INTEGRATION OF BUILDING INFORMATION MODELING (BIM) AND PREFABRICATION: A BOOST TO LEAN PRINCIPLE ENVIRONMENT

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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

MASTER OF SCIENCE

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ABSTRACT

Lean construction, adapted from manufacturing, is focused on reducing waste, customer satisfaction and continuous improvement. However, its Last Planner System (LPS) lacks the automation needed to manage complex projects.

On the other hand, Building Information Modeling (BIM) is capable of developing models that are compliant with LPS planning levels and faster visualization of errors. Prefabrication encourages just in time delivery while benefitting from BIM model capabilities.

The objective of the study is to establish a framework to integrate Last Planner system with BIM and Prefabrication. Literature study and survey inferences were used to identify the potential to integrate. The framework aims to develop smooth workflows and an up-to-date LPS, boosting lean environment. It could be significant to the users of both BIM and prefabrication by having the potential to manage and coordinate progressive BIM models and less variable workflows for prefabrication.

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Most importantly, I want to thank my husband and my family for their encouragement, patience and motivation during my studies.

DEDICATION

I would like to dedicate