, and value (Koskela, 1992). Construction relies on a group of teams which are specialist in its area of expertise, hands over its product to the next team and subsequently complete process integrates to achieve the final product. As an example, the architect hands over the drawing to the designer who in turn hands over the design to the construction teams for its implementation. Hence construction processes involve two most important things to control: (1) transformation of conceptualized ideas into reality and (2) maintaining continues flow of products/information's from one group of a team to another reliably and sustainably. Diekmann et al. (2004) have summarized the 5 principles of LC as customer focus, culture/people, continuous improvement, workplace standardization, and waste elimination. Ballard et al. (2007) also used the same LC principles in their research for the Construction Industry Institute. The main focus of the LC is to reduce wastes within construction by maintaining a constant flow as well as providing the maximum value to the product in a sustainable way and has the capability of continuous improvement over time. All of its principles are set to achieve these goals for the overall benefit of the construction industry. The use of lean construction has ultimately resulted in cost and time controls as well as increased the productivity of the complete construction processes (Locatelli et al., 2013; More et al., 2016; Agbulos et al., 2006)

Over time, several tools and techniques have been identified which can simultaneously be used to achieve the objective of LC. Ballard and Howell (Ballard & Howell, 1994) have contributed to providing a platform with the name of LPS, in which many tools are grouped for efficiently addressing the objectives of LC. LPS emphasizes the role and contribution of the last planner in planning where a last planner is a person who is responsible for the completion of its production unit/individual task at the operational level (Aziz & Hafez, 2013). The concept of LPS revolves around defining the assignments based on what should be done, will be done, can be done, through different stages like the master planning, reverse phase planning, look-ahead planning, and weekly planning. Master and Reverse phase planning determines "*what should be done"* using the pull approach. When the construction starts and things are getting clearer in terms of resources and constraints, activities which "*will be done*" are identified using the look-ahead planning, normally 5-6 weeks before the start of activities. Finally, during the weekly schedule, the construction crew will commit to perform the activities that "*can be done"* based on their capabilities and resource availability. During the execution of the assignments/activities, the outcomes are measured using the metrics Percent Plan Complete (Number of activities executed in a week/Number of activities planned in a week) for carrying out the depth analysis of all performed works. The whole process revolves around achieving efficiency through learning and collaboration by all the construction participants. The schematic explanation of the last planner is given in figure 5.1.

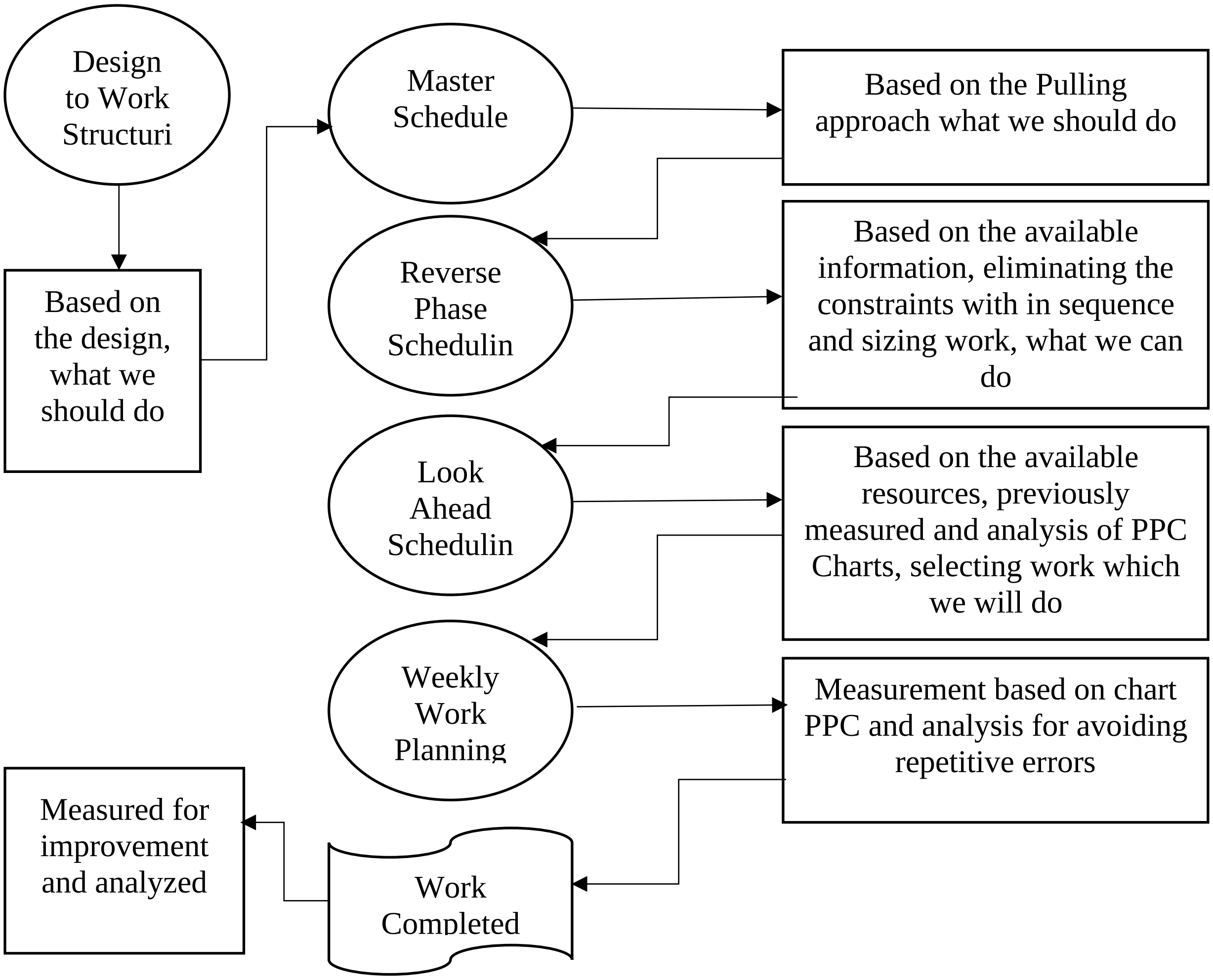

Figure 5.1. Last planner system

5.4. Impact of Last Planner System

Implementation of LPS has resulted in controlling the cost and time overruns as well as enhanced construction productivity. Ballard et al. (2007) assessed the performance of LPS in several projects and found a reduction of cost within the range of 10 to 50% as well as an increase in 30% of the construction productivity by using the LPS. Similarly, other researchers have also tried to measure the performance of LPS in terms of cost and schedule overruns, and productivity increase and concluded results in favor of LPS (Ballard, 2008; Aziz & Hafez, 2013; Fiallo & Revelo, 2002; Babalola et al., 2018). Thomassen et al. (2003) and Mossman (2015) measured the safety-related benefits of LPS and concluded a considerable decrease in safety incidents by the implementation of LPS. Salem et al. [2005] conducted a field study to evaluate outcomes of the six LC tools (LPS, Visualization, daily huddle meetings, first-run studies, 5s Processes and fail-safe for quality and safety) through the lean implementation standards and performance criteria and resulted that only LPS is the tool which is complete in itself and can be applied in construction projects. Whereas the author recommended modifications in all the other tools for effective implementation in construction in lean environments.

In most of the LC studies, the percent plan complete (PPC) is measured in terms of activities executed in a week divided by activities planned in the same week (Ballard, 2008; Ballard & Zabelle, 2000). According to Liu et al. (2010), labor productivity was found to be positively correlated with PPC and recommended to be used as a productivity measuring tool. Lagos et al. (2019) used a sample of 50 projects to corroborate that projects having higher PPC also have higher performances. Since PPC is considered to be the most reliable method of measuring the impact of LPS, hence researchers compared the LPS in terms of change of PPC against existing management approaches. An increase in productivity along with average PPC achieved after implementing LPS is shown in table 5.1.

In comparison to traditional approaches, projects undertaken using LPS have clearly shown an increase in PPC but at the same time, an average of 32% of assignments are still not achieved. Howell & Macomber (2002) further concluded that companies should strive to achieve PPC values over 80% and anything lower than 60% should be considered as lower performance. Similarly, Ballard and Zabelle (2000) also recommended the PPC of above 80% as a benchmark for good performances. However, based on the summary of results, the average PPC achieved after implementing LPS is around 68% which is far less than the expectations. Hence there is a need for improving the LPS by finding out the main barriers that are hindering the construction industry from using LPS to its full potential.

Table 5.1. Impact of the last planner system

Researchers	**Change in Weekly PPC (%)**	**Average PPC achieved (%)**	**Assignment not achieved (%)**	**Remarks**
Ballard et al. (2007)	27	70	30	Electric Contractor Venezuela
	30	70	30	Chile
	24	76	24	Subway projects
Daniel et al., (2017)	Increased	72	28	Project 1
		90	10	Project 2
Fiallo and Revelo, (2002)	Increased	65	35	The foundation stage reached PPC up to 91% but decreased in structure and masonry assignments
Salem et al. (2005)	50	75	25	Garage Parking
Kim, (2002)	-	85	15	7 Projects data
		77	23	
		76	24	
		59	41	
		75	25	
		80	20	
		47	53	
Alcaron et al., (2011)	56	71	29	
Ahiakwo et al. (2013)	100	80	20	
Bortolazza and Formoso [2006]		72.24	28	Industrial building
		68.04	32	Residential buildings

The efficiency of LPS can never be underestimated but one should always remain in search of excellence which will be beneficial for the construction industry as a whole and lean practitioner in particular. LC philosophy advocates attaining the best possible results through continuous improvement and learning from the past. Following the same path, LPS needs to be evaluated for removing the drawbacks and achieving maximum efficiencies.

5.5. Problem Statement and Current Implementation Gaps

Researchers have significantly contributed to developing LPS implementation frameworks and strategies. However, there are some shortcomings in the developed frameworks which need to be addressed for the efficient application of LPS. Fernandez-Solis et al. (2013) identified challenges for successful implementation of LPS at an organizational and technical level but felt short in recommending the remedies for overcoming these challenges. Lagos et al. (2019) supported the implementation of LPS using information technology (IT) however, the use of IT in managing the lookahead/weekly planning by removing the constraints along with strategies to performing corrective actions were meagerly researched. Sabek and McCabe (2018) developed a framework for implementing LPS in mega projects by identifying 31 LPS implementation challenges and then proposing a framework for successfully implementing the LPS. The framework discussed the holistic application of the LPS at the macro level but staged implementation of LPS at the micro-level (reverse phase planning, lookahead/weekly planning) is not elaborated upon. The micro-level implementation strategies explaining each LPS stage will provide a way forward to the new LPS users for implementing it at the project level. Although Khanh and Kim (2016) tried to rank the strategies for successful implementation of LPS but restricted to only look-ahead planning, team workshops, and weekly work plans. In an attempt to develop a framework for successful implementation of LPS in Egypt, Aboseif and Khallaf (2020) proposed 9 strategies for 5 identified challenges only but fell short in providing the methodologies for fitting the strategies into an overall LPS model. Zaeri et al. (2017) developed an automated excel spreadsheet for efficiently utilizing the project data in improving the LPS implementation. The developed spreadsheet can be used as an effective tool in the continuous improvement of the applied LPS. Abusalem (2018) identified critical success factors for implementing LPS at the project level however detailed methodologies for incorporating critical success factors into the LPS model are not explained. Moreover, key barriers and success factors were also identified by other researchers to improve the efficiency of LPS (Vignesh, 2017; Tayeh et al., 2018). Ebbs et al. (2018) endeavored to provide the LPS path clearing approach by considering “shallow and wide” organizational aspects rather than a more traditional “narrower and deep” project approach. According to the authors, the 15 step actions developed during the study can effectively overcome the LPS implementation barriers. This implementation strategy is more focused on overcoming the organizational issues only with a lesser impact on technical/project issues.

In summary, researchers have tried to streamline the implementation process of LPS by developing state-of-the-art frameworks and implementing strategies to remove inefficiencies in the current LPS model however, the necessary linkages between strategies with the current implementation challenges couldn’t be established. In some cases, challenges for successful implementation of LPS are identified but strategies to overcome these challenges are not discussed. This isolation in identifying shortcomings/barriers and implementation strategies of LPS makes the implementation process difficult and complicated. Additionally, most of the LPS implementation frameworks are broad-based and targets the macro aspects of the project whereas, strategies specifically targeting the operations of LPS are marginally discussed.

Because of the above-mentioned gaps, the main motivation for this novel study is to develop implementation strategies by not only identifying the current shortcomings in existing

LPS but also providing strategies at the micro level which could be useful in implementing different stages of LPS. LPS has the capacity for further improvement and making a system that best suits the construction environment and helps in improving the performance of construction by many folds. There are many tools identified by the lean practitioners which can be used in eradicating the drawbacks of LPS. To develop the most efficient last planner tool, the study of all the tools and techniques and the areas targeted by them needs to be evaluated. The shortcomings of LPS can then be addressed based on the operational capabilities of each tool and their adaptability within the LPS. This research is aimed at reducing the shortcomings of the LPS by duly integrating it with other LC tools. This will provide a platform in which benefits offered by each tool can be combined to get the most efficient system which can provide a rational guideline to owners, consultants, and contractors in achieving the best results. The research will provide tremendous benefits to the contractors who are willing in moving towards LC by adopting a technique that can result in maximum benefits in this competitive business. Apropos, the main objective of this research is as under:

- Identifying the shortcomings in the LPS
- Identifying the tools that can best be suited to combat the shortcomings of the LPS
- Developing the efficient integrated last planner model (ILPS) which can result in optimized performance by integrating it with newly identified LC tools.
- Providing guidelines for implementing various stages of ILPS

5.6. Methodology

To achieve the objectives of this study, an extensive literature review was carried out. Database of lean construction journal (LCJ), American Civil Society of Engineers online

(ASCE), Science direct, and International Group of Lean Construction (IGLC) was used as the baseline in selecting the research papers for evaluating objectives of this study. The research was organized into three stages as per the objectives of this study. In stage one, shortcomings of LPS reported by the researchers in literature since 1992 are extracted and summarized. In stage two, the LC tools are identified whose methodology and objectives are such that they can efficiently target shortcomings identified in the LPS. In stage three, a new model of ILPS is developed by integrating lean tools and techniques into its different stages. Keywords were established related to each objective of this research and used as the main method of searching the requisite research paper for respective tools. Identification of requisite papers was made in three steps. In step one, all relevant papers were listed down with the keywords without going into the details of the papers. In step two, the introduction and conclusion are made the basis for the retention of the papers. The last step comprises the final selection of papers based on the complete context. The schematic explanation of the complete methodology is explained in Figure 5.2.

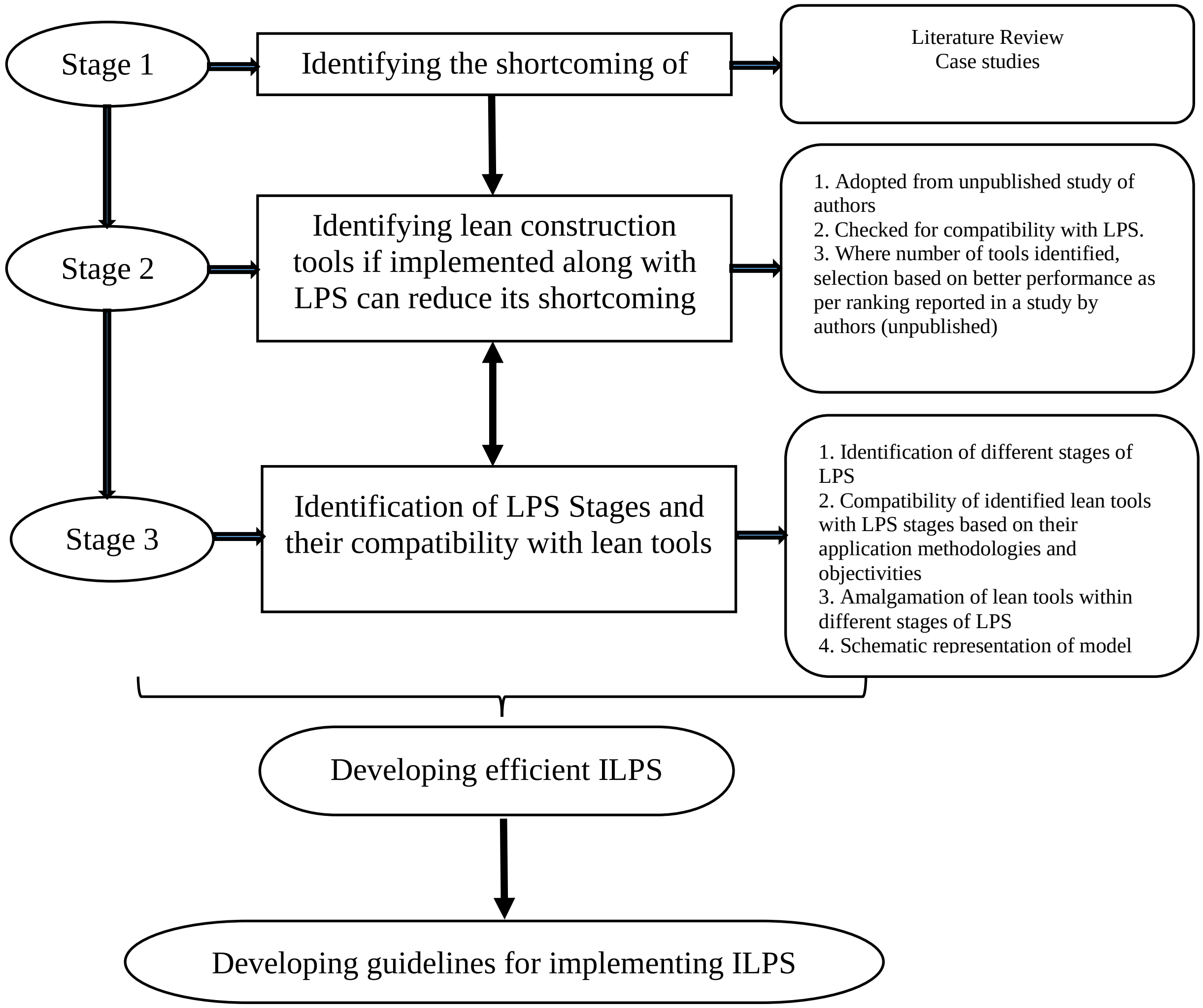

Figure 5.2. Research methodology for chapter 5

The major focus of this study is to develop efficient LPS based on its operational processes only. The aspects related to behavioral, commitments, financial support and education that can cause the hindrance in implementing the LPS in its true form are not included. These are important factors that should be considered after all the shortcomings of the existing LPS are removed and the system is ready to be implemented with its maximum optimization.

5.7. Shortcomings in Implementing Last Planner System and Strategies to Overcome the Shortcomings

LPS has been considered to be the most formidable and complete methodology for implementing LC. However, at the same time, it has been explained theoretically as well as through case studies that LPS has some inherited shortcoming that needs to be addressed for its full utilization. According to Abdelhamid (2003), the major focus of LPS remained on combatting the effects of variabilities whereas for truly achieving the objectives of LC instead of reducing the effects of variability, a mechanism should be developed to eliminate the variabilities by uprooting the root causes of the variabilities. The author recommended the use of six sigma (SS) for eliminating the root causes of variabilities through systematically injecting the concepts of SS into LPS during all the stages of construction. A well-structured framework was also presented by the author for inculcating SS in LPS (Abdelhamid, 2003). Alarcon et al. (2011) measured the impact of LPS by studying more than hundreds of projects. Apart from the efficacy of LPS, few operational drawbacks in the system were also identified. According to the authors, the implementation of look-ahead planning remained a major problem because of the lack of understanding about look-ahead planning. Moreover, corrective actions were also not taken anywhere during the implementation phase because companies find it difficult to accurately measuring and analyzing the performances. Another important shortcoming as notified by the authors was the poor visualization capabilities of LPS in which information from one team could not be understood by the succeeding team. The use of information technology like building information modeling (BIM) in improving visualization has been recommended by the author for further facilitating the implementation of LPS. Similarly, the major challenges identified by Dave et al. (2015) in LPS are weak look ahead planning, missing motivation for continuous improvement, lack of root cause analysis, and collaborative aspects. Quantitative analysis was carried by Bortolazza and Formoso (2006) and reported the lack of effective implementation of look-ahead planning and nonperformance of constraint analysis as the key shortcoming in the LPS. According to the authors, two main categories of LPS (planning and workforce) are too superficial for identifying the root causes of problems normally hampering the performance of the construction. The major reason for the lack of effective implementation of look-ahead planning as highlighted by Friblick et al. (2009) is the non-involvement of employees and subcontractors. Implementation of LPS without the involvement of downstream players can always be detrimental in achieving the true objectives of LC. According to Fuemana and Puolitaival (2013), the non-compatibility of procurement methods with LPS is the key obstacle in implementing the LPS. According to the authors, the traditional point-based design method wouldn't work in harmony with the LPS. Lack of collaboration and employees/subcontractor’s involvement during design and planning processes are a few shortcomings in the traditional method hampering the efficient implementation of LPS. To determine compatible methods of project delivery that work in harmony with LPS, Matthew and Howell (2005), suggested the use of Integrated Project Delivery (IPD) as a solution for the problems in which the whole team functions as a single unit with shared responsibilities.

Ahiakwo et al. (2013) highlighted that lack of material availability as the topmost reason for incomplete assignments after the implementation of LPS along with difficulty in managing the labors, reworks, incomplete design, and poor weather. The authors concluded that the lack of material management, visualization of design into construction, and risk assessment capabilities of LPS in the execution stage are some of the areas needing further elaboration.

Maintaining continuous flow is an essential component of Koskela three partite explanation of LC as Transformation, flow, and value (Koskela, 1992). Lindhard and Wahdahl 2013) analyzed the LPS in depth by considering the mechanism of LPS in which sequence of activities are determined based on the duration and interrelationships whereas the main themes of all types of flow consideration are not considered. According to Lindhard and Wahdahl (2013), in LPS, flow considerations are kept at a look ahead level only in which different activities have to be made ready for construction. The authors recommended incorporating the flow consideration during Phase, look ahead, and weekly scheduling also. The summary of the barriers is listed in Table 5.2 as well.

Table 5.2. Shortcomings in the last planner system

S/No	Shortcomings in LPS	References
1	Lack of effective implementation of look-ahead planning	[14, 16, 21]
2	Nonperformance of constraint analysis	[14, 10, 21]
3	Nonperformance of root cause analysis and corrective actions	[13, 16, 20, 21]
4	Lack of supply chain integration	[14, 18]
5	Lack of collaboration	[16, 20, 45, 46]
6	Difficult to handle downstream players and subcontractors/suppliers	[19, 42, 45]
7	Noninvolvement of key stakeholders in different phases of construction	[19, 42, 45]
8	Contracting and legal issues	[12, 45, 47]
9	Lack of training	[42, 47]
10	Lack of considerations to all flows	[20]
11	Lack of communication	[20]
12	Lack of visualization capabilities	[18, 20]
13	Nonperformance of risk analysis	[20]

Notes: References numeric codes
Daniel, 2017 - 10
Abdelhamid, 2003 - 13
Alarcón et al., 2011 - 14
Dave et al., 2015 - 16
Fuemana & Puolitaival, 2013 - 19
Lindhard & Wandahl, 2013 - 20
Ahiakwo et al., 2013 - 18
Matthews & Howell, 2005 - 45
Koskenvesa & Koskela, 2012 - 46
Porwal et al., 2010 - 47
Bortolazza & Formoso, 2006 - 21

5.8. Selection of the Lean Tools

To utilize LPS to its full capabilities, it is essential to overcome challenges that are hindering its successful implementation. LPS provides a set of tools as shown in figure 5.1 for its implementation. These tools have to be reinforced with other lean tools and techniques which should directly target the shortcomings and facilitate LPS implementation as per its true spirit. Apart from LPS, many LC tools have been identified and measured for their importance and efficacy. As shown in chapter 3 and 4, 23 major LC tools are evaluated based on their performances and are shown in table 5.3. This study provides a guideline for selecting tools and techniques based on their acceptability within the construction industry and performance evaluation. Results of the study indicated that LPS alone cannot signify construction as lean, rather a group of tools and techniques when implemented together with positive commitment and cultural acceptance, will make the construction leaner. In another unpublished work of authors, it was established that each LC tool is built to target certain areas of construction. For example, a tool like Just in time (JIT) is for improving the supply chain of the construction project rather than scheduling, LPS is more closely related to the planning and execution aspect of the project rather than quality or design and value stream mapping (VSM) is more focused on reducing the non-value adding activities within the processes

The amalgamation of LPS with other lean tools and techniques will help in removing shortcomings associated with LPS. It should be ensured that lean tools and techniques have objectivities and application methodologies that are fully compatible and aligned with the LPS processes. Lean tools and techniques for this study are selected from the unpublished work of authors, in which each lean tool is characterized by its objectivity and application methodologies. It facilitated the selection of lean tools for targeting the specific shortcoming of LPS.

Table 5.3. List of major LC tools and techniques (Chapter 4)

LC Tools	**Abbreviation**
Last Planner System	LPS
Pull approach	PULL
Just In Time	JIT
Concurrent Engineering	CE
Poka Yoka	PY
Daily Huddle Meeting	DHM
Set Based Design	SBD
Visual Management	VM
First Run Studies	FRS
Kanban	KAN
Line of Balance	L of B
Six Sigma	SS
Prefabrication/Modular	PF/MOD
Fail-Safe for quality and safety	FSQS
Integrated Project Delivery	IPD
Building Information Modelling	BIM
Value Stream Mapping	VSM
5S	5S
Theory of Constraints	TOC
Target Value Design	TVD
Standardized Process	SP
Kaizen	KAIZ
Failure Mode and Effect Analysis	FMEA

5.9. Integration of Lean Tools with Last Planner System to Overcome its Shortcomings

Based on the objectives and functionalities of lean tools, a matrix as shown in table 5.4 is developed in which targeted shortcomings are cross-matched with the suitable tools that can overcome shortcomings within LPS. Several tools are having objectives and application methodologies targeting the specific shortcomings in LPS. As an example, tools like FRS, FSQS, SS, KAIZ, PY, and TOC can facilitate LPS in finding out the root causes of problems and suggesting corrective measures. Similarly, VM, FRS, 5S, KAIZ, BIM, and VSM can provide excellent visualization capabilities during LPS. Although many tools are targeting the same shortcomings which at one side causing a state of confusion among the construction industry in deciding the best tool but on the other side also increasing the opportunity window for selecting the best tool that can fit into the organizational and project environment. Organizations implementing LPS have to decide which tool best fits within their operational needs and compatible with organizational needs. Moreover, the benefits offered by the tools and techniques can also be a source for identifying the tools that can facilitate the implementation of LPS. The data in table 5.4 can be used as a guideline in selecting the tools for the successful implementation of LPS. However, based on the theoretical research and number of case studies conducted based on performance evaluation, the compilation of data and subsequent ranking among the tools can be used as an effective means in selecting the most appropriate tool.

Efforts are made in proposing at least two tools for each area of improvement within LPS to give a broader window of selection for the adopters of the LC concepts. Tools are recommended based on the objectives and application methodologies as discussed in Chapter 4. The recommended tools are shown in Table 5.5.

Table 5.4. Targeted tools to eradicate the shortcomings in LPS

Short comings	**VM**	**DHM**	**FRS**	**5S**	**FSQS**	**SS**	**KAN**	**JIT**	**KAIZ**	**CE**	**PF**	**LOB**	**PY**	**TOC**	**SP**	**BIM**	**IPD**	**SBD**	**TVD**	**VSM**	**FMEA**	**BR**
Root cause Analysis			*		*	*			*				*	*								*
Visualization	*		*	*					*						*	*				*		
Supply Chain Management				*			*	*														
Lack of communication	*															*	*	*				
Constraint Analysis									*			*		*	*						*	*
Contracting and legal issues										*							*					*
Lack of collaboration		*	*			*		*	*	*				*	*	*	*	*	*			*
Nonperformance of risk analysis					*									*		*					*	
Issues related to flow	*	*	*	*			*	*	*	*	*	*		*	*	*	*	*		*	*	*
Involving people /Subcontractors/ Suppliers		*	*	*		*		*	*	*				*	*	*	*	*	*	*	*	*
Lack of training		*	*			*																*
Issues with Look ahead planning	*		*			*			*					*	*	*	*			*	*	*

Table 5.5. Recommended tools for integration with LPS

S/No	Targeted shortcoming	Recommended Tools	Perceived benefit
1.	Root cause Analysis	SS and FRS	Conducting root cause analysis and suggesting corrective actions
2.	Visualization	BIM and VSM	Schedule planning will become more reliable based on the future prediction of outcome in collaboration with multidisciplinary teams
3.	Supply Chain Management	5S, JIT, KAN	Improves the supply chain of the project and reduce the wastes related to materials
4.	Lack of communication	BIM and VM	Automatic generation and upkeep of all information with access to all key stakeholders at any time
5.	Constraint Analysis	SS, VSM, LOB, and TOC	Pre-visualization of all upcoming constraints and eliminating the constraints that are continually coming, Reduction of all non-value-adding activities thereby improving the schedule and reducing waste related to people
6.	Contracting and legal issues	IPD and CE	Improves relationship between all key stakeholders including the subcontractors
7.	Lack of collaboration	IPD, BR, and DHM	Increased collaboration among all stakeholders, simultaneous involvement of downstream players and subcontractors
8.	Nonperformance of risk analysis	BIM, TOC, FMEA	Effect of external risks like climate change, site restriction, material availability, etc can be minimized
9.	Issues related to flow	BIM, SBD/TOC, FRS, VSM, 5S	Improves and maintains continuous flow during construction Minimize the conflicts that can occur due to either wrong interpretation of design Add value and reduce design changes
10.	Involving people /Subcontractors/ Suppliers	IPD, DHM, BR, VSM	Subcontractors will start owning the project and give their best because of the pain/gain concepts
11.	Lack of training	FRS, BR	Provides firsthand knowledge about processes and implementation strategies for any activity
12.	Issues with Look ahead planning	BIM, BR, TOC	Better visualization and collaboration, removal of constraints

5.10. Development of Integrated Last Planner System (ILPS)

The biggest challenge for lean practitioners is to integrate different lean tools and techniques into various phases of LPS. Each LPS phase has been developed to plan and execute construction activities during various phases of construction. The master and phase schedules have to be developed well before the start of construction to identify the key milestones that must be planned using reverse planning. Lookahead plans are developed during the construction for removing the likely constraints and making the work process ready. Only activities that are constraint-free are kept for construction. Weekly schedules are developed to align the planned work process ready for smooth execution. In the end, complete construction is monitored and continuously improved for achieving the desired efficiency. All these phases have distinct functions and outcomes which must be managed separately. The diversity within LPS compels the users to manage each phase separately. The problem arises when LPS is treated and managed as one unit thereby neglecting the diversity of each LPS stage. To remove shortcomings of existing LPS, the lean practitioners must manage every LPS stage independently by taking measures that can increase the efficiency of each phase. The use of different lean tools and techniques during various LPS stages can be an effective way to manage LPS.

As already explained, lean tools have exclusive objectives and functionalities that can only work in harmony with each LPS stage, if they are compatible and complementary to each other. As an example, just in time (JIT) can be an effective tool in planning and managing supply chain activities during the look-ahead stage. Whereas, use of JIT during the master schedule can be less effective. Similarly, the theory of constraint (TOC) can be used to remove constraints during lookahead planning. Based on the objectives and functionalities of lean tools that can effectively remove LPS Shortcoming during different stages of LPS, a schematic model as presented in figure 5.3 is developed and explained below:

5.10.1. Increased Collaboration

Collaboration through the big room (BR) has to be ensured during all phases of LPS and the extent of collaboration will decide the degree of implementation of LPS. More collaboration among project participants will result in better performances of LPS. Collaboration from the key stakeholders at the early stages and involvement of all team members including subcontractors in later planning will eradicate the coordination problems among the project teams.

5.10.2. Improved Visualization During Design and Construction

BIM is the most powerful tool that should be utilized in visualizing the construction and should be incorporated in all the planning stages of LPS (master, reverse phase, look ahead, and weekly). During the design stage, the integration of BIM and SBD/TVD will ensure the eradication of all later on design and construction conflicts and also improves the workflow. Coupled with VSM, it will add value to the project in designing and master planning the project by incorporating all design/cost alternatives and removing/minimizing non-value adding activities respectively. During master planning, the use of BIM will be beneficial in identifying the milestones and planning the project in a way it is best visualized. Efforts should be made that the design and master plan should be as realistic and constructive to reduce the later on changes in design and schedule to a minimum.

5.10.3. Improved Relationships

The implementation process will be reinforced by using the IPD method which works in harmony with the LC philosophy. IPD promotes collaboration, builds confidence and trust among stakeholders, and ensures in taking measures that can be beneficial for all the project participants.

5.10.4. Risk Analysis

Reverse phase scheduling is based on the pull technique where the succeeding activity decides the delivery date of the preceding activity. Consideration of likely risks during this phase will remove uncertainties in planning. Moreover, the use of FRS to streamline the implementation processes will enlighten the teams in performing tasks and will gear them up for the coming assignments. To evaluate the external risks, risk analysis should be performed after the master planning or scheduling is complete and should be given due weights in the reverse phase scheduling by using tools like FMEA. VSM will further refine activities based on their value-adding capabilities. After performing the risk analysis and streamlining the implementation process, the tasks that can be performed will be identified and retained for look-ahead planning.

5.10.5. Improving Lookahead Planning

Two important challenges for look-ahead planning are the lack of constraint and root cause analysis. The reverse phased schedule can further be scrutinized by performing constraint analysis to identify final tasks ready for work. Tools like TOC can be used in assessing the likely constraints and identifying the recommended strategies in removing the constraints. Working procedures should be redefined after removal of the constraints by using BIM and FRS and involving downstream players along with subcontractors and suppliers. Their involvement will help in adjusting the tasks that have to be performed on-site. SS is an excellent tool for analyzing the quality and performance data and for identifying the likely causes of low performances. JIT and KAN will effectively facilitate in planning the issues related to supply chain and material management. Material management has to be deliberately planned and coordinated during look ahead and weekly planning respectively using the JIT approach.

5.10.6. Improving Weekly Planning

Weekly planning is carried out for all the works that have to be performed and for which the organization is fully equipped and ready for the likely responsibilities. Last-minute coordination and refinement within the schedule are carried out. Downstream players and subcontractors/suppliers are extensively involved in this stage for identifying their state of readiness and giving their inputs. BIM can provide an excellent platform for coordinating and final alignment of all teams for their respective tasks. FRS can be utilized in refining the skills and getting acquainted with the new/uncommon activities. Tools like JIT and KAN can be utilized for ensuring the timely delivery of materials from suppliers. Storage places if required are further reconciled based on the site requirements and adjustments are made. Worker's tools can be arranged using 5S to smoothen the issuing procedure and ensuring safety at the site. The project will kick off after weekly planning and will be measured for continuous improvement and assessed regularly during look ahead and weekly planning stages. DHM also provides a key platform in which cross-functional teams work together to resolve the issues in a coordinated manner. The whole cycle has to be performed periodically so that the implementation of LPS can result in enhanced benefits.

5.10.7. Continuous Improvement

Organizations should develop performance measurement tools so that they can analyze their performances and further improvements can be carried out. LPS uses weekly PPC as an effective measurement tool for measuring construction productivity. However, apart from PPC, the number of defects identified and rectified in weekly assignments should be recorded and further analyzed to ensure quality completion of construction assignments. Analysis and results of both these measurements will be used to ensure the refinement in the processes by correcting the malfunctions and finally a system should be evolved that looks to build itself through continuous learning

5.10.8. Suggested Guidelines for Implementing ILPS

No matter how good a model is, if it's not implemented properly, the results can be damaging. Unfortunately, the construction industry is struggling in getting the full potentials of LPS due to the non-availability of any robust implementation plan. Implementation of ILPS will always be a challenge for the construction industry due to its integration and amalgamation of many tools and techniques. Realizing the implementation challenges, a complete implementation guideline for ILPS is prepared based on the model presented in figure 3. Each ILPS stage is further explained in table 5.6 to streamline the input, processes, and outputs required for its successful implementation. The organizations implementing ILPS can follow the guidelines as shown in table 5.6 to develop their implementation techniques by duly incorporating lean tools and techniques based on their capabilities, expertise, resources, project environment, and prevailing site conditions.

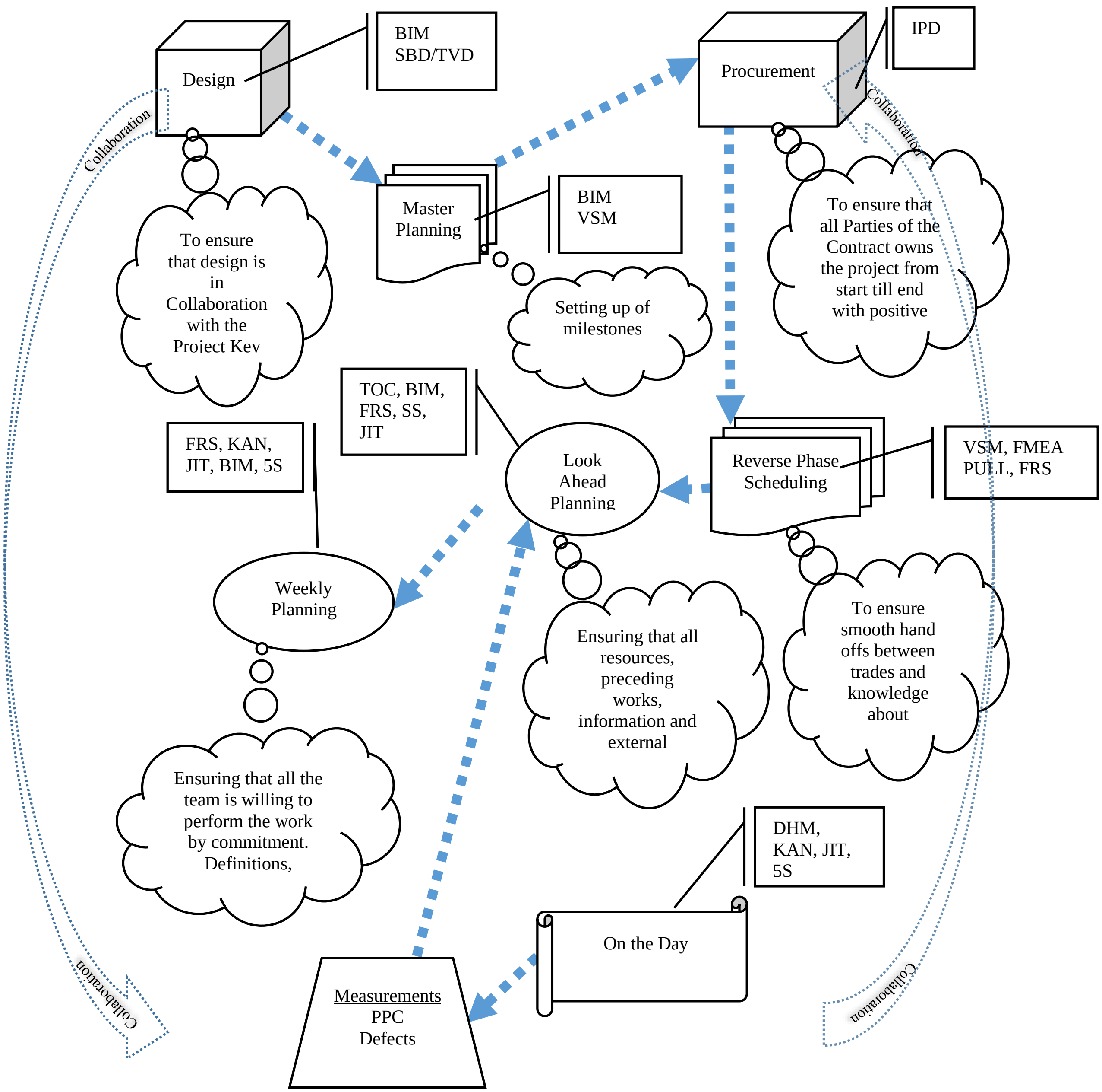

Figure 5.3. Integrated last planner model (ILPS)

Table 5.6. Implementation tool of ILPS

Integrated Last Planner System (ILPS)-Implementation tool for various stages		
Master Planning		
Input	**Process**	**Output**
3D Model for architectural plans 3D Structural design Key personnel’s responsibilities chart Organizational resources Input from owner and architect Target Cost	4D Scheduling using BIM 5D estimating using BIM Collaboration through Big room (BR) VSM	Master schedule/planning Value/non-value adding activities Details of milestones
Reverse Phase Planning		
Input	**Process**	**Output**
Master Schedule Details of milestones Key personnel’s responsibilities chart Organizational resources Input from owner, contractor, architect/engineers Capabilities of sub-contractors and suppliers	Revise 4D Scheduling using BIM Collaboration through Big room (BR) Risk analysis (FMEA) Pull scheduling VSM Identifying requirements of succeeding activities for planning preceding activities	Reverse Phase Schedule Revised Value adding and non-value adding activities Revised milestones Identified risk and allocation of risks to tasks
Look Ahead Planning		
Input	**Process**	**Output**
Reverse Phase Schedule for coming 6 weeks Revised milestones Key personnel’s responsibilities chart Organizational resources Input from the owner, contractor architect, downstream players Capabilities of sub-contractors and suppliers Identified risk and allocation of risks to tasks Updated evaluation of progress	Identifying constraints using TOC Collaboration through Big room (BR) Removing constraints Planning for next 6 weeks Visualization of the complete process through BIM FRS to identify the methodologies of complicated and uncommon tasks Evaluating the shortcomings in the performed tasks and incorporation of suitable remedies for avoiding the malfunctions in the plans	Work-ready list with no constraints Allocation of resources and responsibilities to task - list List of backlogged activities having constraints 6 weeks schedule List for ordering the key material
Weekly Planning		
Input	**Process**	**Output**
6 weeks look ahead schedule Work-ready list with no constraints Key personnel’s responsibilities chart Organizational resources Input from the contractor, subcontractors/suppliers, and downstream players Allocation of resources and responsibilities to task - list Identified risk and allocation of risks to tasks Updated evaluation of progress	Final coordination and commitment from all participants Collaboration through Big room (BR) Check for availability of resources including materials and equipment Planning for the week Ensuring JIT delivery of materials Making storage places ready using KAN and 5S approaches FRS to identify the methodologies of complicated and uncommon tasks	Work-ready list with no constraints Allocation of resources and responsibilities to task - list List of backlogged activities having constraints 6 weeks schedule
Continues Monitoring		
Input	**Process**	**Output**
Executed tasks progress Input from owners, Architects/engineers, contractor, subcontractors/suppliers, and downstream players	Measuring the PPC weekly Measuring the number of defects in processes and quality issues during the week Details about likely barriers in executing tasks Recording the lesson learned and remedial measures Analyzing the progress and identifying the week/strong areas Suggesting the remedies for incomplete assignments and low-quality performances	Updated evaluation of progress Identification of the week/strong actions during execution of the tasks List of likely risks/barriers causing low performances Plan to improve the performances

5.11. Significance of ILPS

Considering the tremendous benefits of LC, organizations are always on a hunt for finding tools and techniques that can facilitate them in adopting lean practices. The success of LPS marked its ascendency over other lean tools and organizations following LPS started considering them as lean companies. However, it was found out that isolated application of LPS exposed many areas in construction that were not managed by lean philosophies. Resultantly, the isolated applications of LPS led to many shortcomings within the system which prevented the optimized performances. ILPS was developed for targeting the shortcomings of LPS by integrating them with other lean tools and techniques. Significance of ILPS are:

- Facilitate organizations in implementing LPS fully
- Shortcomings of LPS can be removed
- Has the capability of targeting all areas of construction as advocated by lean philosophy?
- Organizations can claim themselves as the lean organization as ILPS is developed covering all principles of LC
- Implementation of ILPS will remove inefficiencies and wastes prevalent in construction projects and will improve productivity.

5.12. Conclusions

Construction Industry needs the efforts that can make improve construction productivity and control the time and cost overruns. LC was developed to overcome the performance-based issues of the construction industry. LPS is a tool in practice for the last 24 years to achieve the goals of LC. Although researchers have measured the improved performances by implementing LPS yet the full benefits are still to be explored due to some inherent issues with the LPS. An effort has been made in this study to combat those areas of LPS that are hindering its efficient implementation by integrating the existing LPS model with compatible LC tools and techniques. With the identification of the shortcomings in the LPS and attacking those shortcomings with the best alternative tool, an efficient integrated last planner system (ILPS) is modeled in this study. A toolbox for implementing various stages of ILPS is also presented to facilitate the construction industry for the efficient implementation of ILPS. Theoretically, this study will increase the body of knowledge by explaining the key functionalities and methodologies involved during the efficient implementation of LPS. It will increase the opportunity for utilizing the LPS to its full potential by integrating it with other tools and techniques. Practically, this study will provide the contractors a way forward in implementing the LPS in a manner that will result in the best possible results with improved performances. Although the major aim of this study was to develop the conceptual efficient ILPS model based on the literature and case studies, however, the efficacy of this model should be tested in the field for evaluating its practicability and validity. For the researchers, the ideas presented in this study can provide a foundation for further exploring the integration of LPS with other lean tools and refining the ILPS after its application on construction projects.

6. PAPER 4: EXPLORING FACTORS FOR IMPLEMENTING LEAN CONSTRUCTION FOR RAPID INITIAL SUCCESSES IN CONSTRUCTION[4]

6.1. Abstract

Despite lean philosophies are an emerging phenomenon in manufacturing and construction project management for waste reduction and improving sustainability, still, the construction industry is struggling in utilizing its full benefits either due to lack of awareness or convoluted implementing strategies. Companies who are implementing lean processes but unable to achieve immediate initial successes most likely dissociate themselves from lean in the future due to issues they experienced. This study is to provide robust strategies to the construction companies in the selection and implementation of lean tools with a focus on (1) meeting immediate initial successes and (2) adding elements of practicality. A questionnaire survey was designed after a systematic literature review to explore the factors required for the successful implementation of lean tools and techniques. Series of statistical analyses were performed to identify multiple sub-factors that assist in selecting and implementing lean tools and techniques. Many valuable findings generated from the study eventually lead to practical suggestions for new Lean adopters to implement lean construction. Project managers, who are somewhere struggling in lean implementation, will be benefitted from this study by applying innovative project management approaches as advocated by lean philosophies.

Keywords**:** Project Management; Lean Construction; Lean Project Delivery System; Implementation strategies; Sustainability, Lean tools, and techniques

[4] The material in this chapter was co-authored by Mughees Aslam, Zhili (Jerry) Gao, & Gary Smith and published in Journal of Cleaner Production. Mughees Aslam had primary responsibility of developing and conducting survey from the lean practitioners. Mughees Aslam collected al the data and also performed all the statistical analysis. Mughees Aslam discussed the results and wrote the conclusions that are advanced here. Mughees Aslam also drafted and revised all versions of this chapter. Zhili (Jerry) Gao & Gary Smith guided the study process, directed the framework of the paper and checked the data analysis as well as proofreading.

6.2. Introduction

Lean construction (LC) was developed to overcome the challenges of the construction industry such as productivity loss (CLMA 2016), a tremendous amount of waste (Koskela, 1992; Mossman, 2009; Diekmann 2004), and environmental issues (EPA, 2018; Egan report, 1998). It has been established as a strong enabler for effectively implementing construction operations and supply chain management (Schramm et al., 2006). Over time some successful implementations of lean construction also paved the way for improving the efficiency of the construction industry. According to Dodge and Analytics data (2016), the construction projects undertaken by using lean practices are more likely three times to be completed ahead of schedule and two times to be completed under the budget. Moreover, according to McGraw Hill (2013), more than 70% of 95 responding lean practitioners opined that LC led them to better performances and reduced waste. Similarly, several case studies showed that LC has shortened project schedule by 6- 25% (Ballard and Kim, 2007; More et al., 2016; Erol et al., 2017), saved cost by 5-50% (Ballard et al. 2007), and increased productivity by 5-50% (Locatelli, 2013; Dallasega, 2016).

Despite a strong theoretical base and several successful lean-based construction projects, still, the required affluence for LC is lacking in the construction industry. Simonsen et al. (2014), explained the fact that although substantial evidence is available for lean benefits, however, the data and results mainly reported by lean practitioners are difficult to be compared across projects due to regional differences. Similarly, there are very limited documents available that explained the failures of LC. Green and May (2005) also questioned the realism and practical adoption of LC due to its broad-based terminologies which need to be explained in detail for the general construction industry. According to Leong et al (2015), the reason for the lack of response towards LC is due to failure to properly define what lean means practically. The main challenges as shown in Chapter 3 that are inhibiting the adoption of LC range from complexities in understanding LC, to a general myth that LC is a gradual implementation process but the construction industry is looking for rapid initial successes, to lack of formidable strategies to implement LC at the micro-level (the level at which the downstream players operate)

LC advocates are fully aware of the situation and are trying to evaluate factors for successful and widespread implementation of LC (Kawish, 2017; Sarhan et al., 2018; Bashir et al., 2015; Warcup, 2015; Kim and park, 2006; Alarcón et al., 2011; Ballard and Kim, 2007). However, the factors identified are very broad-based and therefore cause difficulties for the downstream players to implement the LC. This lack of formidable strategies to implement LC at micro-level and broad-based successful factors has made the implementation of LC very complex thereby refraining the construction industry to achieve rapid initial successes.

Currently, very meager research is available in identifying modalities that can lead to immediate successes considering the operational aspects of LC implementation. To address these challenges, an effort has been made in this study to explore successful factors at the micro-level so that more realistic and workable conclusions can be drawn to improve the construction operation and supply chain management by using the Lean approaches. The main research question that how lean implementation protocols can be improved to get the optimized benefits right from the start. This question is explored by analyzing each successful factor based on its practicability and thereby defining strategies to help the construction industry implementing the LC more effectively. This study will provide practical strategies to the construction industry for achieving rapid successes right from the outset. Constructors who are somewhere entangled between LC and its implementation from a practical point of view will be benefitted from this study.

6.3. Research Background

LC is a philosophy conceptualized in the early 90s by visualizing construction in three perspectives as transformation, flow, and value (Koskela 1992) and having its root to the lean production system (or Toyota Production system). The major motivation for using lean concepts in construction is to overcome the tremendous waste already infiltrated within its processes, material, and flow (Egan Report 1998, 2002). According to Diekmann (2004), almost 50% of labor time is being wasted because of many non-value-adding activities like waiting for material or decision, moving, inspections, rework, large inventories, and overproduction (Koskela 1992). Traditional management approaches, like Design Bid Build (DBB), failed to effectively address the non-value adding activities and meeting the customer's requirement because they build on the transformation perspective only. As a result, the construction industry started looking towards LC for overcoming its challenges.

Operations and supply chain management (OSCM) famously was defined as the design, operation, and improvement of the systems that create and deliver the firm's primary product and services (Jacobs et al., 2018). Like OSCM, lean is also concerned with the management of the entire system that produces a product and is considered to be the most significant operation and supply chain approach. In construction, different project participants like contractors, subcontractors, suppliers are tied together in a contractual relationship, and with the owner and architect/engineers (Broft and Pryke, 2019). Moreover, these stakeholders have to effectively manage available resources for the completion of the project. The lean approaches provide a platform for managing the operations of transforming the raw resources into the highest-performing production system by devising the construction layout, material, and information flows (Schramm et al., 2006). Lean supply chain management provides highly transparent partnering, mutually trusting, and longstanding relationships between contractors, suppliers, and vendors to create a physically efficient supply chain (Kerber and Dreckshage, 2011; Emuze et al., 2016). According to Tommelein et al. (2009) supply chain management has become an integral part of lean delivery because it not only facilitates lean supply but also supports work structuring of the production system. By using the conceptual framework of OSCM, LC, if implemented successfully, can have the potential of overcoming most of the challenges of the construction industry.

Apart from reduced wastes, improved productivity, control on the project schedule, and cost, the use of LC has also resulted in reducing the adverse effects of the construction industry on the environment. According to EPA (2015), the construction industry is responsible for generating 548 Million tons of waste in the year 2015 which has a detrimental effect on the prevalent environment. The construction industry is heavily dependent on natural resources like aggregates, cement, petroleum products like fuel and bitumen, wood and steel, etc. Excessive use of such material is causing further deterioration of the limited natural resources available. According to the Egan report (1998), the construction industry is wasting almost 10% of these materials on almost every project. Lean supply chain management, due to its tremendous effect in reducing the wastes, can help in improving the sustainability profile of the construction industry and contributes especially to a reduction in the environmental footprint of the construction industry (Sertyesilisik, 2016; Lamming, 1996; Martinez, 2013).

However, despite strong philosophies and also some successful implementations, the required affluence in adopting lean construction practices is very inadequate. As per the survey conducted from a sample of 193 respondents by McGraw Hill construction (2013), 48% of construction companies in the USA are still not aware of the LC. Similarly, lean concepts are also sparsely welcomed by much of the construction industry in the UK and implemented in pockets only (Bashir et al 2015, Mossman 2009). As per Wandahl (2014), the rate of adoption of LC in the Danish construction industry seemed to be extremely low with only 6% of the sampled respondents were using LC. According to Santorela (2017), 74% of companies that institute lean initiatives in the USA have seen little success and the major reason for these low performances is the lack of meaningful adoption of lean culture within the organizational environment. The major barrier is not respecting people and the lack of opportunities and empowerment provided to the employees to flourish and finding ways of doing the things respectively.

6.4. Hypothesis and Logic Development

Although, the state-of-the-work has been done in identifying factors that can lead to the successful implementation of LC but fell short in providing a more practical framework to implement them during construction. These factors are broad-based and need to be explored at a micro level to indoctrinate the elements of realism and practicability in it. The construction industry is looking for implementing strategies that are more practical and easily adaptable.

As an example, it has been identified that employees should be given enough empowerment for successful implementation of LC (Bashir et al., 2015; Kawish, 2017; Shang and Sui Pheng, 2014) but at the same time, level of empowerment for different actors like field managers, workforce or even subcontractors and suppliers are meagerly explained in lean literature. Similarly, lean advocators consider both standardization and flexibility as key ingredients for lean whereas both terminologies contradict each other. Therefore, there is a need to establish the degree of standardization as well as flexibility in managing lean processes and methods to avoid this conflict.

The selection of appropriate lean tools and techniques is critical for lean successes (Mostafa, 2013; Pavnaskar et al., 2003; Wards, 2015; Shou et al., 2016) but the strategies to select lean tools and techniques are meagerly explained in the literature especially within the context of compatibility with construction processes (Narayanamurthy and Gurumurthy, 2014; Lovatt and Shercliff, 1998), probably because lean developers think that lean is not only about tools (Korb and Ballard, 2018). On the contrary, most construction companies use some kind of tools and techniques to facilitate the implementation of LC. Many researchers believe that even more than one lean tool and technique should be applied to achieve all the principles of LC because one tool is not sufficiently covering all the lean principles and functionalities (Wards, 2015; Aslam et al., 2020a). The importance of lean tools and techniques in facilitating the implementation process and getting optimized results must be explored in detail.

High commitment from project participants is an important factor for the successful implementation of LC. A lot of literature is available which stresses the highest level of commitment from project participants (Enshassi et al., 2019; Warcup, 2015; Ayarkwa, 2011). However practically, it’s not possible to have a top-level commitment from all project participants especially when construction companies are just at the start of their lean journey. Initially, strong resistance might be encountered by some project participants that can affect their commitment. Even a low commitment level at the start doesn’t mean to abolish the decision of moving towards lean. Whereas, at this point, companies must know the minimum threshold level of commitment required from every project participant to achieve initial success.

Researchers have identified that close relations (Nesensohn et al., 2012; McGraw-Hill, 2013), early involvement of partners (Kawish, 2017; Shang and Sui Pheng, 2014) and collaborative contractual agreements play an important role in the successful implementation of lean tools (Kim and Park 2006; Ayarkwa et al. 2011; Ballard and Kim, 2007). However, most of the research in this regard seemed to be biased towards using collaborative contractual agreements like integrated project delivery (IPD). It would be more practical and realistic if the comparison of collaborative agreements to other project delivery methods (PDMs) is carried out to find the differences. This will remove the biasedness and will be more meaningful for the construction industry to understand.

The provision of adequate opportunities for training and understanding lean tools and techniques are considered as the biggest enabler for the successful implementation of lean construction (Mostafa et al., 2013; Sarhan, 2011; Shang and Sui Pheng, 2014). Whereas the most appropriate training methods for imparting required education and knowledge need to be identified. The requirement and importance of utilizing external facilitators/trainers services can be advantageous for the new lean companies that want to have rapid initial successes. However, this aspect needs to be further tested and evaluated.

Many lean practitioners believe that companies should have process-oriented improvement while implementing the LC (Mitropoulos and Howell's 2001). They aim to reduce the number of steps required and remove waste to improve the process for better results. This approach can lead to successes but it will take time for the lean companies to start experiencing rapid successes. Another approach can be using result-orientated outcomes right from the start. Both motivations have their pros and cons; therefore, there is a need in exploring the type of motivation a company should have before moving towards LC for achieving rapid initial successes.

There is a lot of variation in reported successes of LC in the literature. Many lean researchers have witnessed improvement in terms of time, cost, and productivity within the range of 1-30% whereas others have measured the improvements even greater than 30% (Ballard et al. 2007, More et al. 2016, Erol et al., 2017, Ballard et al. 2008, Locatelli 2013, Dallasega 2016). Although lean literature seemed to be against any improvement goals, realistically the companies always want to have some kind of improvement goals which they want to achieve, and that will increase their morale and confidence for implementing that change. Otherwise, the motivation for using LC will be died out if rapid initial improvement goals are not achieved.

To increase the initial success rate of LC, it is important to evaluate success factors at the operational level so that realistic implementation of lean practices can be made possible. To fill this gap, the objective of this study was set to identify factors at the micro-level for Implementing LC for rapid initial successes in construction

To achieve the objective of this study, the following alternate hypotheses (H_a) were tested:

- Rapid initial successes can be achieved if companies have the motivation of gaining a better competitive advantage
- A lean organization should have a main focus on improving the processes irrespective of the results
- External trainers can help in implementing lean construction
- Progress should be measured weekly for successful lean implementation
- Few of the initially selected tools can achieve optimum results
- Most of the initially selected tools are implemented properly
- There is some tendency to selecting the wrong tools and techniques
- Delivery methods other than Collaborative project delivery (IPD) can also facilitate the successful implementation of LC

- Top-level commitment is required from all the management tiers along with external actors and the workforce for starting LC.
- Equal and high-level empowerment should be given to all the management tiers along with external actors and the workforce for starting LC?
- Provision of additional training is the most important additional support that should be given to the lean teams for successful implementation of LC, in contrast to additional funding
- Benefits expected initially using LC should be greater than 20%

Apart from testing the hypothesis above, this study also explored the selection and modification of the construction process, lean tools, and field management, and workforce training.

6.5. Methodology

To find answers to the problems identified in this study, the main approach consisted of two major components: literature review and self-structured questionnaire. A literature review was carried out to determine the prevailing barriers and factors associated with the successful implementation of LC. The identified barriers and factors are further mapped with the prevailing LC principles or focused areas as mentioned in the literature. Resultantly, certain gaps and areas are identified which are hampering the progression of LC and need immediate attention and discussed in section 5. An overview of the complete methodology is shown in figure 6.1.

6.5.1. Questionnaire Development

The questionnaire was developed to address the gaps already identified above (section 4). Each question was specifically designed to get clear and meaningful responses for identifying the factors leading to successful selection and implementation of lean tools and techniques. To achieve this, every category is further subdivided into sub-factors for evaluation at a micro-level. The questionnaire was administered in four parts. The first part addressed questions (4) relating to the respondent’s experiences, organization type, and responsibilities. The second part relates to questions (3) regarding the overall LC program. The third part includes questions (10) related to lean-based projects. The fourth part (13) is specifically designed to get the respondent’s views for successful lean projects only. Depending upon the nature of the questions, four types of responses were asked as binary, multiple options, Likert scale (vary from factor to factor), and open-ended questions. The complete questionnaire survey is given in Appendix B.

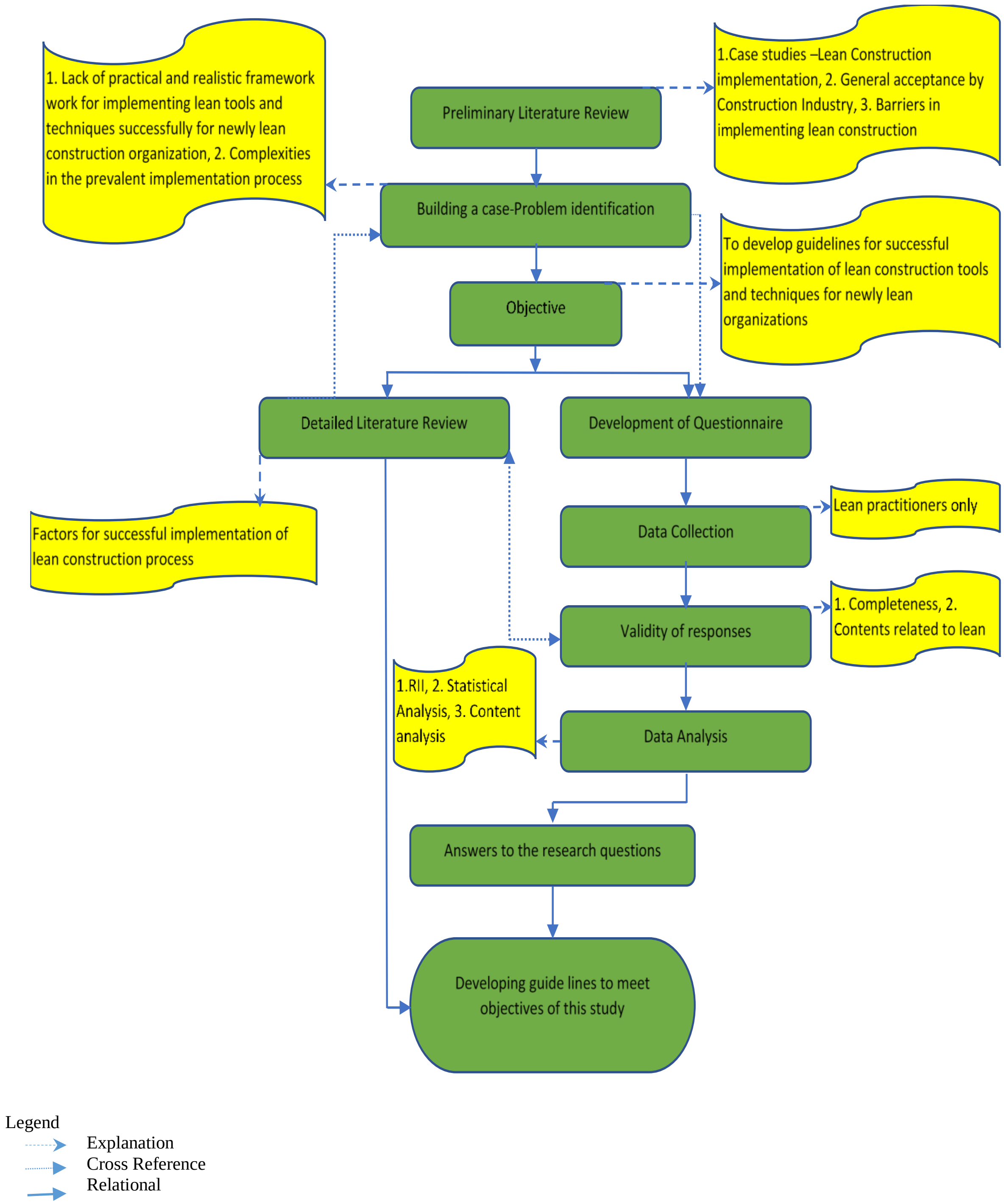

Figure 6.1. Research methodology for chapter 6

6.5.2. Sampling Technique

To test the hypotheses and finding answers to the questions, it was mandatory to get responses from those who have been using lean practices frequently. Resultantly, purposive sampling techniques were adopted to get responses from those respondents who have lean experience and belonged to an organization that has implemented LC. To remove any biasedness, it was ensured that respondents are part of different organizations who worked on varying types of projects. The forum of Construction Users Roundtable (CURT) and Lean Construction Institute (LCI) was used as the main source for identifying individuals who worked for organizations engaged in LC practices. Questionnaires were sent to respondents who were at a different level of management for getting diversified responses.

The questionnaire was sent to 184 respondents, however, a total of 66 responses are received back. Initial scrutiny is carried out for the completeness of the survey. Only those responses are kept for analysis which has a completion rate of more than 50%. The open-ended questions are further scrutinized to see whether respondents are true representatives from the population of LC practitioners. In the end, a total of 58 responses are kept for further analysis making a response rate of almost 30% which is considered to be good for construction (Black et al., 2000)

6.5.3. General Information About the Respondents

Out of the 58 lean practitioners who responded to the questionnaire, 36.21% were from construction manager firms, 22.41% from contractors, 20.69% from the owner, and 18.97% from Architect/Engineers firms. This implies an even distribution of responses from all types of organizations. 24.56% of project managers and lean coordinators each, 29.82% of construction managers, 5.26% of the superintendent, and 14.04% from other categories responded to the survey. Other categories included lean manager, directors, designer, chairman, and contract manager. The bulk of the respondents (73%) have an average lean experience between 1-4 years and 5-10 years. Whereas 18.64% have lean experience for more than 10 years. The minimum response rate (8.47%) was from respondents having less than 1 year of experience.

Overall response pattern suggested that survey results would be quite valid as it embodied a sample that has the lean experience, is equally represented by all types of the construction organization, and is evenly responded by respondents having different responsibilities.

6.5.4. Data Analysis

The collected data were analyzed using the statistical package SPSS 17, relative importance index (RII), and content analysis. Because of the non-parametric nature of the data, analysis is restricted to non-parametric tests like Chi-square, binomial, Wilcoxon, Friedman, and post hoc Friedman tests.

6.5.4.1. Chi-Square and binomial test

The chi-square test of goodness is used to determine whether there is a significant difference between subfactors. A significance value (α) of 0.05 was used to test the differences. For values lesser than 0.05, the binomial test was used for finding the differences between two options at 0.5 proportions. The significance value obtained from the binomial test was adjusted by using Bonferroni correction because of multiple numbers of comparisons possible and has been recommended by Chen et al (2017). A chi-square test was used to find the difference between single or multiple responses under the same category.

6.5.4.2. Wilcoxon test

Wilcoxon test was performed to check the threshold weight of the specific individual factor with the following hypothesis tested at the significance level (α) of 0.05.

- Null Hypothesis = Sample median is less or equal to the specified weight
- Alternate Hypothesis = Sample median is greater than the specified weight

6.5.4.3. Friedman and post-Friedman test (PHOC-FRIED)

Friedman's test was carried out to check the difference of medians between different factors within a single category using a significance level (α) of 0.05 and 0.1. The p-values between 0.1-0.05 will yield some difference whereas values lesser than 0.05 indicate a strong difference between factors. To determine which two factors, differ, the post hoc Friedman test was performed.

6.5.4.4. Cronbach's alpha

To check the reliability of Likert scale responses, internal consistency was performed using Cronbach's alpha (α). Research indicated that data values are internally consistent and suitable for further values if (α) value is 0.7 (Punnakitikashem et al., 2013; Yunus et al., 2017). The results for this study show that at on average the Cronbach's alpha value is 0.8 with the highest value for responses of commitment and empowerment level (0.821), followed by Improvement ranges (0.824) and tools and process selection (0.80). The values greater than 0.7 indicated that all sub-factors are reliable and measured with the same consistency and can be used for further analysis.

6.5.4.5. Relative importance index (RII)

Considering the non-parametric nature of data, it is not suitable to establish a meaningful ranking among factors based on mean and standard deviations (Chan and Kumarasway, 1997).

Instead, RII is the most common method of identifying the relative importance among each identified factor (Gudienė et al., 2013; Choudhry et al. 2014). RII was performed by using the following equation (Gudienė et al., 2013; Choudhry et al. 2014):

$$RII = \sum(aX)/A \times N$$

Where, a = weights given to each response, ranging from 1 (first scale or lowest scale) and increased numerically by addition of 1 till the last scale (Highest weight), X=Frequency of occurrence of “a”, A=Highest weight and N=Total number of respondents

The analysis procedure differs for different response types. The complete analysis procedure for different types of responses is shown in table 6.1.

Table 6.1. Analysis theme

Response type	**Internal Consistency**	**RII**	**Chi Square α = 0.05**	**Binomial test - Comparing two levels α = 0.05**	**Wilcoxon test α= 0.05**	**Friedman test α = 0.05 & 0.1**	**PHOC FRIED α= 0.05**	**Content analysis**
Multiple options			x	x				
Single option			x	x				
Likert Scale (multiple Cells)	x	x			x	x	x	
Binary			x					
Likert Scale (single Cell)			x	x	x			
Open-ended								x

All the open-ended responses were analyzed using the content analysis approach. Keywords were established and matched for similarities in the responses. The frequency of the matched words was used as the main method for analysis. Narratives of open-ended questions were not intended to deduce separately from the data but to highlight those aspects which were not covered in the questionnaire and deemed necessary for the implementation of lean tools and techniques.

6.6. Results and Analysis

6.6.1. Descriptive Analysis and Relative Importance Index (RII)

For process selection, ranges between 73%-80% indicate that all identified factors are important in selecting the construction processes for lean intervention. The inefficiency of exiting practices in managing the process (80%) and sensitivity of the processes in terms of time and cost (80%) are considered as the top two factors which can motivate the construction industry for lean intervention. For tool selection, ranges between 76-85% indicate that all the identified factors are important in selecting the LC tools and techniques. Applicability of lean tools with construction processes, maximum value/benefits in terms of cost, time, and productivity, alignment of lean tools and techniques with LC principles and organizational expertise are considered to be the top four factors to select lean tools and techniques, as all these have RII values greater than 80%. The results are enlisted in Table 6.2

Table 6.2. RII of factors for selecting construction processes and LC tools and techniques

Factors for Construction process selection	**RII (%)**	**Factors for LC Tools and Techniques selection**	**RII (%)**
The process couldn't be managed efficiently using existing practices	80	Selection of lean tool and techniques based on the most applicable tool for the construction process	85
Sensitivity of the process in terms of time and cost	80	Maximum value/benefits in terms of cost, time, and productivity	83
Compatibility of the process with the lean tool	73	Alignment between the objective of a lean tool and techniques with lean construction principles	80
The process is affordable in terms of resources	78	Organizational expertise	80
As a trial irrespective of the outcomes	76	Ease of implementation with existing other management tools	79
Organizational expertise in respective process	75	Tools and techniques which consume fewer resources to implement	76
The spillover effect of benefits to other processes 73	73	Selecting only those lean tools and technique that are familiar and traditionally tested	76

Collaborative delivery methods like integrated project delivery (IPD) or others are given the highest weights with an RII value of 85%. Whereas lifecycle delivery methods and design-build have RII (%) of 76% and 75% respectively. Delivery methods like construction manager at risk and design bid build have very low RII values. The details are shown in figure 6.2.

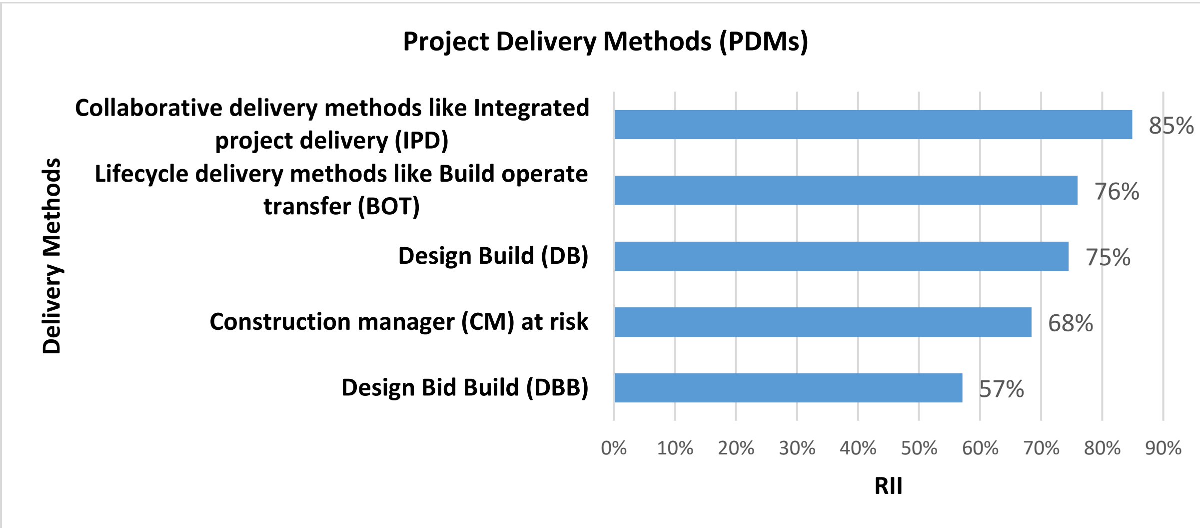

Figure 6.2. RII: Project delivery methods

The highest commitment level is required from upper, middle, and field managers with RII values greater than 80%. Similarly, the commitment level of the workforce, subcontractors, and suppliers in making the lean effort successful had RII of 73%, 71%, and 69% respectively. Upper and middle managers were highly empowered in successful lean projects with RII values of 87% and 83% respectively. Whereas, RII - 77% for field managers also shows that adequate empowerment is given to them as well. However, there is a need to empower the subcontractors, workforce, and suppliers to a certain degree for the successful implementation of lean tools and techniques. The details are shown in table 6.3

Table 6.3. Relative importance of commitment and empowerment level

Key personnel's/stakeholders	**Commitment level**	**Empowerment level**
Upper management	88%	87%
Middle management	83%	83%
Field management	80%	77%
Workforce	73%	67%
Subcontractor	71%	73%
Supplier	69%	67%

Lean respondents believed that on-the-job training for lean tools and techniques is the most effective training method for the implementation of lean tools and techniques with RII of 70%. Classroom lectures for training teams are the least effective method for learning the implementation process of lean tools and techniques with RII of 48%. The details are shown in table 6.4. Out of all the additional support parameters, additional time for preparation and training was given the most importance (88%) followed by upper management trust (85%). Authority for using companywide resources and additional funding or time support have comparatively lower RII (%) than others. The details are shown in table 6.4

Table 6.4. Relatively important training methods and additional support required

Training Methods	**RII (%)**	**Additional support required**	**RII (%)**
On the job	79	Additional preparation and training	88
Site visits	58	Upper management trust on "no fear on failure"	85
Workshops	53	Authority of using companywide resources	81
Videos	51	Additional Funding and/or time support	76
Classroom Lectures	48		

6.6.2. Hypothesis Testing

The developed hypotheses are tested by using a response pattern and the suitability of the statistical analysis tests. The test results along with the concluding remarks are given in tables 6.5, and 6.6 for chi-square, binomial, and Wilcoxon as explained in the methodology section.

Table 6.5. Test results-chi square test/binomial test

Categories	Chi-Square (at 0.05 Sig[@])	Binomial test (at 0.1 /0.05 sig[@])	Conclusions
Motivation			
Required by project agreement (M1)	0.031	1(0.1)	[*]SE at 0.1 sig that rapid initial successes can be achieved if companies have a motivation of M2 and M3
To gain Competitive advantage (M2)		1(0.1)	
To improve company image+ (M3)			
Goals			
Process Oriented	0.992	> 0.1	Not SE that a lean organization should have a main focus on improving the processes irrespective of the results, both are important
Result oriented			
Requirement of external trainers			
Internal trainers only	0.003	1(0.05)	SE at 0.05 sig that external trainers can help in implementing lean construction
Both internal and external		1(0.05)	
External only			
Frequency of measuring performance			
Weekly	0.000	1(0.05)	SE at 0.05 sig that successful implementation of LC is facilitated by measuring performances weekly, However, no difference found between weekly and monthly measurements
Monthly			
All others (quarterly, annually, at the end)		1(0.05)	
Never measured			
Effectiveness of Standardization			
None	0.212	> 0.1	Not SE that standardization is an effective measure for successful implementation of LC
Limited			
Some			
Very Effective			
[*]SE - Sufficient evidence			

Table 6.6. Results-Wilcoxon test/chi-square

Categories	Null Hypothesis Specified weight*	P-value	Conclusions at 0.05 Significance
Decision Process			
Initially selected tools achieved optimum results	> Few	0.000	SE that only a few of the initially selected tools achieved optimum results
The tendency of selecting Wrong tools and techniques initially	> Some	0.000	SE that there is a more tendency of selecting the wrong tools and techniques
Proper implementation of initially selected tools and techniques	>Few	0.000	Not SE that most of the initially selected tools are implemented properly
Project Delivery Methods			
Integrated Project Delivery (IPD)	> Somewhat	0.001	Not SE that delivery methods other than Collaborative project delivery (IPD) can also facilitate the successful implementation of LC IPD is the most suited delivery method for implementing the LC with influence scale values between "somewhat" to "great extent"
Design-Build (DB)	> Very Little	0.000	
Build-Operate-Transfer (BOT)	> Very Little	0.000	
Construction Manager (CM) at risk	> Very Little	0.028	
Design-Bid-Build (DBB)	> Very Little	0.914	
Commitment level			
Upper Management	> High	0.000	SE that top-level commitment is required from upper, middle, and field management for starting LC Not SE that top-level commitment is required from workers, suppliers, and subcontractors for starting LC. However, they should have some commitment to implementing LC.
Middle Management	> High	0.003	
Field Management	> High	0.024	
Suppliers	> Little	0.048	
Subcontractors	> Little	0.167	
Workforce	> Little	0.001	
Empowerment level			
Upper Management	> High	0.002	SE that high-level empowerment be given to upper and middle management for starting LC Not SE that high-level empowerment be given to workers and suppliers for starting LC. However, there should be given some empowerment while implementing LC. Field Managers and Subcontractors should be given more empowerment as compared to workers and suppliers.
Middle Management	> High	0.012	
Field Management	> between little and high	0.002	
Subcontractors	> between little and high	0.014	
Suppliers	> Little	0.000	
Workforce	> Little	0.000	

Table 6.6. Results-Wilcoxon test/chi-square (continued)

Categories	**Null Hypothesis Specified weight***	**P-value**	**Conclusions at 0.05 Significance**
Type of additional support			
Additional funding and/or time support	> Between Limited and reasonable	0.948	SE that Reasonable support should be provided for preparing and training for the lean tools and techniques and giving confidence to the lean teams instead of additional funding
Authority of using companywide resources	> Between Limited and reasonable	0.599	
Upper management trust on "no fear on failure"	> Between Limited and reasonable	0.023	
Additional preparation and training	> Between Limited and reasonable	0.009	
Improvement Ranges – Chi-square			
Time	> 20% > 30%	0.05 0.053	SE that improvement in reducing the time would be greater than 20% and lesser than 30%
Cost	> 20% >30%	0.070 0.332	Not SE that improvement in reducing the cost would be more than 20%
Productivity	> 20% >30%	0.013 0.784	SE that improvement in increasing productivity greater than 20% and lesser than 30%
Quality	> 20% >30%	0.092 0.40	Not SE that improvement in the quality would be more than 20%
Safety	> 20% >30%	0.027 1	SE that improvement in safety would greater than 20% and lesser than 30%

* Only the highest weight where significance is achieved is shown. lower ranges are already significant

@SE - Sufficient evidence

6.6.3. Content Analysis

Content analysis was carried out for all open-ended questions as described in the section above. Regarding the need for modifications in the tools and techniques, out of the 34 respondents, 53% agreed on the requirement of some kind of modifications in lean tools and techniques depending upon the projects. Whereas 21% recommended minor modifications, and 9% linked modifications to some conditions like required only for implementing purposes or when combining tools. 18% didn't favor the modifications in lean tools and techniques and recommended applying all lean tools and techniques as it. Respondents identified that project uniqueness is the major reason for modifying the tools implementation process.

For increasing awareness of LC, respondents suggested strategies at a large and small scale. On a large scale, the mass construction industry should be approached using platforms like workshops, seminars, conferences, publications, presentations organized by LC organizations. At a small scale, the use of charts/posters, awareness through IPD/lean culture, maintaining processes discipline, measuring tools performance, and showing to others in the form of success stories are suggested by the respondents to increase awareness within the organization. Whereas 10% have highlighted that LC organizations should increase networking with other construction companies to increase awareness for lean.

6.7. Findings and Discussion

Once the respondents were asked, whether the wrong selection and implementation of lean tools and techniques is a common problem faced by the lean organizations or not, the result indicated that many of the lean organizations are still unable to select the right tools and techniques and also struggled in implementing them properly especially at the start of their lean journey. As a result, these companies are unable to achieve optimized outcomes initially. These results further validated the need for conducting this study and necessitates devising robust methodologies for selecting lean tools and implementing LC so that optimum results can be achieved right from the start. Initial successes will define the future courses of action for the organization to sustain lean initiatives. Immediate and rapid initial successes will increase the morale of the project participants and will have a huge impact on changing the culture and mindset of project participants in favor of lean. The effort has been made in this study to develop guidelines for the newcomers for the successful implementation of lean tools and techniques.

Based on the data analysis, findings can be concluded regarding a total of 13 perspectives or categories in implementing LC below:

6.7.1. Motivations

The result of this study confirms that organizations should start a lean journey at their will, with major motivation to get a competitive advantage and improve their company image which could lead to initial successes. Where competitive advantage motivates the construction companies in improving their performance by implementing LC, the improvement in company image will increase the expectations towards more contract awarding after adopting LC. The results are in line with the report published by McGraw Hill (2013) which identified greater profitability and competitive advantage as key drivers on the uptake of LC. According to Tezel et al. (2017), the Client push for implementing LC is found out to be the top-ranked motivation factor. Whereas other factors like improving company image to getting more contracts as found out in this study match the top-ranked motivational factors found out in the study conducted by Tezel et al. (2018).

6.7.2. Project Goals

LC advocates the need for improving the processes by simplification, reducing the number of steps, and removing the wastes (Tezel et al., 2018; Mitropoulos & Howell, 2001) By doing so, lean experts believe that performances would improve gradually. According to this study, it can be concluded that companies should have both process-driven and result-oriented goals for the successful implementation of lean tools and techniques. In a more practicable term, the overall aim can be result-oriented with a focus on cost, time, quality, and safety (Bateman, 2001) but to achieve the overall aim, buy-in from the masses can be acquired using a process-driven approach (Mitropoulos & Howell, 2001). Both goals would complement each other and will result in rapid early successes. The result also matches with the conclusion presented by Ward (2015) in which no specific preference of process-driven over results-oriented goals is drawn for successful implementation of LC.

6.7.3. Performance Benchmarks

According to this study, LC can improve performance within the range of 11-20% for all categories (cost, time, productivity, safety, quality). However, at the same time, still, 14% and 30% of the lean respondents were able to achieve improvements greater than 50% and 30% respectively. It shows that lean tools and techniques have the capability of improving performance even more than 11-20% at times. The companies that apply LC with their true spirit can be able to achieve better performances while others either struggle or unable to achieve the anticipated benefits. It would always be a better option for newcomers to target around 20% of improvement during their initial applications and later on, once required expertise is achieved, they can even plan for more than 30%. There is a large variety of lean improvements reported in the LC literature as well, ranging from 5% to >50% (Conte and Gransberg, 2001; Agbulous et al., 2006; Locatelli et al., 2013, CLIP, 2006) and must be considered for setting up the target improvement ranges. However, for new lean users, the outcome of this study can provide a strong basis for setting the improvement goals which can be easily achievable and if achieved, will improve the morale of the construction supply chain performers for sustaining and refining the lean concepts (Sarhan, 2011; Bashir et al., 2015).

6.7.4. Construction Process Compatibility

The selection of construction processes for lean intervention is one of the key concerns in LC. Lean practitioners considered the sensitivity of the process in terms of time and cost as one of the topmost criteria for selecting any process for lean intervention. All those processes which can impact significantly in improving the overall outcome of the project must be identified and considered for lean intervention. Due importance should also be given to those processes which are not efficiently managed using the existing management methods. Moreover, the construction process should be checked for its compatibility with lean tools and techniques for smooth and efficient implementation. Apart from them, other criteria that should be kept in mind while selecting a construction process includes resource affordability, organizational expertise in handling the construction process, and spillover of benefits to other processes. Due to very meager research available in this area, it was not possible to cross-refer the results of this study with the existing literature however Narayanamurthy and Gurumurthy (2014) presented a 7A process selection model for general lean Implementation. Factors like the sensitivity of the process, existing inefficiencies within the processes, and compatibility with tools and techniques can be further added to the author's model for construction purposes.

6.7.5. Lean Tools and Techniques

Results indicated that lean practitioners considered the compatibility of lean tools and techniques with construction processes as the topmost criteria for selecting lean tools and techniques. The application methodology of lean tools must be compared with the construction process for its suitability for implementation. In a very detailed study conducted by Aslam et al 2020a, the compatibility of lean tools with construction processes is considered as the significant criterion for selecting lean tools. As an example, tools like just in time and 5S are more compatible with supply chain and material management in construction. Similarly, tools like the last planer system LPS are suitable for the planning and pull approach. The second important criteria are the selection of those tools which can give maximum benefits in terms of cost, time, and productivity. Construction companies should be aware of benefits that are generally associated with respective tools and techniques to achieve their overall aim. To become lean, the objectives of lean tools and techniques should be aligned to LC principles. As an example, the big room is a tool with the objective of efficient collaboration among all project participants whereas extreme collaboration is one of the core principles of LC. LPS optimizes planning through collaboration by involving downstream participants, pull approach, and waste reduction by targeting core principles of LC (Daniel et al., 2017). Selecting the lean tool in which organizations have developed expertise can also be effective in implementing it. The organization should be able to analyze its capabilities in handling lean tools and techniques so that once a tool is selected, they are ready to implement it. Expertise can be developed through past experiences, better knowledge, and the availability of experienced people for handling these tools.

6.7.6. Project Delivery Methods (PDM)

Lean practitioners who undertook a survey, have nominated collaborative delivery methods like IPD as the most compatible PDM with LC. The success of LC is most dependent on a collaborative form of the delivery system. The results are very much in line with the prevalent literature that also highlights the necessity of using a collaborative delivery method (IPD) for lean implementation (Rached et al., 2014; Matthews and Howell, 2005). Apart from IPD, lifecycle delivery methods like BOT and DB are also considered to be effective in implementing LC. Overall, any collaborative delivery method, which can bring all the project participants to the same table right at the outset of a project is considered to be the most suitable delivery system for the successful implementation of lean projects. IPD supports almost all the tools and techniques like last planner system (LPS), just in time, big room, target value design, building information modeling (BIM), etc. because of its strong collaboration, trust, and early involvement of project stakeholders. The use of BIM can further facilitate in improving the visualization within a highly collaborative integrated project delivery system (Sacks et al. 2010). That is the reason that 73% of the respondents nominated BIM as the most formidable tool for the successful implementation of LC along with LPS (54%).

6.7.7. Commitment Level

To make any effort successful, top-level commitment from all the project participants is required. According to Bateman (2001), contribution and buy-in from improvement teams is a strong enabler for the sustainability of process improvement activities. However, it’s not practical to assume that the highest level of commitment from all participants would be evident right from the start of the lean effort. There can be resistance or conflicting attitudes towards change from a few participants. But this lack of commitment should not compel construction companies to abolish the decision of moving towards lean. The results of this study indicated that most of the companies were able to achieve success even when the commitment of subcontractors, suppliers, and the workforce was not at the highest level (around the medium level). This implies that construction companies shouldn’t wait for the highest level of commitment by subcontractors, suppliers, and workforce rather they should start implementing LC even at lower commitment levels. Once the benefits would be evident to them, the commitment level would be increased to the highest level. Apart from subcontractors, suppliers, and workforce, results also showed that in any case, upper, middle, and field managers should always be highly committed to the successful implementation of lean.

The use of a collaborative delivery system, in which every stakeholder is involved from the start of the project and sharing the pain/gains, can be an effective tool for increasing the commitment level of subcontractors and suppliers (McGraw Hill 2013). To increase the commitment level of the workforce, they should be involved in the planning stage, and responsibilities be shared equally among themselves (Ballard et al. 2007). Their opinions should be given due importance during the big room or other meeting sessions. Their commitment level can be increased by providing a certain type of effective incentive system or additional support for the accomplishment of their tasks.

6.7.8. Empowerment Level

According to lean theory, project participants should be given adequate empowerment to take decisions for their tasks to accomplish the goals of the project (Bashir et al., 2015; Ayarkwa et al., 2011). In the construction supply chain, there are several stakeholders involved and the empowerment level has to be decided among them. As an example, the workforce cannot be given full empowerment like upper management, but they should be empowered within their area of expertise. To develop this threshold, lean practitioners were asked to rate the overall empowerment level of different project participants during their successful implementation of lean tools and techniques. Results indicated that subcontractors, suppliers, and the workforce should also be given adequate but comparatively lesser empowerment in comparison to upper and middle management. Even, subcontractors and suppliers should be given empowerment equal to the field management. These specialty contractors should be entrusted to complete their tasks with full freedom and authority. Whereas, the workforce should be empowered enough to take full control of the tasks assigned to them. However, the degree of empowerment should be based on the type and quantum of tasks, expertise available, trust, and commitment level (Kawish, 2017). These should be defined during the collaborative sessions and with mutual understanding.

6.7.9. Training Requirements

The training of supply chain teams in implementing LC and sustainable construction has been becoming increasingly studied since it not only facilitates the successful implementation of LC but also provides comprehensive solutions to the environmental problems we face today and thus takes care of the needs of future generations (Valdés et al., 2018). Results showed that on job training is the most suited method for learning the skills and implementation techniques for lean tools. The results are very much in line with the studies conducted by Ballard et al. (2007), and Warcup (2015) but differ from Ward (2014) who concluded against the results of this study. In this study, on job training method was found to be highly ranked and also used by most of the lean organizations for imparting training to their field managers and workforce. However, as per lean practitioners, imparting training through classroom lectures is the least efficient method of learning and ranked at the bottom. But at the same time, most of them still using classroom lectures as the main source of imparting basic knowledge to their employees. On one side, the lean team needs to know the basics about lean tools and techniques and on the other hand, they should know the implementation process. With prior basic knowledge, it would be easy for the organization to select and implement LC. That is the reason that most of the lean respondents during their successful lean journey, used multiple training techniques. For basic knowledge and understanding, training methods like classroom lectures, workshops, and videos can be used but for implementation and experience, on job training and site visits are the most effective ways of learning. Lean practitioners also highlighted the importance of using the services of external trainers. The use of both internal and external trainers proved to be the most effective way of training their teams. Even expert lean organizations are not convinced with their internal training system and want to use the services of external lean facilitators.

6.7.10. Sustainable Support

For the successful implementation of lean tools and techniques, respondents agreed on additional support to be provided to the lean teams. According to them, lean teams should be given reasonable additional time for preparation and training to get them acquaint with all lean formalities. Similarly, they should have enough confidence and trust by the upper management to perform without any fear of failure. However, the result also showed that substantial additional funding and authority of using companywide resources are not that much significant as perceived by most of the construction companies. However, limited additional funding or resource usage should be provided to lean teams to improve upon their learning and training needs (Bashir et al, Shou et al 2016). This negates the general myth of the construction industry that LC requires additional funding or resources for its successful implementation (Marhani et al., 2013; Porwal et al., 2010, Sarhan et al., 2018).

6.7.11. Assessment

Lean practitioners considered the weekly form of measurement as most suitable for the successful implementation of lean tools and techniques. LC theory also advocates maintaining weekly PPC assignments which must be analyzed regularly to achieve excellence (Enshassi et al., 2019; Mostafa et al., 2013). However according to the results of this study, apart from weekly, some of the lean organizations have measured outcomes on monthly basis with the successful implementation of lean practices. Other measurement frequencies are scarcely used by the lean practitioners considering them as insignificant. No significant difference was found between the respondents measuring progress weekly or monthly. Since respondents were from experienced lean organizations with refined implementation processes, they can afford to measure progress monthly but for newcomers in lean, progress should be measured weekly to locate the loopholes early and correcting them as soon as possible.

6.7.12. Standardization Vs Modification

LC advocates standardization of processes, tasks, and methods during lean implementation. No matter standardization helps in improving and refining the tasks but still, the results showed that this concept is not warmly welcomed in the industry. It all depends upon the nature of the project and the environment that dictates the degree of standardization required. Organizations which undertake similar kind of projects like health care, residential, etc., would be having more chances of success by standardizing their tasks, processes, and materials. Moreover, companies that involve prefabrication can also devise standardized procedures for increasing their chances of success. The standardization of processes and material will reduce construction waste thereby making the construction more sustainable (Yasin and Rjoub, 2017).

In contrast to standardization, most of the respondents believe that some kind of modification is always required to lean tools and techniques from one project to another. Project uniqueness has been identified as the main reason for modifying the tools. Moreover, due to rapid developments in tools and techniques, new protocols and procedures need to be incorporated which requires some kind of modification. Similarly, lean tools and techniques also need to be modified when project participants or teams are changed from one project to another. Few respondents believe that basic concepts of lean tools and techniques should never be changed but a minor modification in implementation be carried out to align them with the project and team's needs.

Based on the results of this section, it can be deduced that full standardization in construction may be difficult however basic methodologies, processes, tasks, and materials can be standardized to a certain level and further adjusted with some modifications to align with projects. Modifications are required during the implementation processes to meet the project environments as also stated by Salem et al. (2006) and Mostafa et al. (2013) The organizations which are involved in the diverse nature of projects struggles in standardizing their tasks, processes, and material. There is a need of establishing facts that can increase standardization within the construction industry.

6.7.13. Awareness Program

Results showed that to promote LC in the construction industry, lean organizations have to share their lean experiences with the construction industry through conferences, publications, congresses, and regular meetups. Leong et al. (2015) have further emphasized the need for a robust lean site assessment to test the leanness of construction projects onsite to show current performance benchmarked against potential excellence, derived from successful LC projects. Individual companies can perform a lean site assessment and can present the changed performance in comparison to the previous practices. LC institute has put in tremendous efforts in promoting LC widespread by providing a standard lean platform to the construction industry. However, individual organizations that execute lean practices can play a significant role in promoting LC with results that can blow the construction industry to accelerated uptake of LC. The same types of awareness strategies are also proposed by other researchers (Sarhan, 2011; Bashir et al.,2015).

6.8. Suggestions for New Lean Adopters

Lean practitioners think that newcomers should be able to acquire adequate knowledge about LC and its tools and techniques before moving towards lean. Once required knowledge is attained, lean tools should be immediately implemented, measured, and analyzed for their performance and further evaluated for corrective actions if required. Almost in every section, respondents emphasized the efficacy of learning through experiences for the effective implementation of lean tools and techniques. Before implementation, two important decisions: a selection of construction processes for lean intervention and selection of LC tools and techniques must be given adequate importance.

6.8.1. 7.1 Suggested Guidelines

As a suggestion to newcomers who want to start a lean journey, the majority of the respondents believe that organizations should follow major actions as shown in figure 6.3 for making their lean effort successful and sustainable.

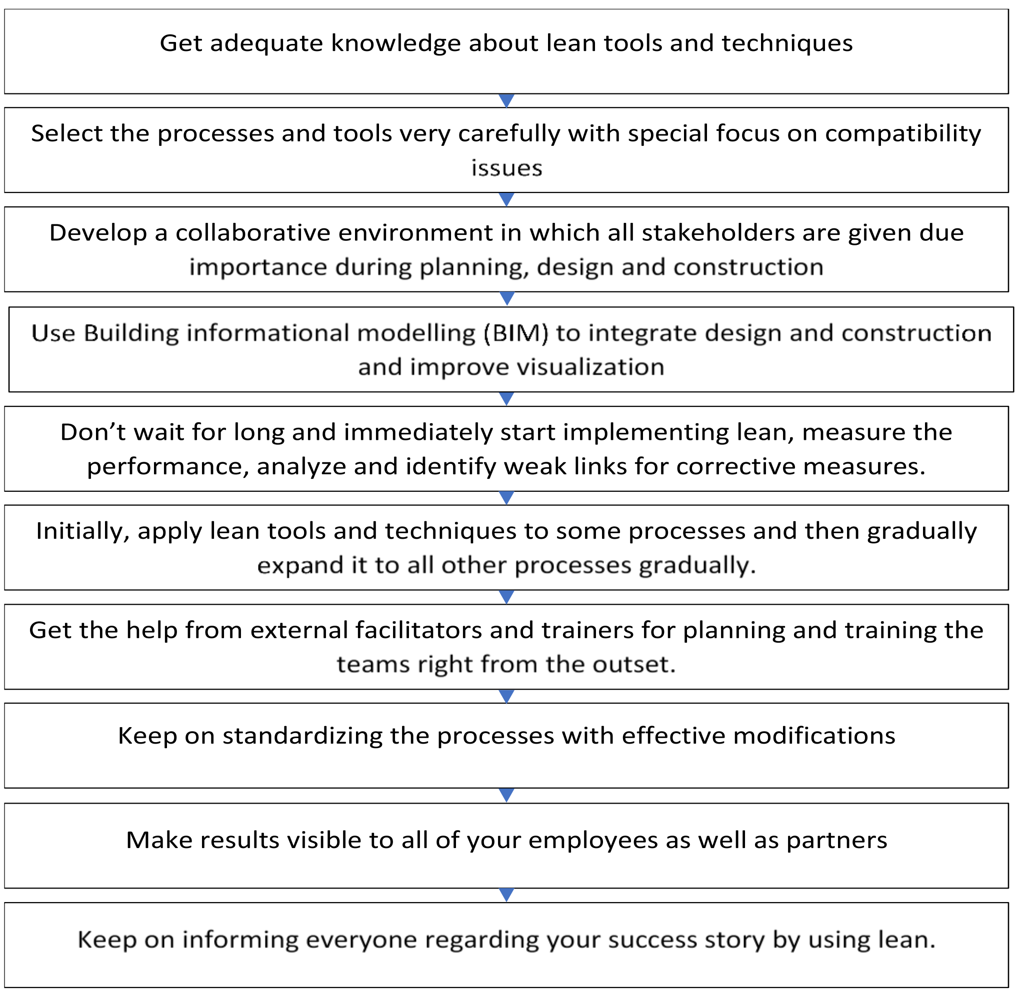

Figure 6.3. Guidelines for newcomers to start successful LC practices

6.8.2. Suggested Implication

The outcome of this study will have a very positive implication for both theoretical and practical bodies of knowledge in project management. Theoretically, this study will provide a deep understanding of lean concepts and will encourage the construction companies to start a lean journey for removing wastes and inefficiencies from existing management techniques. The removal of waste within the construction projects will make construction more sustainable and facilitate preserving not only the natural material but also the effort required to undertake the work. Thereby having a huge positive impact in decreasing the environmental issues associated with the construction industry. The dormant companies who never want to change can find alternate opportunities in achieving excellence and getting a competitive advantage over others. The results of this study will help in developing the faith for this innovative project management approach as lack of faith and fear for using new management techniques are presently the strongest barrier in adopting the LC by the construction industry. Practically, the outcome of this study will provide a way forward to the construction companies for managing their projects by using a lean approach. Companies can develop strategies for successfully implementing lean construction based on the factors and suggestions identified in this study. The prevailing lean implementation challenges, that are prohibiting the construction companies from using lean can be combatted by using the approach as proposed in this study. Resultantly, complexities can be removed, and simpler plans can be made to implement LC successfully during the projects. This will increase the uptake of lean construction and will lead towards that management level where projects can be delivered with no wastes and inefficiencies and improve sustainability.

6.9. Conclusion

Keeping in view the challenges of the construction industry and subsequent use of LC in improving the construction processes as well as sustainability, an effort has been made in this study to provide guidelines to the construction industry for the successful start of the LC. Results indicate that organizations should start LC with a clear goal of improving results and processes through commitment and collaboration by all project participants. Immediate and early successes would improve the morale and commitment of project participants in favor of lean. For rapid early successes, the construction companies must select the right tools and techniques that are compatible with construction processes and implemented using a collaborative project delivery system to achieve success in the future. Each project participant should be given adequate empowerment depending on their responsibilities and tasks. One of the key findings of this study is that lean tools and techniques should be implemented gradually by introducing a few lean tools and techniques to some processes initially and then expanding them to the complete project. Companies should always be on the hunt for improving their lean performances through weekly and monthly evaluations carried out periodically. Opportunities should be provided to field managers and the workforce to learn basic knowledge of lean tools and techniques through collaborative classroom, workshop, and video sessions followed by on-job training. The results of this study would remove complexities within the minds of constructors for adopting lean and also provides them with more realistic and practical guidelines to implement lean on their projects.

Where other researchers provided the general picture of the LC, this study further investigated LC deployment focusing on lean tools and techniques, processes, PDMs, training, commitments, additional support, standardization, and modifications, for new lean adopters. A larger sample size would have given way to further analyses like a principal component or factor analysis that may have better explained the significance of factors. A similar study with more sample size can be conducted to refine the outcomes of this research.

7. PAPER 5: DEVELOPMENT OF INTERPRETATIVE STRUCTURAL MODELING (ISM) BASED LEAN CONSTRUCTION IMPLEMENTATION FRAMEWORK[5]

7.1. Abstract

By using Lean construction (LC), the construction industry has witnessed some improvements on project performance; however, these improvements vary drastically from one organization/project to another within the range of none to even greater than 30%. These variations were caused by a fact that LC implementation process is not yet standardized and every organization is implementing LC on its own way. Although some researchers have endeavored to develop LC implementation frameworks, these frameworks either only explain the theoretical aspects of LC or were developed based on the inputs only from few lean experts and are therefore difficult for the construction companies to follow. This study has developed a robust LC implementation framework using a more structured Interpretative Structural Modeling (ISM) technique combined with statistical methods, which identified the relationships between a variety of success factors from the inputs of 82 LC companies and statistically analyzed for significance using pairwise comparisons. 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 framework standardizes the lean implementation processes and improves the lean culture within organization. This is especially

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[5] The material in this chapter was co-authored by Mughees Aslam, Zhili (Jerry) Gao, Gary Smith, Ying Huang & Megan Orr. Mughees Aslam had primary responsibility of developing and conducting survey from the lean practitioners. Mughees Aslam collected all the data and also performed all the statistical analysis and interpretative structural modelling. Mughees Aslam discussed the results and wrote the conclusions that are advanced here. Mughees Aslam also drafted and revised all versions of this chapter. Zhili (Jerry) Gao, Gary Smith, Ying Huang & Megan Orr guided the study process, directed the framework of the paper and checked the data analysis as well as proofreading.

useful for the new LC companies for moving towards lean, and also facilitate the successful implementation of LC for the entire construction industry.

Keywords: Lean Construction, Success factors, Statistical analysis, Implementation framework, Interpretative structural modeling

7.2. 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 up to 20% (CLIP, 2005; Conte and Gransberg, 2001; Agbulos, 2006) while others also experienced more than 30% improvement (Mao & Zhang, 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 comply lean principles (Chapter 3).

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; EI-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 (2020c) 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.

7.3. Methodology

The methodology of this study includes several steps: (1) confirming LC successful factors from 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 7.1 with details of some major steps as follows:

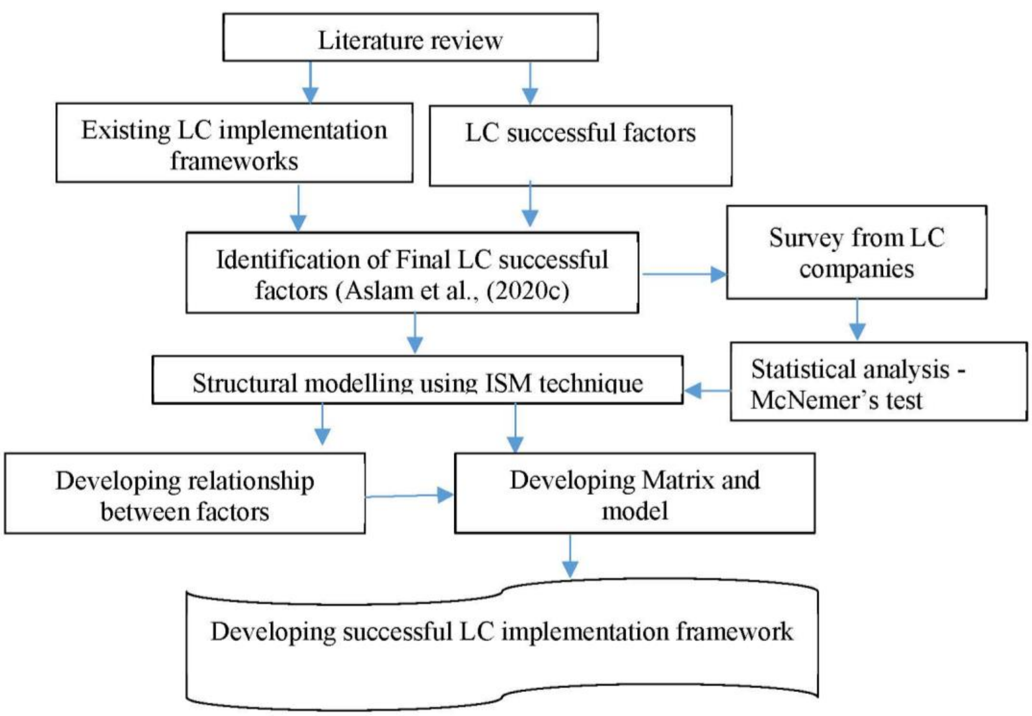

Figure 7.1. Research methodology for chapter 7

7.3.1. 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., (2020c) provided a comprehensive list of CSFs after analyzing the survey results from the lean experts in the US. To increase the reliability of CSFs, this list of CSFs is further confirmed from the previous studies and to add other factors also. The CSFs identified in previous work that are critical to the LC implementation framework are shown in Table 7.1:

Table 7.1. Critical success factors (CSFs)

Factor Number	Factor description	Adopted from	Confirmatory references
1	Imparting requisite knowledge and training regarding lean construction principles, tools/techniques, and objectives	Aslam et al., (2020c) (Chapter 4 & 6)	(Ballard et al., 2007: Mostafa et al., 2013; Koskela, 1992)
2	The initial selection of appropriate construction processes	Aslam et al., (2020c) (Chapter 4 & 6)	(Narayanamurthy and Gurumurthy, 2014; Lovatt and Shercliff, 1998; Aslam et al., 2020a)
3	Improving collaboration, communication, and visualization	Aslam et al., (2020c) (Chapter 6)	(Ballard et al., 2007; Sacks et al., 2010; Koskela, 1992; Cano et al., 2015; Shou, 2016; Steven 2014)
4	Selection of appropriate lean tools and techniques/system	Aslam et al., (2020c) (Chapter 3, 4 & 6)	(Ward 2015; Pavnaskar et al., 2003; Swefie, 2013; Marhani et al., 2018, Aslam et al., 2020a)
5	Ensuring adequate commitment from Project teams	Aslam et al., (2020c) (Chapter 6)	(Ballard et al., 2007: Sarhan et al., 2019; Yahya et al., 2016)
6	Ensuring adequate empowerment be given to the workforce.	Aslam et al., (2020c) (Chapter 6)	(Bashir et al., 2015, Kawish 2017; Diekmann et al., 2004)
7	Adoption of continuous improvement	Aslam et al., (2020c) (Chapter 6)	(Ballard et al., 2007: Mostafa et al., 2013; Koskela, 1992; EI-Sabek et al., 2018)
8	Standardizing the lean processes	Aslam et al., (2020c) (Chapter 6)	(Diekmann et al., 2004; Ayarkwa et al. 2011; Bajjou & Chafi, 2018)
9	Improving cultural adaptability and commitment towards lean construction	Aslam et al., (2020c) (Chapter 6)	(Sarhan and Fox, 2013; Ballard et al., 2007; Diekmann et al., 2004)
10	Providing additional support and incentive to the lean teams and partners	Aslam et al., (2020c) (Chapter 6)	(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., 2020b)	Aslam et al., (2020c) (Chapter 5 & 6)	(Lindhard and Wandahl, 2014; EI-Sabek et al., 2018; Aslam et al., 2020b)

7.3.2. Determination of Relationships between Factors

After identifying the CSFs, the second step requires 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 (Attri 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 of 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 7.2. Complete questionnaire for the survey is given in Part 3 of Appendix C.

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 7.2. Example question

7.3.2.1. 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 7.3.

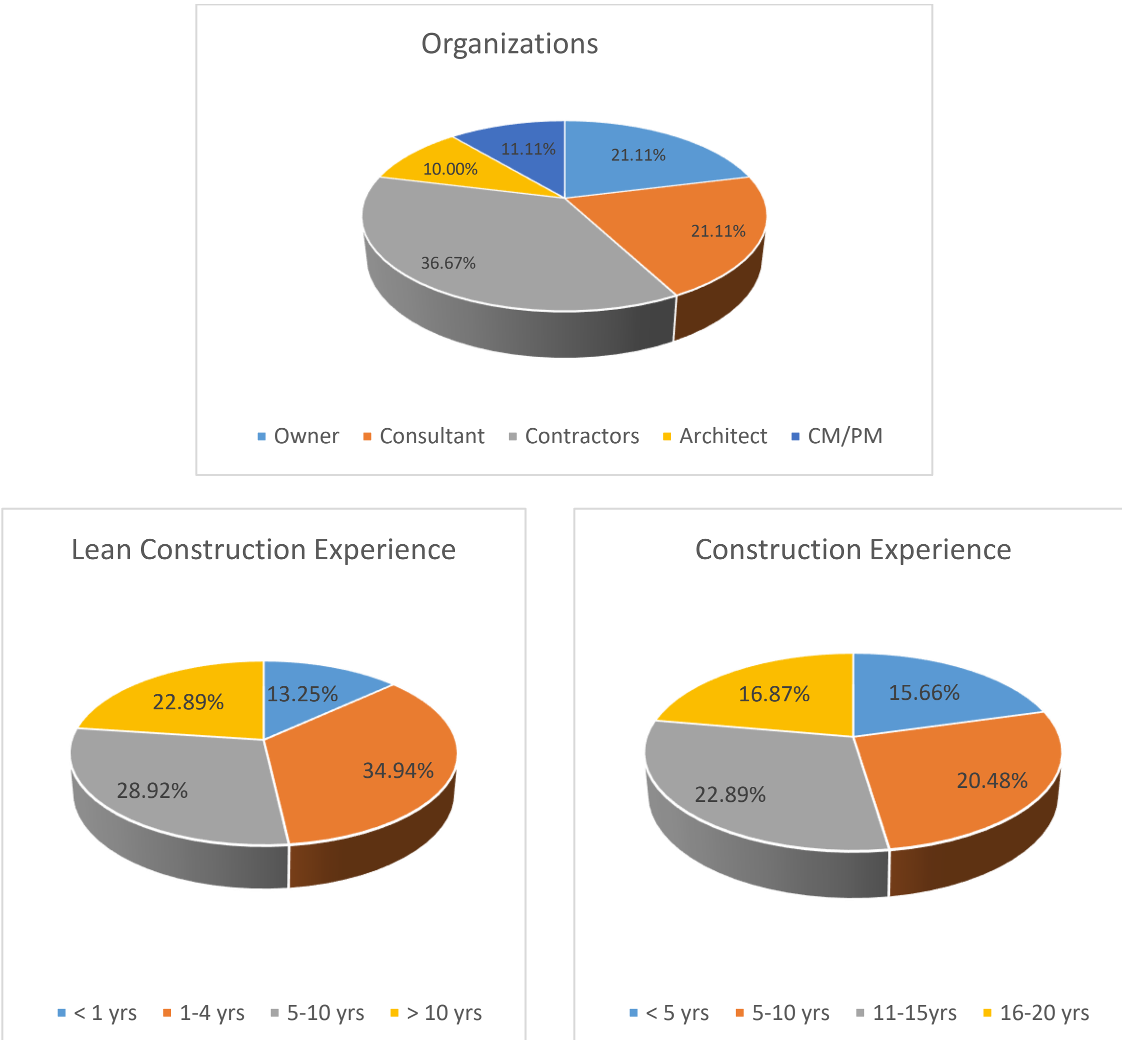

Figure 7.3. Demographic information about respondents

Figure 7.3 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 the LC, thereby increasing the reliability of the responses.

7.3.2.2. 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 7.4. 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

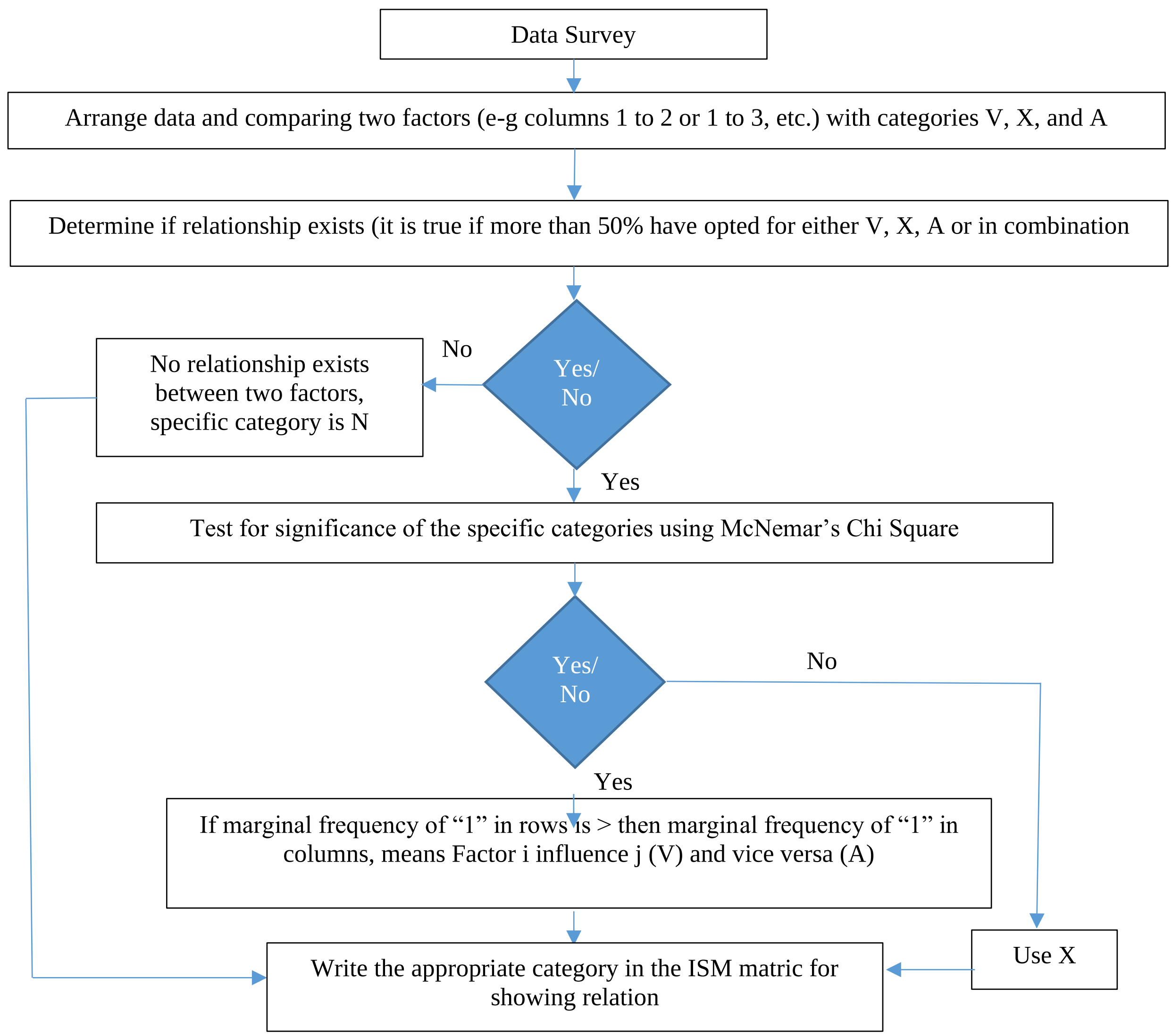

Figure 7.4. Methodology for pairwise comparison between factors to identify relationships

7.3.3. Developing ISM Based Matrices and Model

The further steps for performing ISM are enlisted in Table 7.2.

Table 7.2. ISM based matrices and model development steps

Steps	Description
Developing structural self-interactive matrix (SSIM)	Develop a matrix showing factors in the first row and first column (12x12). Write corresponding relation (V, A, X, or N) in respective cells.
Initial reachability matrix	Replace the SSIM (V, A, X, or N) entries by 1 or 0. The (i, j) entry in the SSIM can either be V or A or X or N, Replace them as per the following rule: If V, then the (i, j) entry in the reachability matrix becomes 1 and the (j, i) entry becomes 0 If A, then the (i, j) entry in the matrix becomes 0 and the (j, i) entry becomes 1 If X, then both (i, j) and (j, i) entry becomes 1. If N, then both (i, j) and (j, i) entry becomes 0
Final reachability matrix (incorporate transitivity)	If element A is related to B, and B is related to C, then A is also related to C. Replace 0 with 1* as a transitivity
Level partitions	From the final reachability matrix and for each factor, find reachability (factors in rows) and antecedent (factors in columns). If all the reachability set is intersected with antecedent sets, strike out the factor, that factor will be the most dependent and should be in level 1. Repeat the same for all the other factors. The factor struck out at the last is the most independent factor and should be in the top highest level.
Diagraph	Join the nodes with arrows after removing the transitivity links as developed in the final reachability matrix
Convert Diagraph into an ISM based model	Replace nodes with statements of the factors
Review the model	Review the framework for conceptual differences and adjust if theory/context supports

7.4. Literature Review on Existing Lean Construction Frameworks

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 in the actual field performances. The results after its implementation would dictate the success/failure of the theory. Theories and philosophies related to LC are no exception to it. The concepts of LC have been exceptionally explained in the literature and also 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 the period, the 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. 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. 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; EI-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 the 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 like 1) management commitment to identifying/driving out wastes, 2) standardizing the workplace, 3) developing a lean culture, 4) client involvement and 5) finally continuously improving the whole process. Later on, 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, and 7) visual inspections.

Sarhan et al., (2019) developed the LC implementation framework by using the 12 CSFs and further developing the relationships between the CSF by 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 the 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 the 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.

7.5. Identification of Relationships and ISM Matrices Development

7.5.1. Identification of Relationships from Survey Data

Criteria for determining whether the relationship exists between any factors is shown in Fig. 7.4. The analysis shows that some kind of 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 help 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 7.3. 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 (but can be found in Appendix D); however, the pairwise comparisons along with the relationship of factors 1 and 2 are shown in Table 7.3. 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 considers 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 7.3. 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**	**Sig@**	**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
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

@ Significance

7.5.2. 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 7.4.

Table 7.4. 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												

7.5.3. Initial Reachability Matrix

Initial reachability matrix is developed by coding the relationships with 1 and 0. The matrix is shown in Table 7.5.

Table 7.5. 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	

7.5.4. 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. 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 that indicates the dependence and independence power of the factors. As an example, Factor 1, 5, and 3 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 7.6.

Table 7.6. 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

7.5.5. 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 attain some level. A total of 7 iterations as shown in Table 7.7 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 would have the highest dependency on all the other factors and will 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 7.7. 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
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

Table 7.7. Iteration process (continued)

Factors	**Reachability set**	**Antecedent set**	**Intersection set**	**level**
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

7.5.6. Directed Graph (Diagraph)

Based on the final reachability matrix (Table 7.6) and levels attained (Table 7.7), 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 7.5. 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 7.7 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 7.5.

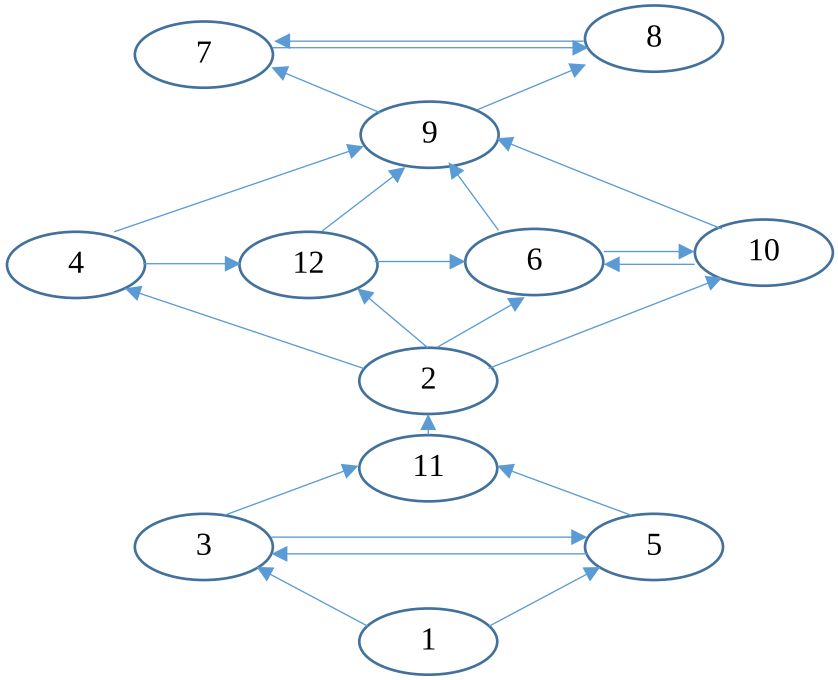

Figure 7.5. Directed graph (Diagraph)

7.6. ISM Model Development

Diagraph as shown in Figure 7.5 is converted to ISM model by replacing the nodes of the diagraph into the factor statements as shown in the Methodology section (Table 7.1). The final ISM Model is shown in Figure 7.6 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 and (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 others factors.

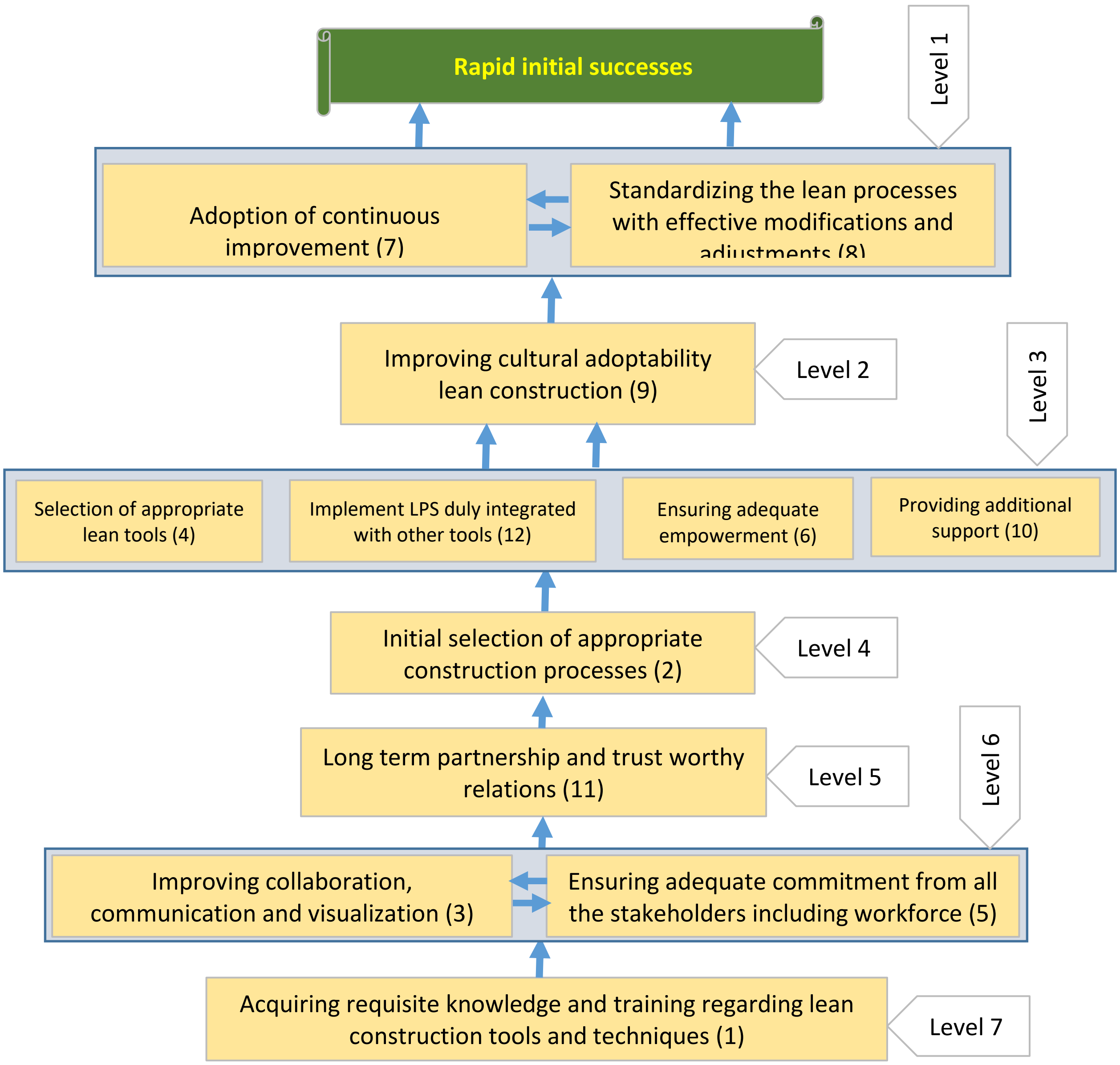

Figure 7.6. LC implementation framework for rapid successes

7.7. 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 7.6. Both the driving and dependence powers of each factor are plotted on a diagraph as shown in Figure 7.7. 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.

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 7.7, none of the factors falls 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.

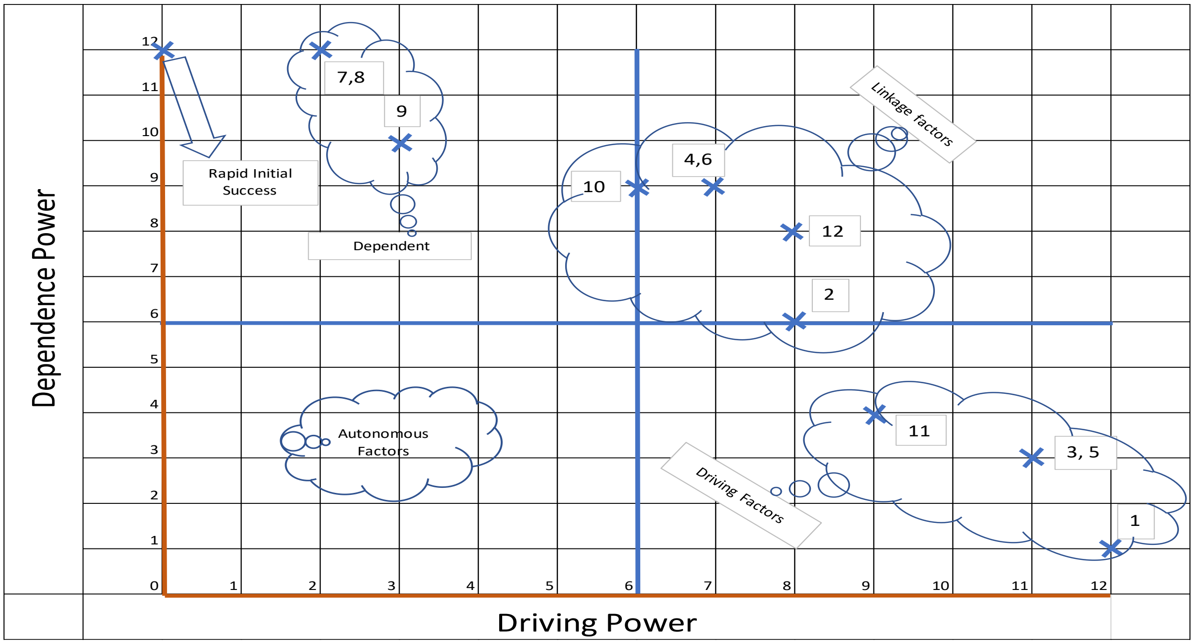

Figure 7.7. MICMAC analysis

7.8. Validation of the LC Implementation Framework

The final framework in Figure 7.6 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 Sarhan et al's model, however, the same factor is among the top-level within this framework. This difference is acceptable considering the countries where the research is applied. According to Ballard et al (2007), rapid successes can help in changing the organizational culture towards LC and the developed frame work actually leads to rapid success which in turn improves lean culture. Similar to 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).

7.9. Impacts and Contribution of Developed LC Implementation Framework

7.9.1. Impact of Relationships

From McNemer's test, it was found out that all the factors have some kind of 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). The factors like improving collaboration and ensuring adequate commitment levels are found to be interdependent. Similarly, interdependencies are also observed in between factors like 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 carried on again and again (Ballard et al., 2007).

7.9.2. 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 are considered to be the most important factors and failures to implement any of these factors 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.

7.9.3. 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 the 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, 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., 2020b). Selection of tools/techniques requires adequate inputs from the employees or the persons who have to 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 one or another. 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.

7.9.4. 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 assuring the independent and linkage factors, companies should look towards the cultural changes for adopting LC within their organizations. It is always difficult for the companies to change the existing culture which these companies have adopted for so many years. However, the companies that have truly adapted to 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 assuring the independent and linkage factors. That is why the factor of cultural adaptability is among the groups of dependent factors. Many companies fail to adapt to lean culture without realizing the benefits of the LC. Once the benefits are envisaged by ensuring the implementation of bottom-level factors, the companies will start transforming into lean cultural. The cultural adaptability for LC will lead to the continuous improvements and standardization of the LC implementation processes. Implementation of LC is a continuous process in which companies endeavor to achieve excellence by improving through implementation. The outcomes will be measured and lessons learned will be recorded, further modifications/improvements will be made and finally, implementation is carried out. However, the same process of continuous improvement and standardization is repeated after each implementation.

7.9.5. Cautions for the Use of Developed Framework

Currently ISM-based models only show the direct relationships between the factors; however, many indirect relationships could exist between the factors (Attri et al., 2012). From Table 7.4 (SSIM), it can be seen that the preceding factors can help in achieving all the factors at the above level 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, the factors like knowledge/training, collaboration, and commitment along with other preceding factors should always be taken into consideration.

Additionally, the 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 the LC especially during the actual construction stage and will impact the LC implementation to a great extent.

7.9.6. Significance of Developed Framework

The major critique on the existing LC frameworks was that mostly these frameworks are theory-based and 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 finally developed framework will provide complete guidelines and a step-by-step procedure for implementing the LC and achieving successful results. The construction companies who are hesitant in implementing the 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 for implementing LC.

7.10. 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 future use.

One of the most important contributions of this study is where most of the previous research focused on developing the framework based on theories or in some cases inputs from the general construction companies (might be familiar with LC or not), the reliability of the framework incorporating the years of experience of the company officials who have been working in a lean environment.

However, to further increase the efficacy of the framework, it is imperative to validate the developed framework by comparing the construction industrial practices in implementing LC with the overall impact on the project outcomes. This validation process will determine the potentials 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.

8. PAPER 6: VALIDATION OF LEAN CONSTRUCTION IMPLEMENTATION FRAMEWORK USING PARTIAL LEAST SQUARE – STRUCTURAL EQUATION MODELING (PLS-SEM)[6]

8.1. Abstract

Several frameworks have been developed to standardize Lean Construction (LC) implementation to achieve the benefits of LC. However, the applicability of these frameworks within the construction industry are seldom validated by using robust validation approaches. Therefore, many construction firms struggle with implementing these frameworks. The purpose of this study is to establish a robust validation approach from the input of LC companies. An LC implementation framework that is validated using a structured Partial Least Square (PLS)-Structural equation modeling (SEM) was used for both modification and validation of an LC implementation framework previously developed (Chapter 7). The efficacy of the LC implementation framework was assessed by measuring its potentials against eight (8) performance outcome measures like time, cost, profits etc. The necessary modifications were carried out to resolve reliability and validity issues by giving due consideration to the content validity. The final/best fit model is compared with the initial LC framework for validation. The final LC implementation framework comprised 19 valid constructs and 38 indicators to explain each of the identified constructs. As a result, the final validated LC framework has the capabilities of explaining approximately 65% of the variance in construction performance outcomes. It was also found that the most attention should be given to improving the culture and

[6] The material in this chapter was co-authored by Mughees Aslam, Zhili (Jerry) Gao, Gary Smith, Megan Orr & Ying Huang. Mughees Aslam had primary responsibility of developing and conducting survey from the lean practitioners. Mughees Aslam collected all the data and also performed all analysis and structural equation modelling steps. Mughees Aslam discussed the results and wrote the conclusions that are advanced here. Mughees Aslam also drafted and revised all versions of this chapter. Zhili (Jerry) Gao, Gary Smith, Megan Orr & Ying Huang guided the study process, directed the framework of the paper and checked the data analysis as well as proofreading.

commitment for LC. However, to improve the LC culture, the LC companies should be looking for rapid initial successes that can motivate the companies in adopting the LC culture and commitment. The outcome of this study provides a well-structured and validated LC implementation framework to facilitate new LC companies in achieving initial implementation success.

Keywords: Lean Construction; validation; implementation; framework; Structure Equation Modelling

8.2. Introduction

Considering the potential of Lean construction (LC) to improve construction performance, researchers have been using a variety of methods to develop LC implementation frameworks, such as 1) theoretical explanations (Koskela, 2000), 2) interviews from the experts (Nesensohn, 2014), 3) literature review (Bajjou et al., 2019), and 4) case study (Ballard et al, 2007). However, these methods lack a rigorous validation process to verify the applicability and usefulness of LC framework. The most commonly applied validation technique is seeking out opinions from experts in the construction industry on the applicability, practicality, efficacy, and acceptability of the developed framework (EI-Sabek et al., 2018; Ghosh and Heidenreich, 2018). Other researchers applied their framework on actual projects (Swefie, 2013) or used simulation packages for assessing the efficacy of the frameworks against project outcomes (Erikshammar et al., 2013). Although those adopted validation techniques are acceptable as validation processes (Ritchie et al., 2003; Miles and Huberman, 1994), some significant limitations exist: 1) expert opinions have built-in biases (Döringer, 2020), 2) single project (case study) based validation can only work well for that particular project but may be doubtful for different project environments/characteristics (Bajjou, et al., 2019), and 3) simulation based validation does not totally match with the actual project conditions due to very theoretical or very limited project data as input parameters (Kleijnen, 1995). Additionally, some researchers have tried to compare the best practices on a successful real project to match with their developed LC implementation frameworks for validation purposes (Heravi and Rashid, 2018). However, alignment of the project implementation and framework would be a difficult match.

In the construction industry, stakeholders like contractors and owners always want to adopt new developments that can have a considerable positive impact on their project outcomes. However, evaluating the impact of LC implementation on the project outcomes is another area that is seldom evaluated during the validation process. Very few researchers have reported the potential impact of their developed LC frameworks on project outcomes (Al-Aomar, 2012; Abbasian-Hosseini et al., 2014). Validating LC implementation frameworks based on their potential impact to project performance will help improve the general acceptance of the construction industry towards LC adoption.

In summary, it has been observed that although deliberation, care, and robustness is given to the development of LC implementation frameworks, however, the limited validation of these frameworks is a significant weakness for their usability and efficacy for the real projects. There is a demonstrated need for a robust validation of LC implementation frameworks with special emphasis on construction industry demands and environment.

The purpose of this study was to determine a robust validation approach from the input of the LC companies to produce a standardized validated LC implementation framework. Key questions to be examined in the validation of an LC framework would be as follows:

- Will the developed LC implementation framework have the capability of improving construction performances?

- How to improve the initially developed LC framework for achieving optimized construction performances?
- Are the identified indicators within the framework considered relevant and important by the LC practicing companies?

The complete validation process is carried out to achieve the following specific objectives:

- Develop the best fit/improved LC implementation framework and determine the potentials of the improved LC implementation framework in improving the construction performances
- Determine the relevancy of the improved LC implementation framework with the initially proposed framework
- Determine the relevancy and importance of the identified constructs and indicators in improving the construction performances

8.3. Methodology

The overall methodology of this study, shown in Figure 8.1, include several steps: 1) identify the indicators for constructs of LC framework, 2) measure indicators using questionnaire survey, 3) load indicators to the initially developed framework, 4) perform PLS- SEM analysis using a software of SMART PLS3, 5) Check for validity, and 6) modify the framework.

The initially developed LC implementation framework (Chapter 7) is evaluated and further scrutinized by getting the inputs from the LC companies that have implemented LC on their projects through a questionnaire – survey. Each construct within the initial framework will be linked with its indicators and the indicators will be measured based on the inputs from the LC companies continuously implementing the LC. The efficacy of the indicators will be assessed based on its impact on the eight project performance indicators as cost, time, quality, safety, profit, lawsuits, financial losses, and relationships.

This will provide a data set in which all the indicators and their contribution in predicting the construct are recorded. The data set will be further analyzed using Partial least square (PLS) - structural equation modeling (SEM) to validate the impact of the developed framework on project outcomes (key performance output parameters) (Hair et al., 2016; Garson, 2016). The initially developed LC framework will be modified based on the industrial data to finalize the most robust and authenticated LC framework that will have the capability of providing outcomes that mostly relates to the acceptable industrial practices.

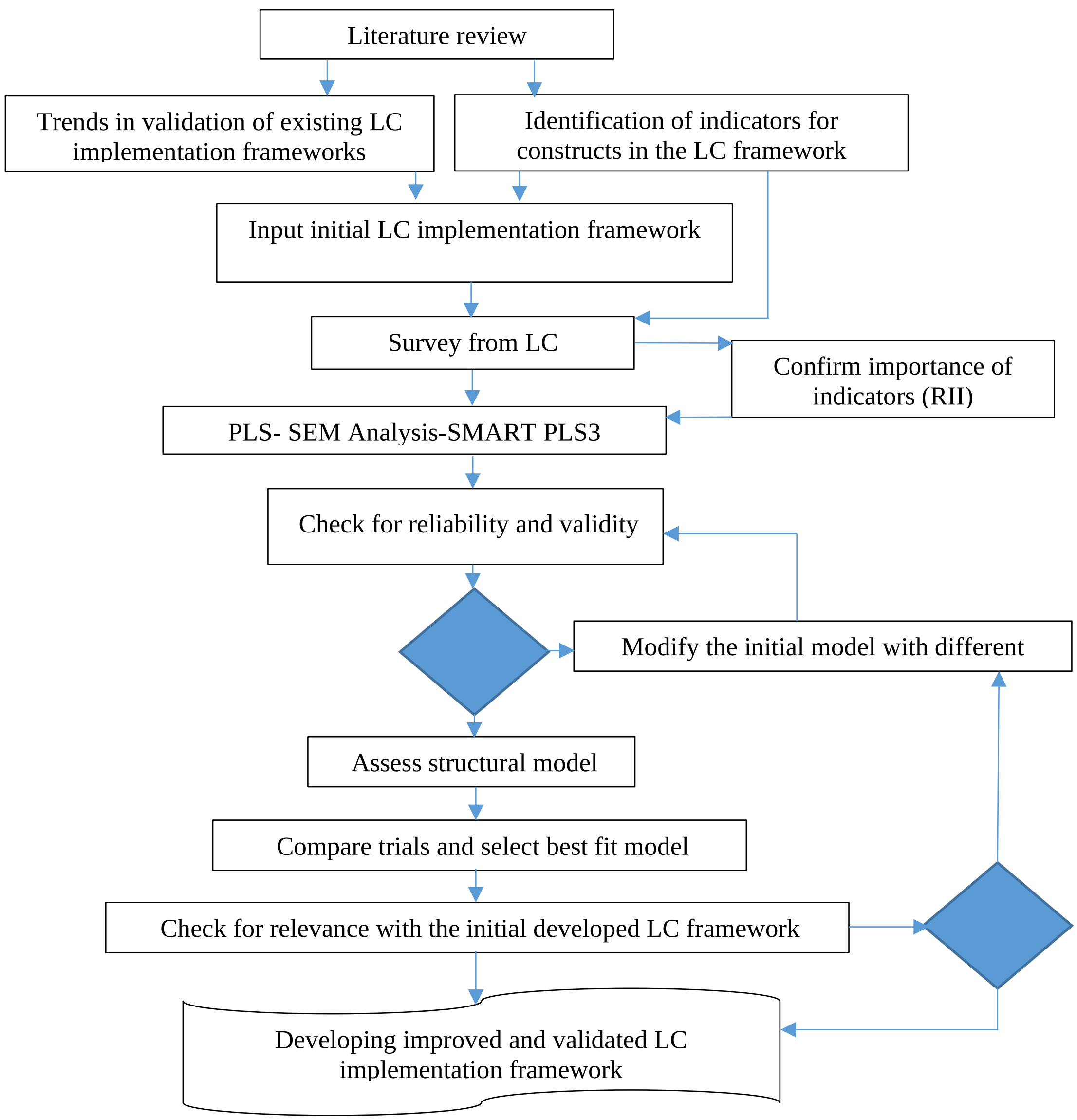

Figure 8.1. Research methodology for chapter 8

8.4. Validation Approaches

One of the most important processes in any research effort is to validate its outcomes by using dependable, robust, and practical approaches. The successful validation of the outcomes will make its findings more trustworthy, and meaningful for the potential users (Hair et al., 2016). In the case of research involving the development of models/frameworks, there is always a need for robust validation techniques because of the issues of biasedness (interpretation of the data by one or a few groups of researchers) and inconsistencies among different research analysis techniques in generating the same results (Richie et al., 2013; Miles and Huberman, 1994). Similarly, difficulties in obtaining the data that truly represent the population is another area that requires the research outcomes to be validated.

Over the period, researchers have resorted to different validation approaches to confirm their outcome models and convince the readers about the authenticity and trustworthiness of their research efforts. Some of the validation approaches commonly used in the research involving the development of models/frameworks/tools are as follows.

8.4.1. Internal Validation

- Comparing the outcome with the results of the other objectives leading to the outcomes (Denzin, 2009)
- Exploring the convergence between the findings with the published research and common academic and industrial practices (Manu, 2012)
- Statistical tests to check the internal consistencies of the data or checking the accuracy of fit (Ritchie et al., 2013)

8.4.2. External Validation

1. Triangulation

- Theory triangulation: According to Richie et al., (2013) the outcomes/results can be validated from different theoretical perspectives. The results are matched/compared with the already validated theories to see differences and similarities.
- Triangulation of sources:
- Different approaches such as observations or survey or interviews can be used to compare the data (Ritchie et. al., 2013)

- Validating the findings by using an alternate approach that is a case study in which comparing/observing the similarities between the best practices applied in the case study with the developed models/frameworks/tools (Heravi and Rashid, 2018; Al-Aomar, 2012)
- Methods triangulation: Just changing the method of data collection from qualitative to quantitative or vice versa (Ritchie et al., 2013)
- Triangulation through multiple analysis:
- Changing both the sample respondents and analysis techniques to compare the developed framework/model with the outcome from the new data analysis.
- Statistically validating the framework/model (developed qualitatively) by using structural equation modeling by collecting data from the industry/common practices (Demirkesen, 2019; Jain and Ajmera, 2018)

2. Member or respondent validation

- Replicating the research process with the same or another group of samples having the same experience/characteristics (kerlinger and lee, 2000; Rosenthal & Rosnow, 1991) to see if the developed framework is confirmed by a new group (Miles & Huberman, 1994)
- Reaching out to the experts for getting their opinion on the final outcome (Herrera et al., 2019; Bashir, 2015; Silverman, 2006)
- Action-based research: Applying the outcomes in an actual environment to measure its efficacy or trial implementation of the proposed findings into industrial projects (Swefie, 2013)

- Predicting the outcome through simulations: Use of simulation models to test the efficacy of the developed model/framework/tool (Abbasian-Hosseini et al., 2014; Bajjou and Chafi, 2020; Erikshammar et al., 2013)

The choice between the validation approach depends on several factors such as availability of enough time and cost, degree of accuracy required, difficulties in getting a response from the targeted population (in terms of access and reachability), willingness to participate by the expert's population and the prevalent environmental effects (as an example: impact of COVID -19 on construction projects) (NATA, 2012; Ritchie et al., 2013; Miles & Huberman, 1994). Moreover, it should also be kept in mind that all the validation approaches as discussed above are not free from limitations (Ritchie et al., 2003) because of a lack of independent and completely reliable access to reality (Hammersley, 1992). It is the responsibility of the researchers to ensure the adequacy of their validation process by ensuring the most accurate source and methods of analysis.

8.4.3. Validation Approaches

The validation of models/frameworks is a challenging task because LC models/frameworks are often modeled for a specific population. As a result, researchers have had to identify the most suitable methods of validation to authenticate their research. Koskela (2000) was the pioneer in developing the initial theoretical framework (transformation flow and value, TFV) for implementing LC and applied the theory triangulation validation approach by explaining (1) the historical justifications, (2) comparing new theory to prior theories, and (3) contributions of the new theory to new understanding and improved performances. Diekmann et al., (2004) developed a theoretical LC wheel and questionnaire to find conformances and validated the LC conformance instrument using interviews of case study contractors. Al-Aomar

(2012) developed an LC implementation framework by incorporating LC practices into different stages of a Lean Project Delivery System (LPDS) framework and further assessed the efficacy of the framework with a case study by measuring overall improvements in cost, time, quality, waste, and value by using six sigma ratings. Swefie (2013) conducted interviews with 5 experts to validate the LC implementation framework by asking their opinion about the applicability and efficiency of the proposed LC framework. Similarly, EI-Sabek et al (2018) validated their Last Planer System (LPS) implementation framework for international mega-projects using input from a 15-member focus group. Their opinion about the impact of the LPS framework against prescribed criteria was collected. The validated framework was further tested on an ongoing project. Some researchers validated their LC implementation frameworks by reaching out to experts or focus groups (Ghosh and Heidenreich, 2018; Nesensohn, 2014; Bashir et al., 2015; Herrera et al., 2020; Heravi and Rashid, 2018). Few used simulation models to validate the outcome of the LC practices (Abbasian-Hosseini et al., 2014; Bajjou and Chafi, 2020).

In summary, it was observed that efforts in evaluating the efficacy of the developed frameworks in terms of their impact on the project outcomes are not explored consistently within the validation process. Although expert opinion can provide some level of validation, the validation process remains relatively generic if it is lacking any concrete evidence of how the developed frameworks can impact the project outcomes.

8.5. Initial LC Implementation Framework

The initial LC implementation framework, in Figure 8.2, was developed using the interpretative structural modeling (ISM) technique in which the relationship between the factors was identified from the input of 82 Lean companies (Chapter 7). The LC implementation framework consists of 12 main factors/constructs which were identified through a questionnaire survey of 55 lean experts.

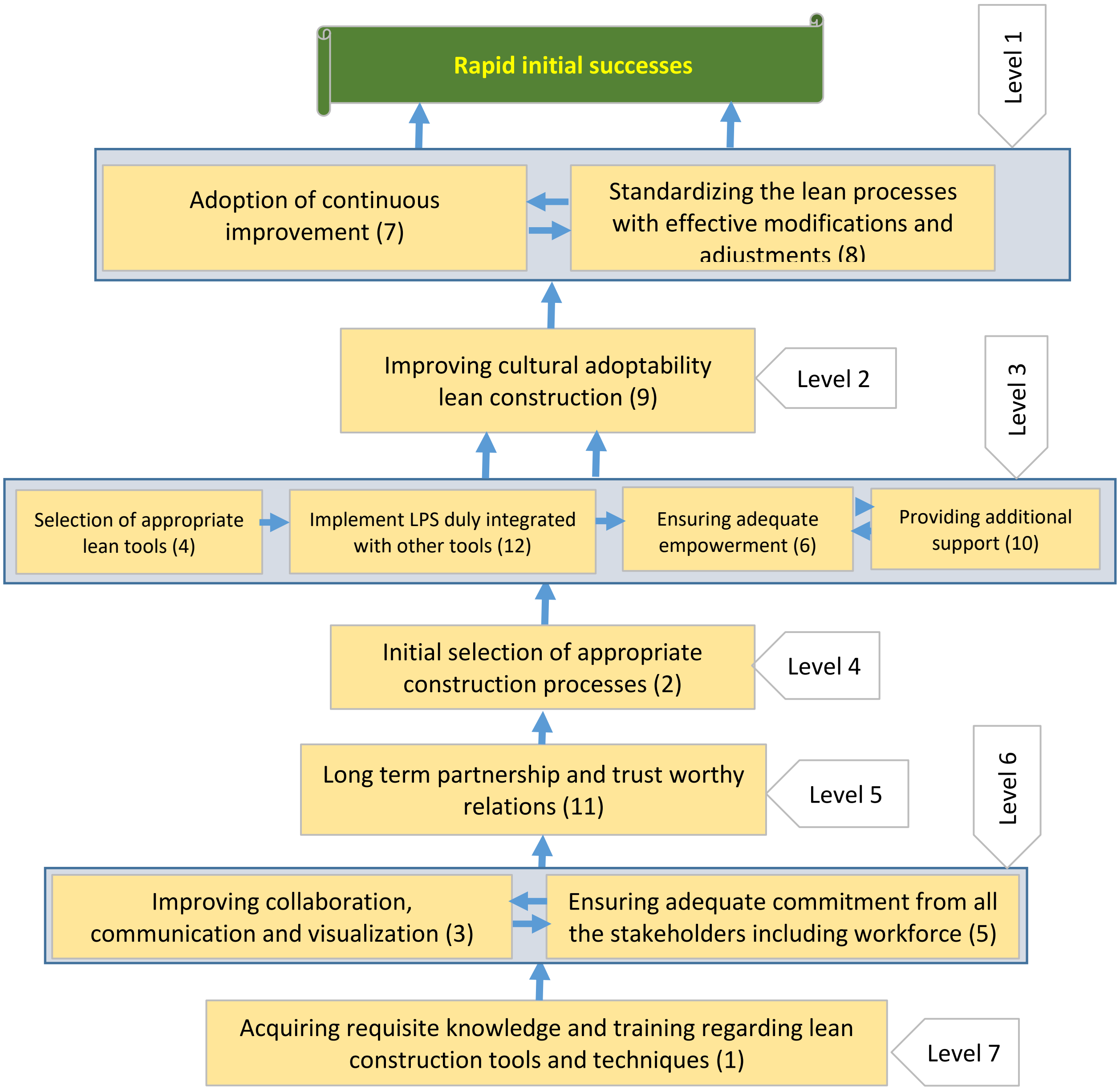

Figure 8.2. Initial LC implementation framework (reproduced from chapter 7)

8.5.1. Identification of Indicators for Constructs/Factors

Literature studies have further revealed that almost all the LC implementation frameworks are composed of either critical success factors (CSFs), LC principles, or LC tools and techniques arranged in a hierarchal order to guide the construction industry in implementing

LC (Ballard et al., 2007; Ghosh and Heidenreich, 2018; Sarhan et al., 2019). However, each factor itself needs to be further explored to provide modalities for achieving that particular factor. It would be of great value to the potential lean practicing companies if the second-order explanation of the factors in the form of indicators is mentioned in the framework.

A total of 38 indicators for measuring the implementation level of 12 factors/constructs were already been identified by Aslam et al., (2020c) and explained in chapter 6. However, in chapter 6 these indicators are referred as the key subfactors for achieving the major 12 factors/constructs. Other indicators were also identified based in the literature whose inclusion would better capture the full implementation level of every construct/factor. Apart from 38 indicators, eight (8) key performance output parameters were also identified that can be used to measure the efficacy of the LC implementation framework. The overall list of factors/constructs along with their measured indicators are shown in Table 8.1.

Table 8.1. Constructs and indicators

Constructs and Indicators	**Abbreviated name used in the SEM**
Construct 1: Acquiring requisite knowledge and training regarding lean construction tools and techniques (1)	**KNOW**
Getting help from external/internal facilitators in understanding lean concepts.	TRGHELPEXT
Evaluating the training needs of their employees	TRGNEEDS
Providing training opportunities to the project teams by arranging lean workshops or on job training sessions.	TRGWKSP
Providing opportunities to the key project team members for attending lean conferences/congresses/seminars.	KNOWCONF
Ensuring the key personnel are effectively educated and well trained to start the lean construction practice.	KNOWTRAINED
Construct 2: Initial selection of appropriate construction processes	**PROCESS**
Initially selecting those processes for lean intervention that were not effectively managed.	PROCMGT
Initially selected those processes for lean intervention that was affordable in terms of resources.	PROCAFFORD
Initially selected those processes for lean intervention that could significantly impact time and resources.	PROCTIMECOST
Construct 3: Improving collaboration, communication and visualization	**COLL**
Involving all the project participants, like architect/designers, contractors/subcontractors/suppliers at an early stage of the project	EARLYINV
Regularly undertaking projects using Integrated Project Delivery (IPD).	COLLIPD
Early involvement of all project participants with shared risks and rewards helped in waste reduction, meeting customer's requirements, and maintaining flow in your project.	EARLYIMPR
Using big room sessions for increasing collaboration among project key stakeholders as well as project teams.	COLLBIG
Using technologies (like BIM or others) to improve visualization and communication among project participants.	COLLBIM
Construct 4: Selection of appropriate lean tools and techniques/system	**LC TOOLS**
Selecting lean tools and techniques based on their compatibility with construction processes.	TOOLCOMP
Selecting lean tools and techniques based on the alignment between the objective of lean tools and techniques with lean construction principles.	TOOLALIGN
Selecting lean tools and techniques that can maximize value/benefits in terms of cost, time, and productivity.	TOOLBENEF
Construct 5: Ensuring adequate commitment from Project teams	**COMMT**
Starting lean construction only after your top, middle and field management is highly committed to implementing lean construction.	COMTOP
Starting lean construction only after your workforce and your partner organization (such as subcontractors or suppliers) are adequately (not necessarily highly) committed to implementing lean construction.	COMEMP
Initial achieving improvements within the range of 10-20% in categories of cost, time, quality, and safety increases the commitment and trust for lean construction among your teams.	INIIMPRO
Identifying the defects/quality issues on their own and rectifies them before moving forward by project teams	SELFIMPR
Construct 6: Ensuring adequate empowerment be given to field management and workforce	**EMPOWER**
Adequately empowering field management and workforce to implement workplace improvement during the lean process.	EMPFELD
Active participation of key workforce personnel and subcontractors/ suppliers actively during master, lookahead, and weekly planning meetings.	EMWORK

Table 8.1. Constructs and indicators (continued)

Constructs and Indicators	**Abbreviated name used in the SEM**
Construct 7: Adoption of continuous improvement	**CI**
Periodically measuring the project outcomes weekly or monthly.	CIWEEKLY
Continuously improving the lean processes through regular progress outcome measurements.	CIPROCESS
Continuously improving the lean processes by regularly performing Plan, Do, Check, Act (PDCA) cycles or conducting First Run Studies (FRS).	CIPDCA
Construct 8: Standardizing the lean processes	**STAND**
Standardizing lean processes/methods with effective modifications on every project.	STANDMOD
Construct 9: Improving cultural adaptability and commitment towards lean construction	**CULT**
Gradually implementing lean tools and techniques improved commitment and trust for lean construction	GRAD
Regularly sharing goals/objectives, commitments, mutual benefits, and project results to the other project partners and internal project teams.	CULSHARE
Collaboration among your project participants ensures mutual agreement on implementing lean construction.	CULTCOLL
Promoting a culture of team work during projects	CULTTEAM
Celebrating initial successes with all the project partners and internal project teams.	CULTCELBSUC
Construct 10: Providing additional support and incentives to the lean teams	**ADLDLSP**
Provided additional preparation and training resources to lean teams, once you start your lean journey.	ADDLSUPPREP
Providing upper management and trusted “no fear of failure” once you started your lean journey.	ADDLSUPCONF
Ensuring team rewards for lean teams, once you start your lean journey.	REWTEAMS
Ensuring incentive systems for partners, once you start your lean journey.	INCENPARTNRS
Construct 11: Long term partnership and trustworthy relations	**LONGTRUST**
Relationships between your organization with other project parties are based on long-term partnerships.	LONGTERM
Relationships between your organization with other project parties are based on trust and transparency.	TRUST
Construct 12: Implementing LPS duly integrated with other tools	**INTEGTOOLS**
Ensuring integrated implementation of Last planer system (LPS) with other LC tools and techniques	INTEGLPS
Performance measurement indicators	**OUTCOME**
control cost overrun	CNTRLCOST
control schedule overrun	CNTRLSCHEDULE
improve quality	IMPQUALITY
improve safety	IMPSAFETY
increase profit	INCPROFIT
reduce financial losses	REDLOSSES
reduce lawsuits	REDSUITS
Improve relationships among different parties	IMPRRELATION

8.5.2. Steps Involved Conducting PLS-SEM

SEM is a sophisticated multivariate data analysis method that utilizes statistical methods to simultaneously analyze multiple variables. The capability of estimating the unobserved variables (latent variables/constructs) by directly measuring the indicator variables is a very powerful capability of SEM for research involving the validation of frameworks. PLS-SEM is one of the types of SEM which maximizes explained variance of the dependent (endogenous) variable by estimating partial model relationships in an iterative sequence of ordinary least square (OLS) regression. The use of PLS-SEM has been recommended for testing and validating the theoretical models due to its capabilities of dealing with multiple independent and dependent variables at one time (Henseler et al., 2009; Garson, 2016). PLS-SEM also can efficiently analyze small sample sizes (Mendy et al, 2019) that have a non-parametric nature with no rigid requirement of specific distributional assumptions, although data should not vary greatly from normality (Cassel et al., 1999; Garson, 2016). Various stages involved in conducting the PLS-SEM analysis are adopted from the previous works of literature (Hair et al.,2016; Garson, 2016) and are used for this study in a way as described below.

Stage 1: Specifying the structural (inner) model**:** In this study, the LC implementation framework (Chapter 7) is specified as the basic input model and reproduced in Figure 8.2. The framework consists of 12 constructs with dependencies on each other while the 13th construct (performance outcomes) is the target of interest against which the efficacy of the framework will be assessed.

Stage 2: Specifying the measurement (outer) model**:** Since the constructs are not directly observed and estimated using a direct measurable indicator, it is necessary to assign these variables to the respective constructs. As a result, 46 indicators as shown in Table 8.1 are assigned to their respective constructs in the structural model. The model comprising of indicators is called as outer or measurement model.

Stage 3: Data collection and examination: The data was collected using a questionnaire-survey technique from the targeted population of companies that have used-LC during their projects. The questionnaire was prepared with four Likert scale items (strongly disagree to strongly agree). The complete questionnaire is given in Appendix C part 2. To validate the developed LC implementation framework, it was imperative to reach out to only LC companies that can provide the most relevant information based on their experience. Total 251 companies identified as members of Lean Construction Institute-United States (LCI) or known to have significant LC experience were contacted. Eighty-two (82) companies responded to the questionnaire survey for a response rate of 33%. The thumb rule for estimating the sample size for PLS-SEM is the 10-times rule. The number of predictor variables (either indicators or construct) pointing to a particular construct is multiplied by 10 to have an acceptable sample size. In the developed LC framework, the construct performance outcome has a maximum of eight (8) indicators, hence the minimum sample size required is 8 x 10 =80. Therefore, 82 responses meet the rule of thumb samples sized expectation.

The data was examined to eliminate responses having more than 15% missing values (Hair et al., 2016). None of the surveys had greater than 15% of missing values, hence all the 82 responses were kept for analysis. Similarly, for indicators, the number of missing values in the data per indicator were less than 5% and missing values were replaced with mean values of the indicator (Hair et al., 2016). With values of kurtosis and skewness between negative (-1) and (+1), no major normality issues were found except for indicators of "reduced losses (performance outcomes)" that had a kurtosis value of 1.22. However, in the case of the construct performance outcomes, there are other seven indicators also measuring the same construct, hence this deviation was not considered an issue, and the indicator was retained.

Stage 4: Run the PLS-SEM algorithm and estimate the model: The basic concept on which the PLS-SEM algorithm functions is using the indicator data as the main input to estimate the constructs. The scores of the estimated constructs are used as input for partial regression models within the model. Except for the first and last construct, every other construct in the framework has some dependent and independent variables (predecessors and successors), hence there is a partial regression model for every dependent latent variable (construct) to estimate all the path coefficients.

Stage 5: Assessing the reliability and validity of the measurement model: The main purpose of this stage is to ensure that the measured indicator variables are reliable and valid and should be kept in the model for further analysis. In case of issues, the respective indicator is either eliminated from the model or reassigned to other constructs based on its correlation with that construct, or a new construct can be added that relates to these indicators. This stage improves the model based on the best fit model as determined by the highest R^2 values.

Stage 6: Assessing Structural Model: The main purpose of this stage is to examine the predictive capabilities and the relationships between the constructs within the structural model. The first step in assessing the structural model is to check for collinearity. The path coefficients might have an issue of biasedness if the estimation involves a critical level of collinearity among the predictor constructs (dependent variables). To check for collinearity issues, Variance inflation factor (VIF) values are assessed with a tolerance of value 0.2 (VIF values above 5) (Hair et al.,2016). In case of the collinearity issues with the constructs, one should consider either eliminating the construct or merging predictors into a single construct, or creating higher-order constructs (Hair et al., 2016).

8.6. Best Fit Model

In Stage 5 instead of eliminating indicators that have reliability and validity issues, their correlation with other constructs is checked for reassignment. Each time the indicator is reassigned, the PLS-SEM model is rerun to check its effect in improving the AVE and HTMT values. Several trial runs are required to find the most suitable location of that indicator within the measurement model. Similarly, after Stage 6, there can be paths within the structural model that are less significant based on improvement to the R^2 value. These paths are either eliminated or reassigned to assess the model that can best explain the performance outcomes with optimized R^2 values.

8.7. Validation Results

8.7.1. Relative Importance Index (RII) for the Indicators

Before the initial trial run, the importance of each indicator is checked using the relative importance index (RII) that aids in deciding on retention or elimination of the indicators within the framework. RII was performed by using the following equation (Gudienė et al. 2013):

$$RII = \sum(aX)/A\times N$$

Where, a = weights given to each response, ranging from 1 (first scale or lowest scale) and increased numerically by addition of 1 till the last scale (Highest weight), X=Frequency of occurrence of “a”, A=Highest weight and N=Total number of respondents. The RII values for 37 indicators measured with the Likert scale are shown in Table 8.2. For the indicator, Integrated LPS, the relative importance index was not calculated as this question is in a Yes or No format in the analysis. It can be seen that almost all the indicators have RII values greater than 75%, this suggests that all the indicators are regularly used by the LC companies to improve their construction performances. The RII values imply that all the indicators are important and should be kept in the framework. However, the assignment of these indicators within 12 constructs has to be confirmed through PLS-SEM.

Table 8.2. Relative importance index for indicators

Indicators	**RII**	**Indicators**	**RII**
Indicators for constructs within Framework			
TRGHELPEXT	0.75	SELFIMPR	0.79
TRGNEEDS	0.77	EMPFELD	0.77
TRGWKSP	0.76	EMWORK	0.79
KNOWCONF	0.76	CIWEEKLY	0.80
KNOWTRAINED	0.79	CIPROCESS	0.82
PROCMGT	0.75	CIPDCA	0.77
PROCAFFORD	0.75	STANDMOD	0.78
PROCTIMECOST	0.78	GRAD	0.79
EARLYINV	0.81	CULSHARE	0.81
COLLIPD	0.79	CULTCOLL	0.81
EARLYIMPR	0.76	CULTTEAM	0.81
COLLBIG	0.77	CULTCELBSUC	0.82
COLLBIM	0.81	ADDLSUPPREP	0.81
TOOLCOMP	0.81	ADDLSUPCONF	0.80
TOOLALIGN	0.80	REWTEAMS	0.79
TOOLBENEF	0.81	INCENPARTNRS	0.76
COMTOP	0.78	TRUST	0.83
COMEMP	0.73	LONGTERM	0.85
COMPERCENT3	0.77		
Indicators for Performance Outcomes			
CNTRLCOST	0.80	INCPROFIT	0.79
CNTRLSCHEDULE	0.84	REDLOSSES	0.78
IMPQUALITY	0.80	REDSUITS	0.76
IMPSAFETY	0.79	IMPRRELATION	0.80

8.7.2. SEM Analysis

The initially developed framework was used as a basic input model to start the analysis as a Trial 1 in Stage 4. The indicators as shown in Table 8.1 were assigned to their respective constructs. The indicators were assigned based on the theoretical concepts after checking the compatibility of indicators with the constructs. However, the validity and reliability of every indicator was checked when the PLS application was run and the measurement model is assessed for all the reliability parameters. The main purpose of stage 5 was to evaluate the right placement and eligibility of the indicators within the framework. In case the eligibility is not established, the indicators were reassigned and realigned to other constructs or reformed into the new construct without losing the content validity. Keeping in view the importance of every indicator (Table 8.2), it was ensured that indicators are not eliminated from the framework but rearranged in a logical and compatible manner to develop the best fit model. Several trials and runs were carried out to determine the best combination of constructs with indicators. However, the initial (Trial 1) and final trial (Trial 4) runs results are shown in Table 8.3. The criteria for determining the significance of each performed trial were as follows:

- Composite reliability > 0.70 and should not be greater than 0.9 (Hair et al.,2016; Garson, 2016)
- Average Variance Extracted (AVE) > 0.50, if < 0.50 check for sig at α=0.05 (Hair et al., 2016; Garson, 2016; Chin, 1998)
- Indicator reliability,
    - No outer loading should be less than 0.7, if less than 0.4 then it should be eliminated,
    - However, between 0.4-0.7, it may be retained if reassignment and elimination improve AVE and composite reliability (Hair et al., 2016; Garson, 2016)
- Factor cross-loading - an indicator’s outer loadings on a construct should be higher than all its cross-loadings with other constructs

- Fornell-Lacker criteria- the square root of the AVE of each construct should be higher than its highest correlation with any other construct
- HTMT- The values should be less than 0.85 if the constructs are more distinct however it can be 0.9 if constructs are conceptually similar (Henseler et al., 2015; Teo et al., 2008). In no case, HTMT values should be more than 0.9

For the trial run 1, the composite reliability was established as almost all the constructs have composite reliability values of greater than 0.70 indicating that all the indicators are reliable in estimating the respective constructs. However, the AVE value for constructs KNOW, CULT, ADDLSP, and OUTCOME were less than 50%. This means that these constructs explain less than 50% of the indicator's variance. The reliability of most of the indicators is greater than 0.7 indicating these indicators have much in common that is captured by the respective constructs however, 13 indicators out of 46 have indicator reliability between 0.6-0.7. One serious conflict between indicators COLLIPD and COMMIT shows that the indicator COLLIPD has a strong correlation with construct COMMIT also. Fornell-Lacker criterion also revealed some of the correlation issues between the constructs COLL and KNOW and constructs CULT with OUTCOME. Further evaluation of HTMT showed that COLL and KNOW are also highly correlated with values greater than 0.9 and therefore lack discriminant validity. The detailed outputs are given in Table 8.3.

Considering some of the issues with convergent and discriminant validity, the initial framework was modified. However, during these modifications, the integrity of the content was ensured. Before assessing the structural model, the conflicting indicators are eliminated from the framework one by one and checked for their effectiveness in improving the convergent and discriminant measures (AVE, HTMT, Fornell-Lacker). In case the effects didn't improve the reliability and validity measures, these indicators are eliminated from the initial framework. After this analysis the indicators, TRGHELPEXT, TRGNEEDS, TRGWKSP, COLLIPD, COLLBIM, and INCPROFIT were eliminated from the framework in trail 2. The resulting framework in trial 2 showed no issues with indicator and construct reliabilities. Therefore, the trail 2 will be assessed for a structural model in the later section.

Since all the indicators as found out in Table 8.2 are considered important, in other trials, the conflicting indicators are retained without any deletion. However, the position of indicators is changed either by creating new constructs or by reassigning the indicators to some other construct having a high correlation with that particular indicator. After several test trials, the model framework (Trail 4) with new constructs using the same problematic indicators (as eliminated in trial 2) are introduced in the framework. The paths, as well as order of the constructs as shown in the initial LC framework, are kept the same, however, the position of indicators is changed. In Trial 4, new constructs along with indicators are introduced as follows:

- Construct EXTERNALHELP with single indicator TRGHELPEXT
- Construct TRAINING with single indicator TRGWKSP
- Construct KNOW will now have two indicators as KNOIWCONF and KNOWTOP
- Construct LONGTRUST is separated into two constructs LONGTERM and TRUSTWORTHY with indicators of LONG and TRUST respectively
- An altogether new construct RAPID SUCCESS is added with all the indicators that indicate rapid successes is introduced. The indicators are GRAD, SELPIMPR, COMPERCENT, and EARLYINV.

After evaluating the measurement model for Trail 4, it can be seen from Table 8.3 that all required indicators and constructs meet the indicator, convergent, and discriminant validity requirements and can further be assessed for structural evaluations.

Both Trial 2 (after deleting the insignificant indicators from the initial framework in trial 1) and Trial 4 meet the required criteria, therefore, they are carried over and evaluated for structural validity in the next section.

Table 8.3. Test for reliability and validity of indicators and constructs

Indicators and Constructs			**composite reliability**		**(AVE)**		**Indicator reliability**		**Factor cross loading**		**Fornell-Lacker**		**HTMT**	
Indicators	Constructs Trial 1	Constructs – Trail 4	Trial 1	Trail 4	Trial 1	Trail 4	Trial 1	Trail 4	Trial 1	Trail 4	Trial 1	Trail 4	Trial 1	Trail 4
TRGHELPEXT		TRGHELPEXT		1		> 0.5	0.64	> 0.7	>	>		>		< 0.9
TRGNEEDS		TRGNEEDS		1		> 0.5	0.60	> 0.7	>	>		>		< 0.9
TRGWKSP	KNOW	TRGWKSP	0.83	1	< 0.5 Sig with p-0.00	> 0.5	> 0.7	> 0.7	>	>	>	>	> 0.9 with COLL	< 0.9
KNOWCONF		KNOW		0.88		> 0.5	> 0.7	> 0.7	>	>		>		< 0.9
KNOWTRAINED							> 0.7	> 0.7	>	>				
PROCMGT							> 0.7	> 0.7	>	>				
PROCAFFORD	PROCESS	PROCESS	0.85	0.85	> 0.5	> 0.5	> 0.7	> 0.7	>	>	>	>		< 0.9
PROCTIMECOST							> 0.7	> 0.7	>	>			< 0.9	
EARLYINV		RAPIDSUCCES		0.85		> 0.5	0.67	> 0.7	>	>		>		< 0.9
COLLIPD		COLLEARLY		1		> 0.5	0.66	> 0.7	<	>	> Some issue with KNOW	>		< 0.9
EARLYIMPR	COLL	RAPIDSUCCES	0.85	0.85	> 0.5	> 0.5	> 0.7	> 0.7	>	>		>	< 0.9	< 0.9
COLLBIG		COLL		0.86		> 0.5	> 0.7	> 0.7	>	>		>		< 0.9
COLLBIM							0.63	> 0.7	>	>				
TOOLCOMP							> 0.7	> 0.7	>	>				
TOOLALIGN	LC TOOL	LC TOOL	0.82	0.82	> 0.5	> 0.5	> 0.7	> 0.7	>	>	>	>	< 0.9	< 0.9
TOOLBENEF							> 0.7	> 0.7	>	>				
COMTOP		COMMIT		0.89		> 0.5	> 0.7	> 0.7	>	>		>		< 0.9
COMEMP	COMMIT		0.86		> 0.5		> 0.7	> 0.7	>	>	>		< 0.9	
COMPERCENT3		RAPIDSUCCES		0.85		> 0.5	> 0.7	> 0.7	>	>		>		< 0.9
SELFIMPR							> 0.7	0.66	>	>				
EMPFELD	EMPOWER	EMPOWER	0.85	0.85	> 0.5	> 0.5	> 0.7	> 0.7	>	>	>	>	< 0.9	< 0.9
EMWORK							> 0.7	> 0.7	>	>				
CIWEEKLY							> 0.7	0.66	>	>				
CIPROCESS	CI	CI	0.78	0.78	> 0.5	> 0.5	> 0.7	> 0.7	>	>	>	>	< 0.9	< 0.9
CIPDCA							0.67	0.69	>	>				
STANDMOD	STAND	STAND	1	1	> 0.5	> 0.5	1	> 0.7	>	>	>	>		< 0.9

Table 8.3. Test for reliability and validity of indicators and constructs (continued)

Indicators and Constructs			**composite reliability**		**(AVE)**		**Indicator reliability**		**Factor cross loading**		**Fornell-Lacker**		**HTMT**	
Indicators	Constructs Trial 1	Constructs – Trail 4	Trial 1	Trail 4	Trial 1	Trail 4	Trial 1	Trail 4	Trial 1	Trail 4	Trial 1	Trail 4	Trial 1	Trail 4
GRAD	CULT	RAPIDSUCCES	0.83	0.85	< 0.5 SIG with p-0.00	> 0.5	> 0.7	> 0.7	>	>	< OUT-COME	>	< 0.9	< 0.9
CULSHARE		CULT		0.82		> 0.5	> 0.7	> 0.7	>	>		>		< 0.9
CULTCOLL							> 0.7	> 0.7	>	>				
CULTTEAM							0.63	> 0.7	>	>				
CULTCELBSUC							0.67	> 0.7	>	>				
ADDLSUPPREP	ADDLSP	ADDLSP	0.78	0.77	< 0.5 SIG with p-0.00	> 0.5	0.63	> 0.7	>	>	>	>	< 0.9	< 0.9
ADDLSUPCONF							0.63	> 0.7	>	>				
REWTEAMS		REWARD		0.85		> 0.5	> 0.7	> 0.7	>	>		>		< 0.9
INCENPARTNRS							> 0.7	> 0.7	>	>				
TRUST	LONGTRUST	TRUST	0.78	1	> 0.5	> 0.5	> 0.7	> 0.7	>	>	>	>	< 0.9	< 0.9
LONGTERM		LONG		1		> 0.5	> 0.7	> 0.7	>	>		>		< 0.9
INTEGLPS	INTEGTOOL	INTEGTOOL	1	1	> 0.5	> 0.5	1	> 0.7	>	>	>	>	< 0.9	< 0.9
CNTRLCOST	OUTCOME	OUTCOME	0.88	0.88	< 0.5 SIG with p-0.00	< 0.5 SIG with p-0.00	> 0.7	> 0.7	>	>	>	>	> 0.9 with LONG TRUST	< 0.9
CNTRLSCHEDULE							0.68	0.68	>	>				
IMPQUALITY							> 0.7	> 0.7	>	>				
IMPSAFETY							> 0.7	> 0.7	>	>				
INCPROFIT							0.61	0.61	>	>				
REDLOSSES							0.62	0.64	>	>				
REDSUITS							> 0.7	> 0.7	>	>				
IMPRRELATION							> 0.7	> 0.7	>	>				

8.7.3. Evaluation of the Structural Model

Trial 2 and Trial 4 were further assessed for evaluating the structural parameters of the framework. The significance of the path coefficients for both models is tested using bootstrapping procedure in PLS-SEM. Table 8.4 shows the detailed evaluation of the structural model for Trial 2. The analysis shows that except for paths from constructs PROCESS-INTEGTOOLS, PROCESS-EMPOWER, LCTOOLS-INTEGTOOLS, all other paths are found to be significant with P values less than 0.1 ($\alpha = 0.1$). After removing the insignificant paths from Trial 2, it is re-evaluated and renamed as Trial 3. The results for structural evaluation of Trial 3 are shown in Table 8.5. The effective sizes of the constructs are checked by using the following criteria:

- f^2 values of 0.02, 0.15, and 0.35 indicate an exogenous construct's small, medium, or large effect, respectively, on an endogenous construct (Cohen, 1988; Hair et al., 2016)
- The resulting Q^2 values larger than 0 indicate that the exogenous constructs have predictive relevance for the endogenous construct under consideration (Hair et al., 2016).
- Standardized root means square residual (SRMR) should preferably be under 0.08, however for complex models having a high number of independent and dependent variables, it can be under 0.1 (Garson 2016)

In the case of Trial 3, the effect size of respective exogenous (predecessor) construct showed that some constructs have a small impact on their endogenous (successor) constructs while others have medium and high effects. It was found out that only the exogenous construct PROCESS does not affect its endogenous construct INTEGTOOLS indicating that the construct

PROCESS will only affect INTEGTOOLS through either construct LCTOOLS and EMPOWER. The predictive relevance of (Q^2) of all the constructs differs from zero indicating all exogenous constructs can fairly predict the endogenous constructs using out of sample data also. The coefficient of determination (R^2) shows 42.8% of the variation in the construct OUTCOME can be explained by the framework as developed in Trial 3.

In the case of Trail 4, all path coefficients are found to be significant at $\alpha=0.05$ with P-values less than 0.05 except for path CI-STAND, which is significant at $\alpha=0.1$. The details of Trial 4 are shown in Table 8.6. The analysis indicates that all exogenous constructs have a small to high impact on the endogenous constructs as none of the constructs have an f^2 value less than 0.02. Similarly, all the exogenous constructs can fairly predict the endogenous constructs as all the Q^2 values differ from zero. The R^2 value of 0.645 shows that 64.5% of the variation in OUTCOME can be explained by the framework developed in Trial 4. The PLS-SEM outputs for Trail 1, Trail 2, Trail 3, and Trail 4 are shown in Appendix E.

Table 8.4. Assessing the structural model after eliminating the problematic indicators -Trial 2

Paths	**Path significance at α=0.10**	**Sign**	***f^2***	**Effect size (f^2)**	**Constructs**	**R^2**	***Q^2***	**Sig (Q^2)**
KNOW-COMMIT	< 0.05	Yes	0.458	High	KNOW	0.000	0.000	-
KNOW-COLL	< 0.05	Yes	1.264	High	COMMIT	0.314	0.165	Yes
COMMIT-LONGTRUST	< 0.10	Yes	0.033	Small	COLL	0.558	0.275	Yes
COLL-LONGTRUST	< 0.05	Yes	0.151	Medium	LONGTRUST	0.318	0.170	Yes
LONGTRUST-PROCESS	< 0.05	Yes	0.245	Medium	PROCESS	0.197	0.120	Yes
PROCESS-LCTOOLS	< 0.05	Yes	0.483	High	LCTOOLS	0.326	0.187	Yes
PROCESS-INTEGTOOLS	> 0.10	No	0.000	No	INTEGTOOLS	0.107	0.026	Yes
PROCESS-EMPOWER	> 0.10	No	0.044	Small	EMPOWER	0.042	0.028	Yes
LCTOOLS-INTEGTOOLS	> 0.10	No	0.013	Small	ADDLSP	0.037	0.011	Yes
EMPOWER-INTEGTOOLS	< 0.10	Yes	0.056	Small	CULT	0.307	0.139	Yes
INTEGTOOLS-ADDLSP	< 0.10	Yes	0.039	Small	CI	0.245	0.116	Yes
ADDLSP-CULT	< 0.05	Yes	0.444	High	STAND	0.387	0.372	Yes
CULT-CI	< 0.05	Yes	0.324	High	OUTCOMES	0.428	0.188	Yes
CULT-STAND	< 0.05	Yes	0.632	High				
CI-OUTCOME	< 0.05	Yes	0.341	High				
STAND-OUTCOME	< 0.05	Yes	0.140	Small				

Table 8.5. Assessing the structural model -Trial 3 (after improving the model for reliability and validity and significance of paths of Trial 2)

Paths	**Path significance at α=0.10**	**Sign**	***f^2***	**Effect size (f^2)**	**Constructs**	**R^2**	***Q^2***	**Sig (Q^2)**
KNOW-COMMIT	< 0.05	Yes	0.344	High	KNOW	0.000	-	-
KNOW-COLL	< 0.05	Yes	0.268	Medium	COMMIT	0.256	0.132	Yes
COMMIT-COLL	< 0.05	Yes	0.156	Medium	COLL	0.459	0.274	Yes
COLL-LONGTRUST	< 0.05	Yes	0.238	Medium	LONGTRUST	0.192	0.172	Yes
LONGTRUST-PROCESS	< 0.05	Yes	0.179	Medium	PROCESS	0.152	0.089	Yes
PROCESS-LCTOOLS	< 0.05	Yes	0.466	High	LCTOOLS	0.318	0.186	Yes
LCTOOLS - EMPOWER	< 0.05	Yes	0.246	Medium	INTEGTOOLS	0.083	0.057	Yes
EMPOWER-INTEGTOOLS	< 0.05	Yes	0.091	Small	EMPOWER	0.198	0.132	Yes
INTEGTOOLS-ADDLSP	< 0.10	Yes	0.039	Small	ADDLSP	0.037	0.011	Yes
ADDLSP-CULT	< 0.05	Yes	0.444	High	CULT	0.308	0.139	Yes
CULT-CI	< 0.05	Yes	0.325	Medium	CI	0.245	0.116	Yes
CULT-STAND	< 0.05	Yes	0.631	High	STAND	0.387	0.372	Yes
CI-OUTCOMES	< 0.05	Yes	0.311	Medium	OUTCOMES	0.428	0.192	Yes

Table 8.6. Assessing the structural model -Trial 4

Paths	Path significance at α=0.1	Sign	f^2	Effect size (f^2)	Constructs	R^2	Q^2	Sig (Q^2)
TRGNEEDS - TRGHELPEXT	< 0.05	Yes	0.238	Medium	TRGNEEDS	0.00	0.00	-
TRGHELPEXT - TRGWKSP	< 0.05	Yes	0.291	Medium	TRGHELPEXT	0.192	0.127	Yes
TRGWKSP-KNOW	< 0.05	Yes	0.223	Medium	TRGWKSP	0.225	0.207	Yes
KNOW-COLL	< 0.05	Yes	0.612	High	KNOW	0.183	0.116	Yes
COLL-COLLEARLY	< 0.05	Yes	0.282	Medium	COLL	0.380	0.255	Yes
COLLEARLY-COMMIT	< 0.05	Yes	0.418	High	COLLEARLY	0.220	0.198	Yes
COMMIT-TRUST	< 0.05	Yes	0.096	Small	COMMIT	0.295	0.234	Yes
TRUST-LONG	< 0.05	Yes	0.094	Small	TRUST	0.088	0.053	Yes
LONG-PROCESS	< 0.05	Yes	0.178	Medium	LONG	0.086	0.046	Yes
PROCESS-LCTOOLS	< 0.05	Yes	0.491	High	PROCESS	0.151	0.089	Yes
LCTOOLS-INTEGTOOL	< 0.05	Yes	0.058	Small	LTTOOLS	0.329	0.189	Yes
INTEGTOOL-EMPOWER	< 0.05	Yes	0.106	Small	INTEGTOOL	0.055	0.046	Yes
EMPOWER-ADDLSP	< 0.05	Yes	0.113	Small	EMPOWER	0.096	0.047	Yes
ADDLSP-REWARD	< 0.05	Yes	0.207	Medium	ADDLSP	0.101	0.041	Yes
REWARD-RAPIDSUCCESS	< 0.05	Yes	0.225	Medium	REWARD	0.172	0.092	Yes
RAPICSUCCESS-CULT	< 0.05	Yes	0.676	High	RAPIDSUCCESS	0.184	0.093	Yes
CULT-CI	< 0.05	Yes	0.236	Medium	CULT	0.403	0.198	Yes
CULT-STAND	< 0.05	Yes	0.231	Medium	STAND	0.330	0.303	Yes
CI-STAND	< 0.1	Yes	0.063	Small	CI	0.191	0.09	Yes
CI-OUTCOME	< 0.05	Yes	0.169	Medium	OUTCOME	0.645	0.281	Yes
CULT-OUTCOME	< 0.05	Yes	0.334	Medium				
KNOW-OUTCOME	< 0.05	Yes	0.072	Small				
LONG-OUTCOME	< 0.05	Yes	0.087	Small				

8.7.4. Best Fit Framework Criteria

To select the best fit model, the criteria should not only be restricted to one or two measures. Statistical measures like R^2 values have historically been considered as a good indicator for selecting 'best' models. However, many non-significant constructs within the model leading to the endogenous constructs in the structural model have the capability of increasing the R^2 values. As an example, if all the exogenous constructs in trial 4 have an additional path towards the construct OUTCOME, R^2 values can be increased to more than 70% but this increase can be due to the presence of many insignificant paths/constructs. Moreover, it will also increase the complexity of implementing the framework (Hair et al., 2016).

As a result, the criteria along with the effect of both Trials 3 and 4 on these criteria are shown in Table 8.7. It can be seen that Trial 4 will be more efficient than trial 3 as it performed better in most of the criteria. The final improved LC implementation framework is given in Figure 8.3.

8.7.5. Important-Performance Map (I-P Map)

To evaluate the impact of individual constructs on the overall performance improvement (OUTCOME), the total effect of every construct (importance) on the construct OUTCOME and its performance level among the LC companies are mapped in Figure 8.4. The I-P Map shows that the construct CULT has the highest total effect (importance) on the construct OUTCOME followed by RAPID SUCCESS, CI, LONG, KNOW and REWARD, ADDLSP and TRAINING. The other constructs have a comparatively smaller effect on the OUTCOME. However, the performance level of all the constructs is found to be between 65% to 80%. Since CULT has the highest effect on OUTCOME, it is necessary to see which constructs have a greater impact on CULT. Figure 8.5 shows that RAPIDSUCCESS, has the highest total effect on CULT with a performance level of just 70%. Similarly, REWARD, ADDLSP, EMPOWER, and INTEGTOOL will have comparatively more effect in improving CULT as compared to others. The performance of all the constructs is found to be between 65% and 80%. For RAPID SUCCESS, construct REWARDS have the highest total effect followed by constructs ADDLSP, EMPOWER, INTEGTOOLS, and LCTOOLS. The I-P map will help in identifying the constructs that should be given more weight in achieving improved performance outcomes.

Table 8.7. Selection criteria for improved LC implementation model

Criteria	**Trial 3**	**Trial 4**	**Final selection**
R^2 values for explaining the Construct OUTCOME	0.428	0.646	Trial 4
Number of important and valid indicators within the model	39	46	Trial 4
Relevancy with initially developed framework or fully captures the concept	Three paths and 7 indicators have to eliminated from initial LC framework (Trial 1) being insignificant	No path or indicator is eliminated or insignificant	Trial 4
SRMR Values	0.09	0.09	-
Effect size f^2	One construct does not affect its endogenous construct	All constructs have some effect on their endogenous construct	Trial 4
Prevalence Predictive Power Q^2	Relevant	Relevant	-

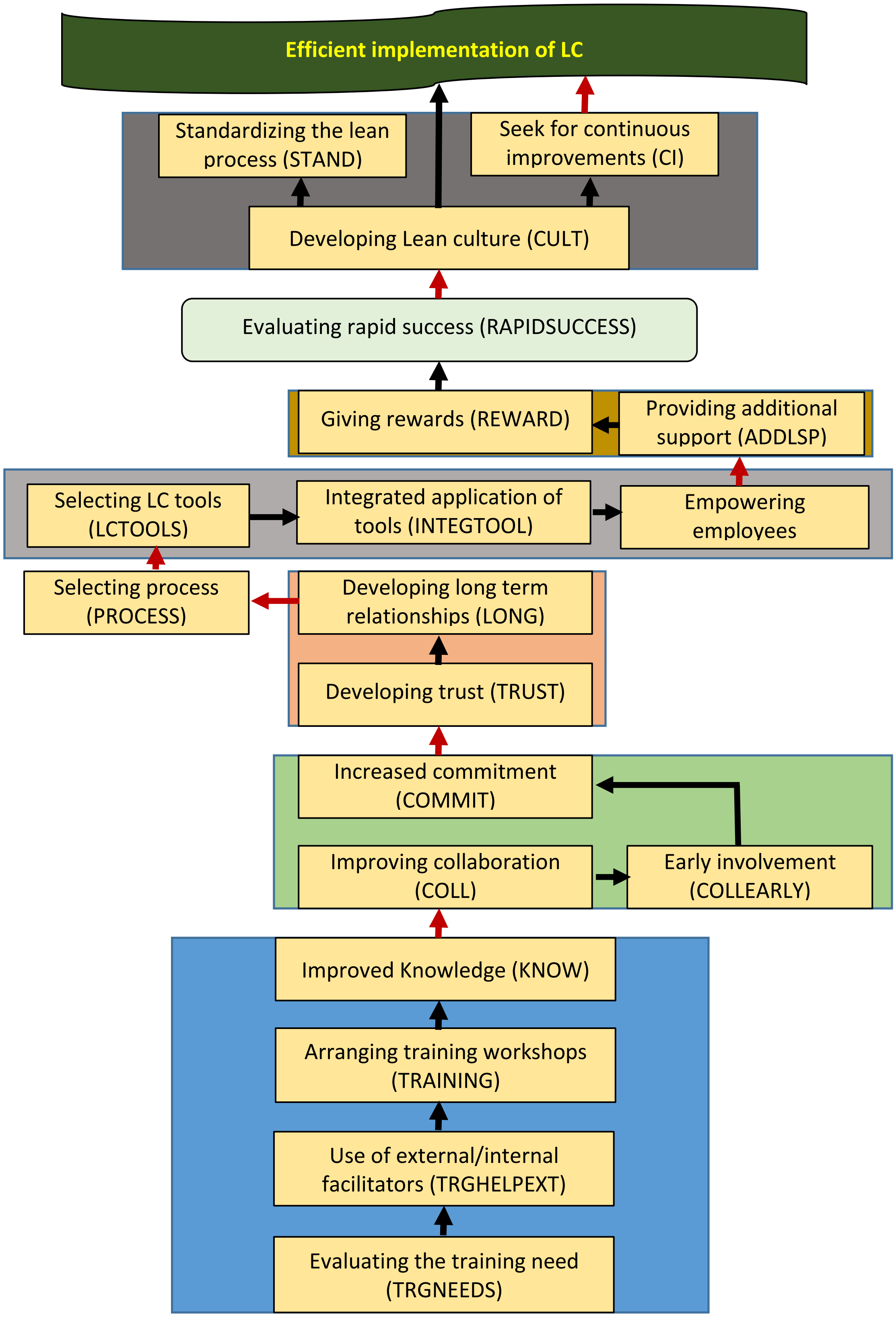

Figure 8.3. Improved/Validated LC implementation framework

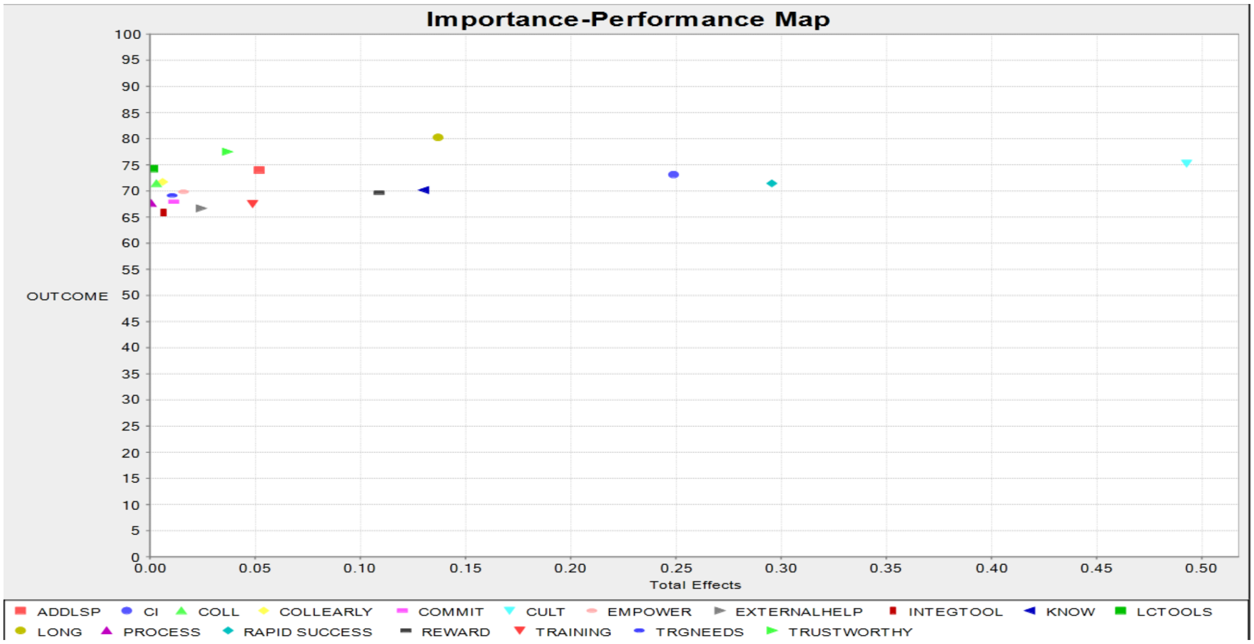

Figure 8.4. Importance -Performance map for influence on OUTCOME

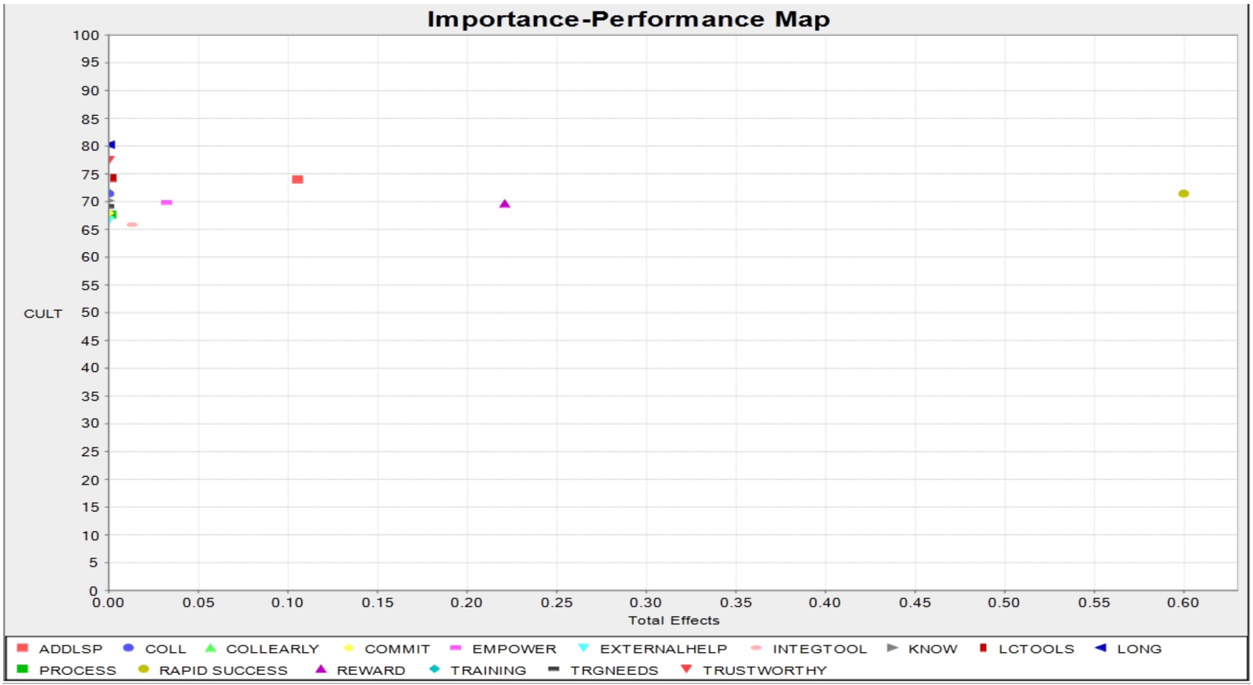

Figure 8.5. Importance -Performance map for influence on CULTURE

8.8. Discussion of Improved Framework

8.8.1. Characteristics of the Improved LC Implementation Framework

Due to convergent and discriminant validity issues with the initially developed framework, different trial models were developed and assessed in the PLS-SEM. The improved LC implementation Framework as shown in Figure 3 has shown the best convergent and discriminant reliabilities along with better measures as compared to the other trials. Where some of the indicators are reassigned into new constructs, a new construct RAPID SUCCESS is added to the initially developed framework. All four indicators, which were measuring some of the effects of LC in improving the commitment, culture, or other performance parameters, were assigned to this new construct: 1) initial achievement of improvements within the range of 10-20%, 2) improved commitment and trust after gradual implementation, 3) visualizing waste reduction, meeting customer's requirements, and maintaining flow in your project due to early involvement of stakeholders, and 4) self-detection/rectification of defects. The introduction of this new construct should motivate lean practitioners to adopt Lean Culture by visualizing the initial benefits at early stages.

All the identified paths are found to be significant with all the constructs having some effect on all of their endogenous constructs. Moreover, an improved/best fit framework was also found to have significant out-of-sample predictive power. This improved/best fit framework yielded the best R^2 values in comparison to others showing that the framework has the capability of explaining 64.5% of the variance in the performance outcome. Unfortunately, since the validating approach in this study is novel for an LC implementation framework, no exact or threshold value is available for the R^2 values. However, in research related to social sciences, any value of R^2 greater than 0.5 indicates a moderate description of the endogenous variables (Hair et al., 2016; Henseler et al., 2009, Chin, 1998 pp. 323). The final model as described by Trial 4 results and illustrated in Figure 8.3 exceeds the 'moderate' description threshold.

8.8.2. Relevance of the Improved Framework

Since the initial framework was developed through strong theoretical and analytical procedures, determining its relevance with an improved/best-fit framework differentiates it from other more theoretical models that are not analytically validated. In the improved framework, the integrity of the original 12 constructs is ensured while reassigning the indicators into new constructs. The new constructs KNOW, TRAINING, TRGHELPEXT, and TRGNEEDS are arranged in a hierarchal order and each of these constructs explains the main construct of acquiring requisite knowledge and training, which is shown at the level 7 (bottom level) of the initial developed LC framework in Figure 8.2. Similarly, these four new constructs are also shown at the bottom level of the improved framework. The paths between these constructs were also found to be significant

Level 6 in the initially developed framework has two constructs of commitment and collaboration. In the improved framework, these constructs remain at the same level; however, the relationships between these constructs are more defined and found to be statistically significant. The level 5 construct of long-term partnership and trustworthy relation is split into two separate constructs for better clarity. Again, no change in hierarchal order between the constructs are necessary at level 4 (appropriate process selection), level 3 (selection of appropriate LC tools, integrated application of tools, giving adequate empowerment to employees, and providing additional support). However, the relationship between the constructs at level 3 has been added in improved LC framework. The original construct of additional support is split into two separate constructs of additional support and rewards. A new construct of evaluating rapid success has been added in the improved framework. The hierarchy and path of this new construct within the improved framework are found to be significant indicating the validity of this new construct within the framework. Similarly, no change in hierarchy and paths (between initial and improved framework) are found between the constructs at level 1 (standardization and continuous improvement) and level 2 (cultural adaptability) of the initial LC implementation framework.

As constructs acquiring knowledge and training, ensuring commitment, improving collaboration, and developing long-term and trustworthy relations have the most driving power as compared to the other constructs. The effects of these important constructs on the endogenous variable performance outcome are checked and it was found out that the path from KNOW and LONGTERM to OUTCOME is found to be statistically significant and will have an improved direct effect towards improving the construction performances.

8.8.3. Identification of Relative Important Constructs

From the Important-Performance Maps, it can be seen that although several constructs have been frequently used, but their total effect in explaining the construct of “performance outcomes” is lower compared to others. The construct of “improving the cultural adoptability and commitment” is found to be the most important construct for efficiently implementing the LC and getting better project outcomes. The construct of “assessing the rapid initial project successes” is found to be the most important construct for building lean culture. Providing incentives to the employees and subcontractors/suppliers along with the provision of additional support and empowerment to the employees can have a significant impact in getting rapid initial successes. As discussed above, not all the constructs have the same effect on improving outcomes. The model suggests that some constructs should be given more attention as 1) the culture adaptability, 2) getting rapid initial successes,3) continuous improvement, 4) long term partnership, 5) knowledge, and training, 6) empowering employees, selecting the most appropriate LC tools, 7) early collaboration through IPD, 8) integrated application of LC tools and 9) providing additional support and rewards. Other constructs have comparatively less effect on outcomes as 1) the selection of appropriate processes, 2) standardization, 3) collaboration through a big room and BIM, and 4) high commitment level from top management and employees. These constructs cannot be eliminated though, since they are important and impact other constructs like ensuring long-term relationships, selection of LC tools, and integrated application of LC tools which are otherwise required for adopting the lean culture and rapid initial successes.

8.9. Conclusion

Potentially new LC companies would be would be interested in a framework that is demonstrated to be reliable, credible, and accurate. A unique approach to validating and improving a LC implementation framework was discussed in this study. The improved model was assessed for its effect on eight construction outcomes (cost, schedule, quality, profit, safety, relationships, and reduction in lawsuits and losses) based on input from active LC companies. It was found that the final LC framework has better capabilities of explaining the construction performance parameters. All the constructs and indicators were found to be significant and have an impact on improving the construction performances. The developed LC framework has the capabilities of explaining approximately 65% of the variance in construction performance outcomes which is an acceptable level.

Based on the model analysis, LC companies should give topmost attention to improving their culture and commitment for LC. However, to improve the LC culture, the LC companies should also be looking for rapid initial successes that can motivate the further adoption of LC culture and commitment. Lean culture would have companies providing additional support and rewards to employees and subcontractors/suppliers respectively for implementing lean tools and techniques. Employee empowerment and involvement in the total process also supports rapid initial successes.

The outcome of this study has many practical and theoretical contributions for the construction industry and academia/researchers respectively. The framework provides a step-by-step approach to the lean companies in efficiently implementing the LC to gain better construction performances. The validity of the framework from the inputs of LC companies and further performing analysis using robust SEM technique will further improve the confidence of the construction industry in using the developed LC implementation framework. Because validation of frameworks always remains an issue for the Lean researchers, this study can help the academia/researchers by providing them with this innovative and easy-to-use approach for validating their developed LC implementation frameworks.

9. CONCLUSION AND RECOMMENDATIONS

9.1. Overall Conclusion

The construction industry is struggling in improving its productivity as compared to other industries. Further advancement on LC has the potentials of overcoming most of the issues of the construction because its theories and practices target the core problems of the construction. This study has thoroughly investigated a systematic way for LC implementation to achieve rapid initial project success. As a result of the study, an effective selection framework has been developed with recommended LC tools and techniques to achieve integrated LC. The study has also identified critical factors for rapid initial LC project success and developed a robust LC implementation framework and an innovative integrated Last Planner System (ILPS). The validated LC implementation framework can predict approximately 65% of the variance in the project outcomes based on eight performance outcome measures.

Specific findings for each objective that make this study novel and practical in the LC field are provided as follows:

9.1.1. Findings for Objective 1

In this study LC tools and techniques has been evaluated based their performance to expose their potentials in achieving the LC principles and functions and their effect on project performance. Moreover, a conceptual framework of LC tools and techniques has been established to help the constructors in selecting the appropriate tools. Specific findings are given below:

- Theoretically, almost all the lean tools and techniques have the potentials of improving construction performance ranging from productivity enhancement, waste reduction, improving quality and safety to controlling the cost and schedule overrun. However, they are currently more often used to improve cost, time, and productivity performance (by more than 10%) but much less to improve quality and safety.

- No single tool/technique alone can address all the LC principles/functions although LPS can address the most LC principles. Rather, integrated application of different selected tools/techniques at the same time can lead to much more optimized results. However, the compatibility of these selected tools/techniques must be carefully evaluated for such integration in the construction processes, instead of just selecting them based on their lean functions. This is because many LC tools and techniques have the same lean objectives but differ in their functions thereby making the selection process more sensitive to their functionalities.
- Apart from objectives and functions, other factors like performance-enhancing capabilities, cultural acceptability among the users, training requirements along with the specific project/organization environments must be considered as well while selecting the most appropriate tools and techniques for implementing LC.

9.1.2. Findings for Objective 2

In this study, a novel platform (ILPS) has been developed for integrated implementation of different tools and techniques to address all the LC principles and functions. The processing tools (inputs and outputs) for each stage of ILPS model provide the implementation modalities of ILPS for the construction industry. Specific findings are given below:

- Although LPS has the potentials of accommodating most of the other LC tools and techniques within its stages due to its diversified nature; therefore, it is considered to be the most comprehensive tool for implementing LC. However, it has some shortcoming that prohibits its optimized use in addressing all the principles of LC and improving the construction performance

- Apart from the inherent tools of LPS (lookahead, master, phase and weekly schedules/meetings, continuous improvement by measuring percent plan complete and pull approach), other LC tools and techniques like a big room (BR), building information modeling (BIM), target value design (TVD), integrated project delivery (IPD), failure mode effect analysis (FMEA), value stream mapping (VSM), first-run studies (FRS), theory of constraints (TOC), and just in time (JIT) delivery can be easily integrated into the existing LPS framework to optimize its operational capabilities.

9.1.3. Findings for Objective 3

In this study, a micro-level evaluation has been carried out on existing broad-based CSFs to determine their execution modalities/protocols (subfactors) for LC implementing at organization and project level. The results show that:

- To get a competitive advantage and improve company image, the best results will come if companies are self-motivated to start their lean journeys with both process-driven and performance-improvement-related goals.
- For new lean users, LC should be implemented gradually instead of going to its full implementation. They should be initially looking for improving those construction processes that are (1) not managed efficiently, (2) highly sensitive to cost and time, and 3) affordable. Later on, when desired expertise is built, companies can go for improving all the process within the project using the LC tools and techniques. Furthermore, they should set their performances (cost,

schedule, productivity, safety, quality) improvement within the range of 10% at the start of their LC journey, instead of hoping for high achievements.

- Integrated implementation of LC tools can be the best way to achieve the maximum benefits. LC tools and techniques must be selected based on their compatibility with the construction processes, alignment with the LC principles/objectives, and potentials for maximizing value/benefit in terms of cost, time, and productivity.
- Collaborative delivery methods like integrated project delivery (IPD) are the most efficient methods and will increase the chances of LC success.
- Where top-level commitment is always desired from the top, middle and field management for implementing LC, companies can start LC implementation even if their workforce or external actors (subcontractors and suppliers) are adequately committed to LC. Once the benefits would be evident to them, the commitment level would be increased to the top level.
- Subcontractors, suppliers, and the workforce should also be given adequate empowerment equal to the field management to take full control their respective tasks. However, the degree of empowerment should be based on the type and quantum of tasks, expertise available, trust, and commitment level.
- The lean teams should be given additional support in terms of providing training opportunities for preparation for LC implementation along with full confidence of the top management to perform without any fear of failures. For basic knowledge and understanding, training methods like classroom lectures, workshops, and videos can be useful but for implementation and experience "on-the-job training"

and “site visits” are the most effective ways of learning LC implementation protocols. External trainers and facilitators can help in planning and implementing the LC successfully.

- Considering the uniqueness of the construction projects, full standardization in construction may be difficult; however basic methodologies, processes, tasks, and materials can be standardized to a certain level and further adjusted with some modifications to align with projects. Additionally, there should be a system of continuous improvement in which all weekly assignments should be measured and analyzed for further improvements.
- Lean construction institutes, lean organizations, governments, and academia can play a vital role in increasing the awareness for LC through conferences, publications, congresses, and regular meetups. The Lean success stories should be shared among the construction industry to keep everyone updated on how lean companies implemented LC and what improvements are experienced.

9.1.4. Findings for Objective 4 & 5

In this study, an ISM based LC implementation framework has been developed after statistically defining the relationships between the factors from the inputs of LC companies. Furthermore, the ISM based framework is validated and modified against eight project performances outcomes through a validation survey using PLS-SEM. Finally, the best LC implementation framework that can explain the maximum variance in the project outcomes has been developed and presented. The results show that:

- Out of 66 pairwise relationships between 12 factors, it was found that most of the factors have some kind of one-way influence in achieving other factors whereas only four (4) relationships are found to be both-way (Both factors help in achieving each other). These relationships are between following factors:

  - Selection of construction process with integrated application of LC tools and techniques
  - Selection of appropriate LC tools and techniques with ensuring adequate empowerment
  - Ensuring adequate empowerment with providing additional support
  - Adoption of continuous improvement with standardization

- Four factors are identified as independent factors and must be ensured right at the start of the LC implementation, including (1) acquiring knowledge and training, (2) improving collaboration, (3) ensuring adequate commitment level and (4) long-term partnership, and trustworthy relations.
- Three factors are found out to be the dependent factors and are required for implementing LC successfully, including (1) cultural adaptability, (2) continuous improvement, and (3) standardization.
- Five factors are identified as linkage factors including (1) selection of appropriate processes for lean intervention, (2) selection of right tools and techniques, (3) integrated application of lean tools and techniques, (4) empowerment, and (5) additional support to employees. These factors are needed for smooth transition from independent to dependent factors.
- 38 out of 46 identified indicators are found important for measuring those 12 factors in the developed LC implementation framework. The remaining eight (8) indicators are found useful for project performance. However, because of a few of

the insignificant paths and indicators, the initial LC implementation framework needs to be modified for structural stability and improvement of the prediction value of the framework.

- Improving cultural adaptability for LC will have the highest effect on performance outcomes followed by rapid initial successes, continuous improvement, and acquiring requisite knowledge about LC. Other factors have a comparatively lesser impact on performance outcomes.
- The incorporation of the additional factor (evaluating the rapid success) is found out to be the most influential factor for developing lean culture and improving commitment towards LC. Continues evaluation and sharing of rapid successes will have a significant impact on the performance outcomes. Similarly, other factors like ensuring a rewards system, providing additional support, adequately empowering the employees, and integrated application of LC tools also contribute to improving the lean culture.
- The initial LC implementation framework was validated and modified but with no major deviations except the addition of new factors that are fully supported by the theory as well as the structured analysis procedure. The validated and modified final LC framework have the capabilities of explaining almost 65% of the variance in construction performance which is quite acceptable within social and management research

9.2. Contributions and Implications

The outcome of this study will add value to the existing body of knowledge in terms of enhanced theoretical explanations of the LC concept and practical utilization of the LC within the construction industry. The study comprehensively explains the key LC concepts in terms of theory, its principles and functions, and LC practices (tools and techniques). The construction industry which is seemed to be struggling in understanding the LC (both theoretically and practically) and thereby fail to implement LC, will be educated as it provides the complete guidelines of implementing LC from the start till its full maturation. Some of the key contributions are summarized below.

Where the existing literature fell short in explaining the modalities of selecting the most appropriate LC tools and techniques, the result of this study will sequentially guide the construction industry in selecting the most appropriate LC tools and techniques. The classification and performance evaluation of LC tools and techniques will facilitate the construction industry in shortlisting the LC tools and techniques based on the degree of improvement required in a respective construction area. Moreover, it highlights the importance of LC tools and techniques in implementing the LC at the operational level along with the likely benefits that can be obtained using LC tools and techniques. Later on, based on the LC tools and technique's selection framework, the most appropriate LC tools and techniques can be picked, implemented, and further improved.

The integrated application of LC tools and techniques is always considered to be a very complicated task that requires a lot of planning and coordination at different levels of project organization. The outputs of this study provide a detailed set of guidelines to facilitate the smooth implementation of different LC tools and techniques.

Although several factors have been identified for the successful implementation of LC, the new and potential lean companies are struggling in ensuring the required application of each of these factors due to a lack of detailed explanation of each factor at a micro-level. The outcome of this study will further bridge this gap. This will facilitate the new lean users in achieving successful implementation of LC.

Where most of the previous research focused on developing the framework based on theories or in some cases inputs from the general construction companies (might be familiar with LC or not), the reliability of the LC implementation framework as developed in this study is more as it incorporates the years old experience of the company officials who have been working under lean environment. Moreover, a more structured approach is adopted to develop and later on validate the efficacy of the developed LC implementation framework. The final framework provides a detailed step-by-step approach to implementing the LC successfully. The validity of the framework from the inputs of LC companies and analyzed using robust SEM technique will further improve the confidence of the construction industry in using the developed LC implementation framework. Moreover, this study can help the academia/researchers by providing them with this innovative and easy-to-use approach for validating their studies in the future.

9.3. Limitations and Future Work

It would be of great value if the LC frameworks developed in this study is implemented on the actual project and measured for their efficiency in a real project environment. Unfortunately, due to the restrictions imposed by the pandemic (COVID-19) along with time and cost issues, it was almost impossible to test the developed LC implementation framework on some actual projects. It is recommended that in the future, the developed framework should be implemented on some construction projects and the efficiency of the framework in successfully implementing the LC should be recorded. LCI or other forums like CURT or AGC, should be approached for supporting the implementation of the developed LC implementation framework in actual/pilot projects. It is beneficial if data can be collected during the implementation process.

In this way, the developed framework will be further improved based on the project environment.

Although the framework is developed considering 12 critical factors and 38 indicators, the developed framework could explain 65% of the variance in construction performances. This implies that there are other factors also which if incorporated within the LC framework can further improve its predictability. It is recommended that a similar approach as proposed in this study should be adopted to identify other factors from a larger number of samples of LC companies. This will improve the prediction power of the LC implementation framework.

Although a detailed conceptual framework is developed for selecting the LC tools and techniques, a similar structured approach as used in this study for developing an LC implementation framework can be adopted to further refine the conceptual LC tools selection framework. Similarly, ILPS can be further validated either by implementing ILPS in an actual project or using other well-structured and robust validating approaches like SEM, etc.

9.4. Challenges and Suggestions for the Industry to Use LC framework

The biggest challenge for the construction industry in using the structured LC implementation framework as developed in this study is how to seek the Government support for federal funded projects and to deal with potential resistance to change existing management approach of different stakeholders. It is very important for new LC companies to have all the stakeholders committed to start implementing the developed LC implementation framework otherwise the LC initiative will not be successful. Government and industry organizations can play a huge role in convincing the construction industry to use LC by offering contract incentives and training.

While all the factors within the developed framework are easy to comprehend and implement, at the project management level, significant effort is required to move towards using the developed framework for their projects. Moreover, the identification of trustworthy partners (suppliers and subcontractors) can also be a challenge for the companies especially when they are at the start of their LC journey.

The development of LC framework largely depended on the inputs of the LC companies and lean experts that have been implementing LC and gone through a transformation phase from traditional management to LC approaches for many years. However, while these inputs provided the most realistic factors that would be encountered during construction stage, it can also lead to the premature assumption by the potential new lean company implementing LC will be easy for them. In reality, the potential LC companies should fully evaluate their existing organization culture, prevalent rules and regulations, and project environments before starting to implement the developed LC implementation framework. If these potential LC companies tailor these basic requirements in favor of LC before actually starting implementing LC framework, it would increase the chances of long-term success and help in sustaining the LC practices.

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APPENDIX A. SUMMARY OF LC TOOLS BASED ON THE OBJECTIVE AND FUNCTIONALITIES/ METHODOLOGIES

S/N	Lean Tools	Objective	Functionalities/Methodologies
1.	LPS (Salem et al., 2005; Ballard et al., 2007; Salem et al., 2006; Linghard and Wahdahl 2014; Abusalem 2017; Gao and Low 2015)	Reduce planning variabilities, improves the workflow, reduce process variabilities, continues improvement, improve visualization, customer focus, improve communication, safety	Master phase scheduling, reverse phase schedule, look ahead schedule, weekly schedule, recording data and analysis, constraint analysis, pull approach reduce complexities, transparency, people involvement, lesson learnt, schedule buffer, collaboration
2.	Visual Management (Salem et al., 2005; Tan et al., 2003)	Improving communication with the workforce, continues improvement, reduce process variabilities	Visual signs, presentations, transparency, people involvement, lesson learnt, early warning system
3.	Daily Huddle Meetings (Salem et al., 2005; Ballard et al., 2007)	Involving the employees, continues improvement, improving working procedures, reduce process variabilities	Reduce complexities, people involvement, lesson learnt, collaboration, daily involvement of crew
4.	First Run Studies (Salem et al., 2005; Abusalem, 2017; Muhammad et al., 2013)	Continues improvement, improve the working procedure, reduce process variabilities, better visualization, improving workflow	Recording data and analysis, visual signs, presentations, root cause analysis, transparency, people involvement, lesson learnt, considering alternate solutions, collaboration, safety analysis and mitigation measures
5.	5S (Salem et al., 2005; Diekmann et al., 2004; Low and Ang 2003; Enshassi & Abu Zaiter, 2014)	Continues improvement, reducing process variabilities, improve working procedures, maintaining material flow, safety	Visual signs, presentations, arranging the stores and material using 5S
6.	Fail-Safe for Quality and Safety (Abdelhamid, T. S. (2008); Salem et al., 2005; Enshassi & Abu Zaiter, 2014)	Defect control, reduce process variabilities, safety	Recording data and analysis, root cause analysis, risk assessment, reduce complexities

S/N	Lean Tools	Objective	Functionalities/Methodologies
7.	Six Sigma (Abdelhamid, T. S., 2003; Han et al 2008; Stewart and Spencer, 2006)	Process and production variability reduction, control defect rates, customer focus, continues improvement	Recording data and analysis, root cause analysis, reduce complexities, people involvement, lesson learnt, collaboration
8.	Kanban Arbulu et al., 2003; Gao and Low 2015)	Reduce process variabilities, improve material flow, safety control	Pull approach, material management, transparency, use of signs for smooth delivery of materials
9.	Just in Time Patil Y. and Patil D., 2015; Ballard and Howell, 1995; Low and Ang, 2003	Reduce planning and process variabilities, improve work flow, improve material flow	Pull approach, material management, inventory control, reduce complexities, transparency, people involvement, lesson learnt, collaboration, standardizing the processes and material
10.	Kaizen Nahmens and Ikuma, 2011; Vivan et. al., 2016	Continues improvement, reduce process variabilities, control defects, improving workflow	Recording data and analysis, constraint analysis, visual signs, presentations, root cause analysis, collaboration, identification and minimizing effect of non-value adding activities, defect identification and analysis, safety analysis and mitigation measures, lesson learnt, transparencies, reduce complexities
11.	Concurrent Engineering Aziz and Hafez ,2013; Karlsson et al., 2008	Customer focus, reduce design variabilities, improve workflow	Removing conflicts in design and construction, reduce complexities, value engineering, collaboration, simultaneously designing and construction
12	Prefab/Modular Ballard and Arbulu, 2004; Jaillon and Poon, 2009	Reduce planning, design and process variability, improve workflow, improve working procedures, customer focus, better visualization	Pull approach, standardizing the processes and material, manufacturing the material away from the construction site
13	Line of Balance Kankainen and Seppänen, 2003; Ammar, 2019	Minimize interruption between workflows, reduce process variabilities, maintaining material flow	Constraint analysis, reduce complexities, transparency, considering alternative solutions
14	Poka Yoka Muhammad et al., 2013; Santos and Powell, 1999	Reduce variabilities in construction processes due to mistakes, improve workflow	People involvement, lesson learnt, defect identification and analysis, safety analysis and mitigation measures, early warning system

S/N	Lean Tools	Objective	Functionalities/Methodologies
15	Theory of Constraints O Connor and Swain, 2013; Sarkar et al., 2018	Improve the rate of low by reducing the constraints, reduce planning, design and process variabilities, maintain material flow, safety	Constraint analysis, root cause analysis, risk assessment, reduce complexities, people involvement, schedule buffer, collaboration, safety analysis and mitigation measures
16	Standardized Processes Aapaoja and Haapasalo, 2014	Continues improvement, reduce process, variabilities, improve workflow, safety, better visualization	Recording data and analysis, reduce complexities, transparency, people involvement, collaboration, standardizing the processes and material identification of repetitive processes
17	BIM Sacks et al., 2010; Zhang et al., 2018; Crowther and Ajayi, 2019	Better visualization, reduce planning, design and process variabilities, customer focus, improve communication, continues improvement	Removing conflicts in design and construction, people involvement, value engineering, considering alternate solutions, collaboration, standardizing the processes and material, defect identification and analysis, safety analysis and mitigation measures, design the new process, increased visualization of project using soft wares
18	Integrated Project Delivery Guide, A. I. A. 2007, Cheng and Johnson, 2016; Rosayuru et al., 2019	Reduce planning, design and process variabilities, improved flow, improve communication	Pull approach, removing conflicts in design and construction, reduce complexities, transparency, people involvement, lesson learnt, value engineering, considering alternate solutions, collaboration, simultaneously designing and construction, standardizing the processes and material
19	Set-Based Design Ballard and Zabelle, 2000; Fernández and Ramos, 2014; Ballard et al., 2007	Reduce design variabilities, defect detection and control, improve communication, improve workflow	Removing conflicts in design and construction, reduce complexities, transparency, people involvement, lesson learnt, considering alternate solutions, collaboration, standardizing the processes and material
20	Target Value Design Ballard et al., 2007; Do et al., 2014; Alwisy et al., 2018	Reduce planning and design variabilities, customer focus	Recording data and analysis, removing conflicts in design and construction, risk assessment, people involvement, value engineering, collaboration
21	Value Stream Mapping Desai and Shelar, 2014; Ballard et al., 2007; Diekmann et al., 2004; Pasqualini and Zawislak, 2005	Better visualization, reduce process variabilities, maintaining continuous flow of information and material, better visualization, customer focus, defect analysis	Recording data and analysis, reduce complexities, transparency, people involvement, identification and minimizing effect of non-value adding activities

S/N	Lean Tools	Objective	Functionalities/Methodologies
22	Failure mode effect Analysis O'Connor & Swain, 2013; Wehbe & Hamzeh, 2013	Defect analysis and control, reduce planning and process variabilities	Recording data and analysis, constraint analysis, root cause analysis, risk assessment, reduce complexities, people involvement, defect identification and analysis, safety analysis and mitigation measures

APPENDIX B. QUESTIONNAIRE 1- FACTORS FOR SUCCESSFUL IMPLEMENTATION OF LC TOOLS AND TECHNIQUES

Part 1: Background and General Lean Construction

Q 1. Your Company/Organization type

(1) Owner
(2) Architect/Engineer
(3) Contractor
(4) Construction manager
(5) Other, please Specify ____
(6) Other, please Specify ____

Q 2. Your Responsibility

(1) Construction Manager
(2) Project Manager
(3) Lean Coordinator
(4) Superintendent
(5) Other, please Specify ____
(6) Other, please Specify ____

Q 3. Years of construction related experience.

(1) < 5 yrs
(2) 5-10 yrs
(3) 11-15yrs
(4) 16-20 yrs
(5) > 20 yrs

Q 4. Number of years implementing lean construction

(1) < 1 yr
(2) 1-4 yrs
(3) 5-10 yrs
(4) > 10 yrs

End of Block: Background and General Lean Construction

Start of Block: Part 2: Overall Organization – Lean Construction Program

Part 2: Overall Organization – Lean Construction Program Please Choose the best choices as per your experience.

Q 5. What were the major motivation factors to implement lean construction? (Please choose all that apply)

(1) To gain Competitive advantage in terms of cost, time, safety, quality and productivity
(2) Required by project agreement
(3) To improve company image+
(4) Other factors or comments ____

Q 6. How would you rate the result of your overall Lean Construction Program?

(1) Failure
(2) Mixed results
(3) Successful

Q 7. What are the threat levels associated with the following issues in successful implementation of lean construction?

	None (1)	Low (2)	Medium (3)	High (4)	Very High (5)
Wrong selection of lean tools and techniques					
Wrong implementation of lean tools and techniques					
Incompatibility of lean tools and techniques with construction processes					
Lean tools were too complex to be implemented					
Limited knowledge about lean tools and techniques					
Insufficient resources to implement lean tools and techniques					
Inefficiency of the selected tools and techniques					

Cultural and behavioral issues	
Commitment issues	
Others (please specify)	
Others (please specify)	

End of Block: Part 2: Overall Organization – Lean Construction Program

---

Start of Block: Part 3: Lean Based Project

Part 3: Lean Based Project

Q 8. Which lean construction tools and techniques have you applied? Please Choose all that apply.

(1) Last Planner system
(2) Building Information Modeling
(3) Virtual and augmented realities
(4) Value Stream Mapping
(5) Just in Time
(6) 5S
(7) Target value design
(8) Others (please specify) ____
(9) Others (please specify) ____

Q 9. How much improvement was measured by using the selected tools and techniques?

	Negative	0%	1-10%	11-20%	21-30%	31-50%	>50%	None
Time savings								
Cost savings								
Productivity enhancement								
Quality improvement								
Safety improvement								

Q 10. Which of the following goal statements best describes your successful lean based project?

(1) The aim was to simplify, reduce the number of steps required and remove waste, and generally improve the process, which we have faith will lead to a better result.
(2) The aim was to improve performance in terms of cost, time productivity, quality and safety.
(3) Comments ____

Q 11. How you would rate the decision process for the selection of lean construction tools?

	None	Few	Some	Maximum	All
Number of initially selected lean tools and techniques obtaining the optimum results.					
Number of initially selected lean tools and techniques that are wrongly selected and could have better alternatives					
Number of initially selected lean tools and techniques not implemented properly					
Comments					

Q 12. How would additional knowledge about the lean construction tools impact your original lean implementation process?

____

____

____

Q 13. What modifications to the lean tools and techniques are necessary from one project to another?

____

____

Q 14. Do you think that all processes involved in construction can be managed by only one or two lean tools?

(4) If yes, please list the tools (2) ______________________________
(5) If no, please list the key tools (1)
____

Q 15. When choosing a process for lean implementation, how much influence do the following issues have on your decision?

	Not at all	Very Little	Somewhat	To great extent
Process couldn't be managed efficiently using existing practices				
Sensitivity of the process in terms of time and cost				
Spillover effect of benefits to other processes				
Process is affordable in terms of resources				
As a trial irrespective of the outcomes				
Compatibility of process with the lean tool				
Organizational expertise in respective process				
Others (please specify)				
Others (please specify)				

Q 16. When choosing lean tools and techniques for implementation, how much influence do the following criteria have on your decision?

	Not at all	Very Little	Somewhat	To great extent
Alignment between the objective of a lean tool and techniques with lean construction principles				
Selection of lean tool and techniques based on most applicable tool for the construction process				
Selecting only those lean tools and technique that are familiar and traditionally tested				
Ease of implementation with existing other management tools				
Maximum value/benefits in terms of cost, time and productivity				
Tools and techniques which consume fewer resources to implement				
Organizational expertise				
Others (please specify)				
Others (please specify)				

Q 17. How do the following project delivery methods influence implementation of lean tools and techniques?

	Not at all	Very Little	Somewhat	To great extent
Design Bid Build (DBB) (1)				
Design Build (DB) (19)				

Collaborative delivery methods like Integrated project delivery (IPD) (20)	
Lifecycle delivery methods like Build operate transfer (BOT) (21)	
Construction manager (CM) at risk (22)	
Others (please specify) (23)	
Others (please specify) (24)	

End of Block: Part 3: Lean Based Project

Start of Block: Part 4: Successful Lean Project

Part 4: Successful Lean Project
All questions in part 4 are only for projects where lean construction tools and techniques were successfully applied.

Q 18. What was the level of commitment of the following project participants in implementing lean construction tools?

	None	Little	High	Very high
Upper Management				
Middle Management				
Field Management				
Suppliers				
Subcontractors				
Workforce				

Q 19. What was the level of empowerment of the following project participants in implementing lean construction tools

	None	Little	High	Very high
Upper Management				
Middle Management				
Field Management				

Suppliers	
Subcontractors	
Workforce	

Q 20. How much lean training was required for your field management and workforce?

(1) Nothing, already trained
(2) Little
(3) Moderate
(4) Substantial

Q21. Please rank the methods used according to their efficacy in learning lean construction tools and techniques? (Please check all that apply - 1 Most important – 5 Least important)

	1	2	3	4	5
Class room Lectures					
Workshops					
Site visits					
On the job					
Videos					
Others (please specify)					
Others (please specify)					

Q22. Which of the following training methods you used in your lean based projects? (Please check all that apply)

(1) Class room Lectures
(2) Workshops
(3) Site visits
(4) On the job
(5) Videos
(6) Other (please specify) ____
(7) Other (please specify) ____

Q 23. Did you use internal trainers with expertise or hire an external facilitator?

(1) Internal trainers only
(2) Internal and external both
(3) External trainers only

Display This Question:

If 23. Did you use internal trainers with expertise or hire an external facilitator? = External trainers only

Q 23a. If you used external lean facilitators, how effective were they?

____

____

____

Q 24. If you used project incentives for lean implementation, what were they and how effective were they?

(1) Incentives Types ____
(2) Effectiveness ____

Q 25. What type of additional support was given to the project teams to implement lean construction tools?

	None	Limited	Reasonable
Additional Funding and/or time support			
Additional preparation and training			
Authority of using companywide resources			
Upper management trust on "no fear on failure"			
Others (please specify)			
Others (please specify)			

Q 26. How often did you measure the performance of lean construction tools?

(1) Never measured
(2) Weekly
(3) Monthly
(4) Quarterly or semi annually
(5) Annually
(6) At the end of project
(7) Other (Please specify) ____

Q 27. How did periodic measurements influence the implementation?

____

____

____

Q28. How would you rate the effectiveness of standardization of tasks, methodologies and processes for successful implementation of lean construction tools?

(1) None
(2) Limited
(3) Some
(4) Very effective

Q29. What do you do to increase the awareness of lean construction in the construction industry?

____

____

____

Q 30. For beginners in lean implementation, what would be your advice for successful selection and implementation of lean tools and techniques with regards to followings?

(1) a. Selection of construction processes for lean intervention
____
(2) b. Identification and selection of lean tools and techniques
____
(3) c. Implementation of lean tools and techniques
____

End of Block: Part 4: Successful Lean Project

APPENDIX C. QUESTIONNAIRE 2- FRAMEWORK ASSESSMENT FOR IMPLEMENTING LEAN CONSTRUCTION

Part 1: Background

Q2 Your Company/Organization type

(1) Owner
(2) Consultant
(3) Contractors
(4) Architect
(5) CM/PM
(6) Other, please Specify ____

Q3 Your overall construction experience

(1) < 5 yrs
(2) 5-10 yrs
(3) 11-15yrs
(4) 16-20 yrs
(5) > 20 yrs

Q4 Number of years implement Lean Construction

(1) < 1 yrs
(2) 1-4 yrs
(3) 5-10 yrs
(4) > 10 yrs

End of Block: Part 1: Background

Part 2: Efficacy of Lean practices - To what extent do you agree/disagree on following statements?

		Strongly disagree	Disagree	Agree	Strongly agree
(5)	Your organization started the lean journey by getting the help from external/internal facilitators in understanding lean concepts.				
(6)	Your organization continuously evaluates the training needs of their employees.				
(7)	Your organization provided training opportunities to the project teams by arranging lean workshops or on job training sessions.				

		Strongly disagree	Disagree	Agree	Strongly agree
(8)	Your organization provided opportunities to the key project team members for attending lean conferences/congresses/seminars.				
(9)	Your organization was effectively educated and well trained to start the lean construction practice.				
(10)	When you were at the start of your lean journey, you only selected those processes for lean intervention that were not effectively managed.				
(11)	When you were at the start of your lean journey, you only selected those processes for lean intervention that were affordable in terms of resources.				
(12)	When you were at the start of your lean journey, you only selected those processes for lean intervention that could significantly impact time and resources.				
(13)	Involving all the project participants, like architect/designers, contractors/subcontractors/suppliers at an early stage of the project, improved your project outcomes.				
(14)	Your organization regularly undertakes projects using Integrated Project Delivery (IPD).				
(15)	Early involvement of all project participants with shared risks and rewards helped in waste reduction, meeting customer's requirements and maintaining flow in your project.				
(16)	Your organization uses big room sessions for increasing collaboration among project key stakeholders as well as project teams.				
(17)	Your organization uses technologies (like BIM or others) to improve visualization and communication among project participants.				
(18)	Your organization selects lean tools and techniques based on their compatibility with construction processes.				
(19)	Your organization selects lean tools and techniques based on the alignment between the objective of lean tools and techniques with lean construction principles.				
(20)	Your organization selects those lean tools and techniques that can maximize value/benefits in terms of cost, time, and productivity.				
(21)	Your organization started lean construction only after your top, middle and field management were highly committed to implementing lean construction.				
(22)	Your organization started lean construction only after your workforce and your partner organization (such as subcontractors or suppliers) were adequately (not necessarily highly) committed to implementing lean construction.				
(23)	During the start of your lean journey, achieving improvements within the range of 10-20% in categories of cost, time, quality and safety increased the commitment and trust for lean construction among your teams.				
(24)	Your project teams identify the defects/quality issues on their own and rectifies them before moving forward.				

		Strongly disagree	Disagree	Agree	Strongly agree
(25)	In your organization, field management and workforce are adequately empowered to implement workplace improvement during the lean process.				
(26)	In your organization, key workforce personnel and subcontractors/ suppliers actively participate during master, lookahead and weekly planning meetings.				
(27)	Your organization periodically measures the project outcomes weekly or monthly.				
(28)	Your organization continuously improves the lean processes through regular progress outcome measurements.				
(29)	Your organization continuously improves the lean processes by regularly performing Plan, Do, Check, Act (PDCA) cycles or conducting First Run Studies (FRS).				
(30)	a. Your organization regularly standardizes lean processes/methods with effective modifications on every project.				
(31)	Commitment and trust for lean construction improved by gradually implementing lean tools and techniques.				
(32)	Your organization regularly shares goals/objectives, commitments, mutual benefits and project results to the other project partners and internal project teams.				
(33)	Collaboration among your project participants ensures mutual agreement on implementing lean construction.				
(34)	Your organization promotes a culture of team work during projects				
(35)	Your organization celebrates initial successes with all the project partners and internal project teams.				
(36)	Your organization provided additional preparation and training resources to lean teams, once you started your lean journey.				
(37)	Your organization believed in upper management and trusted "no fear of failure" once you started your lean journey.				
(38)	Your organization started team rewards for lean teams, once you started your lean journey.				
(39)	Your organization started incentive systems for partners, once you started your lean journey.				
(40)	Relationships between your organization with other project parties are based on long term partnerships.				
(41)	Relationships between your organization with other project parties are based on trust and transparency.				
(42)	Your organization frequently use the following lean tools/techniques/practices to achieve the principles of lean construction:	Choose all that applies			
	a. Last Planner System (LPS®) including Pull Planning, Percent Plan Completion (PPC), weekly/lookahead/reverse /master scheduling.				
	b. Managing supply chain using approaches like Just in Time (JIT) or others.				

	Strongly disagree	Disagree	Agree	Strongly agree
c. Quality/safety improvement through Six Sigma or concepts like built in quality/safety, Fail Safe for Quality and Safety (FSQS), or others				
d. Removing constraints within the flow processes using Theories of Constraints (TOC).				
e. Displaying the project information like lookahead plan, PPC, quality/safety indexes, responsibility charts, targets or others at construction site.				
f. Targeting the Client's value and cost through Target Value Design (TVD) approach.				
g. Identifying value/non-value adding activities during/before the start of the reverse phase and lookahead planning.				
By implementing lean construction, your organization was able to improve lean efficiency in the following aspects:				
(43) control cost overrun on your projects.				
(44) control schedule overrun on your projects.				
(45) improve quality on your projects.				
(46) improve safety on your projects.				
(47) increase profit.				
(48) reduce financial losses.				
(49) reduce lawsuits.				
(50) Improve relationships				

Part 3: Relationship between factors for selecting and implementing lean tools and techniques

Introduction: For the following questions we are asking for pairwise comparisons of each factor to the other factors. The factors are numbered 1-12 and are shown below:

1. Imparting requisite knowledge and training regarding lean construction principles, tools/techniques and objectives
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 workforce.
7. Adoption of continuous improvement
8. Standardizing the lean processes

9. Improving cultural adoptability and commitment towards lean construction
10. Providing additional support and incentive to the lean teams and partners
11. Long term partnership and trust worthy relations
12. Implementing LPS duly integrated with other tools

Q51 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 workforce.
7. Adoption of continuous improvement
8. Standardizing the lean processes
9. Improving cultural adoptability and commitment towards lean construction
10. Providing additional support and incentive to the lean teams and partners
11. Long term partnership and trust worthy relations
12. Implementing LPS duly integrated with other tools

Q52 Does *the initial selection of appropriate construction processes (factor 2)* help in achieving any of the following factors? Choose all that apply

1. Imparting requisite knowledge and training regarding lean construction principles, tools/techniques and objectives
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 workforce.
7. Adoption of continuous improvement
8. Standardizing the lean processes
9. Improving cultural adoptability and commitment towards lean construction
10. Providing additional support and incentive to the lean teams and partners
11. Long term partnership and trust worthy relations
12. Implementing LPS duly integrated with other tools

Q53 Does *improving collaboration, communication and visualization (factor 3)* help in achieving any of the following factors? Choose all that apply

1. Imparting requisite knowledge and training regarding lean construction principles, tools/techniques and objectives
2. The initial selection of appropriate construction processes
4. Selection of appropriate lean tools and techniques/system
5. Ensuring adequate commitment from Project teams
6. Ensuring adequate empowerment be given to workforce
7. Adoption of continuous improvement

8. Standardizing the lean
9. Improving cultural adoptability and commitment towards lean construction
10. Providing additional support and incentive to the lean teams and partners
11. Long term partnership and trust worthy
12. Implementing LPS duly integrated with other tools

Q54 Does *selection of appropriate lean tools and techniques/system (factor 4)* help in achieving any of the following factors? Choose all that apply

1. Imparting requisite knowledge and training regarding lean construction principles, tools/techniques and objectives
2. The initial selection of appropriate construction processes
3. Improving collaboration, communication and visualization
5. Ensuring adequate commitment from Project teams
6. Ensuring adequate empowerment be given to workforce.
7. Adoption of continuous improvement (9)
8. Standardizing the lean processes
9. Improving cultural adoptability and commitment towards lean construction
10. Providing additional support and incentive to the lean teams and partners
11. Long term partnership and trust worthy relations
12. Implementing LPS duly integrated with other tools

Q55 Does *ensuring adequate commitment from Project teams (factor 5)* help in achieving any of the following factors? Choose all that apply

1. Imparting requisite knowledge and training regarding lean construction principles, tools/techniques and objectives
2. The initial selection of appropriate construction processes
3. Improving collaboration, communication and visualization
4. Selection of appropriate lean tools and techniques/system
6. Ensuring adequate empowerment be given to workforce.
7. Adoption of continuous improvement
8. Standardizing the lean processes
9. Improving cultural adoptability and commitment towards lean construction
10. Providing additional support and incentive to the lean teams and partners
11. Long term partnership and trust worthy relations
12. Implementing LPS duly integrated with other tools

Q56 Does *ensuring adequate empowerment be given to workforce (factor 6)* help in achieving any of the following factors? Choose all that apply

1. Imparting requisite knowledge and training regarding lean construction principles, tools/techniques and objectives
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

7. Adoption of continuous improvement
8. Standardizing the lean processes
9. Improving cultural adoptability and commitment towards lean construction
10. Providing additional support and incentive to the lean teams and partners
11. Long term partnership and trust worthy relations
12. Implementing LPS duly integrated with other tools

Q57 Does *adoption of continuous improvement (factor 7)* help in achieving any of the following factors? Choose all that apply

1. Imparting requisite knowledge and training regarding lean construction principles, tools/techniques and objectives
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 workforce.
8. Standardizing the lean processes
9. Improving cultural adoptability and commitment towards lean construction
10. Providing additional support and incentive to the lean teams and partners
11. Long term partnership and trust worthy relations
12. Implementing LPS duly integrated with other tools

Q58 Does *standardizing the lean processes (factor 8)* help in achieving any of the following factors? Choose all that apply

1. Imparting requisite knowledge and training regarding lean construction principles, tools/techniques and objectives
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 workforce.
7. Adoption of continuous improvement
9. Improving cultural adoptability and commitment towards lean construction
10. Providing additional support and incentive to the lean teams and partners
11. Long term partnership and trust worthy relations
12. Implementing LPS duly integrated with other tools

Q59 Does *improving cultural adoptability and commitment towards lean construction (factor 9)* help in achieving any of the following factors? Choose all that apply

1. Imparting requisite knowledge and training regarding lean construction principles, tools/techniques and objectives
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 workforce.
7. Adoption of continuous improvement
8. Standardizing the lean processes
10. Providing additional support and incentive to the lean teams and partners
11. Long term partnership and trust worthy relations
12. Implementing LPS duly integrated with other tools

Q60 Does providing additional support and incentive to the lean teams and partners (factor 10) help in achieving any of the following factors? Choose all that apply

1. Imparting requisite knowledge and training regarding lean construction principles, tools/techniques and objectives
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 workforce.
7. Adoption of continuous improvement
8. Standardizing the lean processes
9. Improving cultural adoptability and commitment towards lean construction
11. Long term partnership and trust worthy relation
12. Implementing LPS duly integrated with other tools

Q61 Does *long term partnership and trust worthy relations (factor 11)* help in achieving any of the following factors? Choose all that apply

1. Imparting requisite knowledge and training regarding lean construction principles, tools/techniques and objectives
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 workforce.
7. Adoption of continuous improvement
8. Standardizing the lean processes
9. Improving cultural adoptability and commitment towards lean construction
10. Providing additional support and incentive to the lean teams and partners
12. Implementing LPS duly integrated with other tools

Q62 Does *implementing LPS duly integrated with other tools (factor 12)* help in achieving any of the following factors? Choose all that apply

1. Imparting requisite knowledge and training regarding lean construction principles, tools/techniques and objectives
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 workforce.
7. Adoption of continuous improvement
8. Standardizing the lean processes
9. Improving cultural adoptability and commitment towards lean construction
10. Providing additional support and incentive to the lean teams and partners
11. Long term partnership and trust worthy relations

APPENDIX D. STATISTICAL ANALYSIS OF SURVEY DATA FOR DEFINING RELATIONSHIPS

Pairwise comparison between factors i to j	Frequency of Factor i influencing j	Frequency of Factor j influencing i	Chi-square	Sig @	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
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

Pairwise comparison between factors i to j	Frequency of Factor i influencing j	Frequency of Factor j influencing i	Chi-square	Sig @	Results
a	b	c	d	e	f
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
3 to 4	50.62%	30.86%.	0.018	Yes	Frequency in Column b > c, so the relationship is V
3 to 5	34.57%,	46.91%.	0.0956	No	Both influence each other equally; the relationship is X
3 to 6	59.26%,	23.46%.	<0.000	Yes	Frequency in Column b > c, so the relationship is V
3 to 7	60.49%,	27.16%.	<0.000	Yes	Frequency in Column b > c, so the relationship is V
3 to 8	45.68%,	24.69%.	0.007	Yes	Frequency in Column b > c, so the relationship is V
3 to 9	48.15%,	27.16%.	<0.000	Yes	Frequency in Column b > c, so the relationship is V
3 to 10	60.49%,	23.46%.	0.001	Yes	Frequency in Column b > c, so the relationship is V
3 to 11	46.91%,	25.93%.	0.001	Yes	Frequency in Column b > c, so the relationship is V
3 to 12	41.98%,	25.93%.	0.036	Yes	Frequency in Column b > c, so the relationship is V
4 to 5	29.63%,	55.56%.	0.001	Yes	Frequency in Column c > b, so the relationship is A
4 to 6	40.74%,	37.04%.	0.6547	No	Both influence each other equally; the relationship is X
4 to 7	56.79%,	27.16%.	<0.000	Yes	Frequency in Column b > c, so the relationship is V
4 to 8	58.02%,	25.93%.	<0.000	Yes	Frequency in Column b > c, so the relationship is V
4 to 9	50.62%,	19.75%.	<0.000	Yes	Frequency in Column b > c, so the relationship is V

Pairwise comparison between factors i to j	Frequency of Factor i influencing j	Frequency of Factor j influencing i	Chi-square	Sig @	Results
a	b	c	d	e	f
4 to 10	46.91%,	19.75%.	<0.000	Yes	Frequency in Column b > c, so the relationship is V
4 to 11	22.22%,	55.56%.	<0.000	Yes	Frequency in Column c > b, so the relationship is A
4 to 12	44.44%,	24.69%.	0.0114	Yes	Frequency in Column b > c, so the relationship is V
5 to 6	55.56%,	33.33%.	0.0044	Yes	Frequency in Column b > c, so the relationship is V
5 to 7	53.09%,	32.10%.	0.0031	Yes	Frequency in Column b > c, so the relationship is V
5 to 8	55.56%,	28.40%.	0.000	Yes	Frequency in Column b > c, so the relationship is V
5 to 9	51.85%,	29.63%.	0.0044	Yes	Frequency in Column b > c, so the relationship is V
5 to 10	49.38%,	28.40%.	0.0065	Yes	Frequency in Column b > c, so the relationship is V
5 to 11	51.85%,	35.80%.	0.042	Yes	Frequency in Column b > c, so the relationship is V
5 to 12	45.68%,	27.16%.	0.0321	Yes	Frequency in Column b > c, so the relationship is V
6 to 7	61.73%,	24.69%.	0.001	Yes	Frequency in Column b > c, so the relationship is V
6 to 8	55.56%,	23.46%.	<0.000	Yes	Frequency in Column b > c, so the relationship is V
6 to 9	58.02%,	23.46%.	<0.000	Yes	Frequency in Column b > c, so the relationship is V
6 to 10	35.80%,	46.91%.	0.1495	No	Both influence each other equally; the relationship is X
6 to 11	17.28%,	56.79%.	<0.000	Yes	Frequency in Column c > b, so the relationship is A
6 to 12	16.05%,	51.85%.	<0.000	Yes	Frequency in Column c > b, so the relationship is A

Pairwise comparison between factors i to j	**Frequency of Factor i influencing j**	**Frequency of Factor j influencing i**	**Chi-square**	**Sig @**	**Results**
a	b	c	d	e	f
7 to 8	60.49%,	55.56%.	0.2850	No	Frequency in Column c > b, so the relationship is A
7 to 9	23.46%,	59.26%.	<0.000	Yes	Frequency in Column c > b, so the relationship is A
7 to 10	24.69%,	64.20%.	<0.000	Yes	Frequency in Column c > b, so the relationship is A
7 to 11	24.69%,	61.73%.	<0.000	Yes	Frequency in Column c > b, so the relationship is A
7 to 12	17.28%,	55.56%.	<0.000	Yes	Frequency in Column c > b, so the relationship is A
8 to 9	29.63%,	53.09%.	0.0038	Yes	Frequency in Column c > b, so the relationship is A
8 to 10	24.69%,	48.15%.	0.0018	Yes	Frequency in Column c > b, so the relationship is A
8 to 11	24.69%,	58.02%.	<0.000	Yes	Frequency in Column c > b, so the relationship is A
8 to 12	24.69%,	56.79%.	<0.000	Yes	Frequency in Column c > b, so the relationship is A
9 to 10	27.16%,	54.32%.	<0.000	Yes	Frequency in Column c > b, so the relationship is A
9 to 11	23.46%,	58.02%.	<0.000	Yes	Frequency in Column c > b, so the relationship is A
9 to 12	19.75%,	54.32%.	<0.000	Yes	Frequency in Column c > b, so the relationship is A
10 to 11	20.99%,	50.62%.	<0.000	Yes	Frequency in Column c > b, so the relationship is A
10 to 12	17.28%,	50.62%.	<0.000	Yes	Frequency in Column c > b, so the relationship is A
11 to 12	44.44%,	18.52%.	<0.000	Yes	Frequency in Column b > c, so the relationship is V

@ Significance

APPENDIX E. OUTPUT PLS-SEM

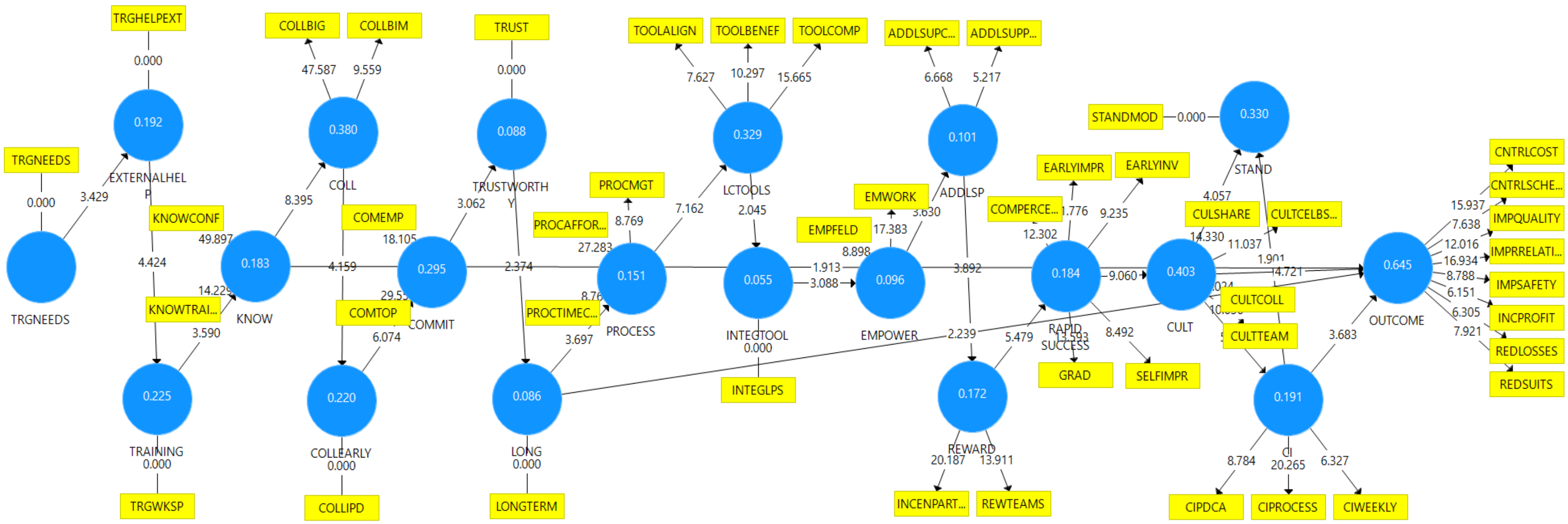

Figure E.1. Output PLS-SEM for Trial 4

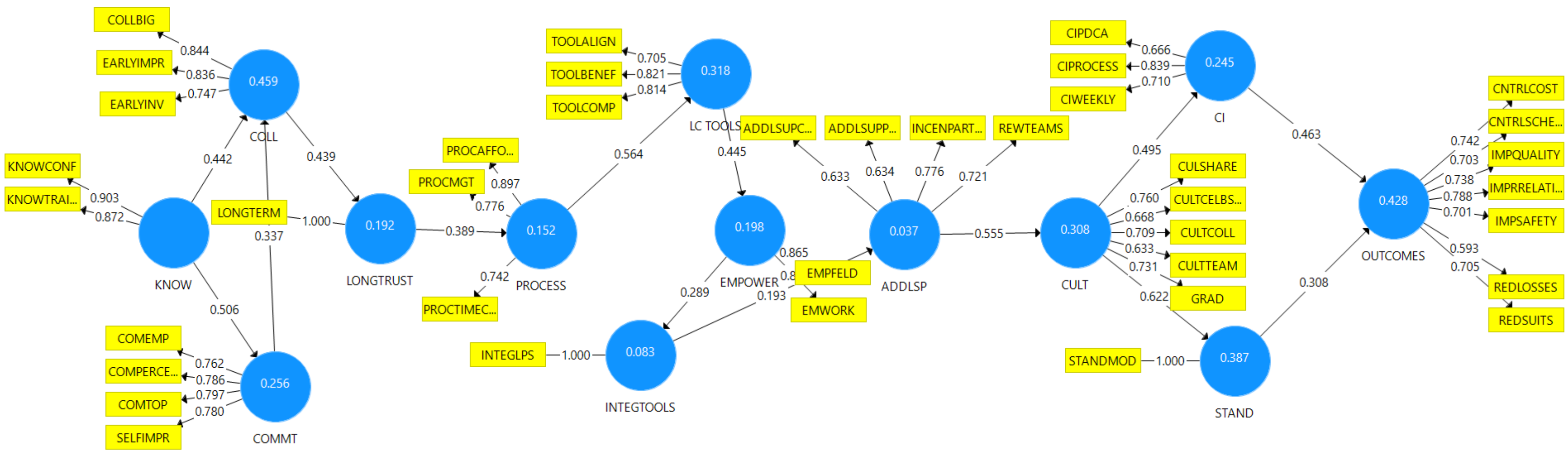

Figure E.2. Output PLS-SEM for Trial 3

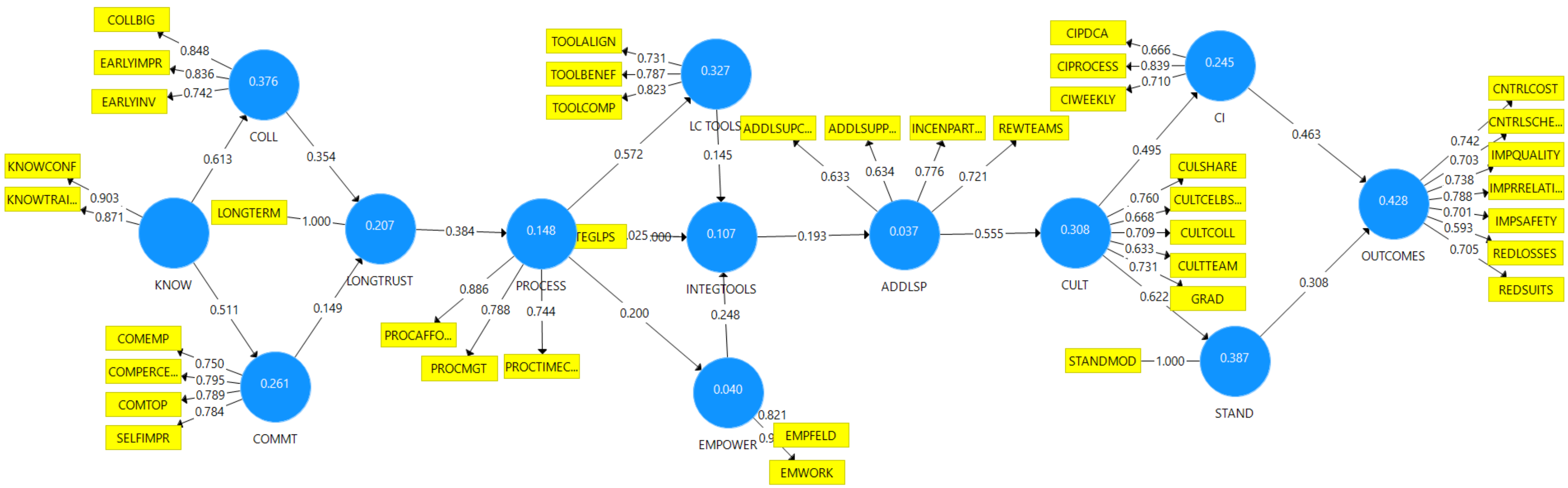

Figure E.3. Output PLS-SEM for Trial 2

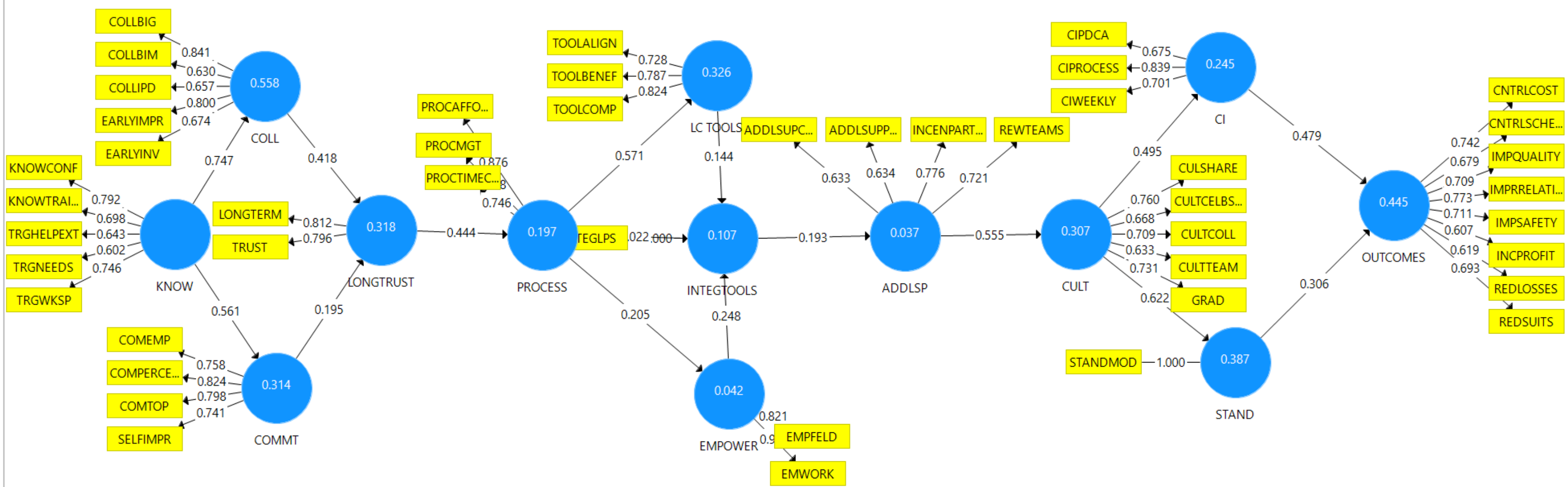

Figure E.4. Output PLS-SEM for Trial 1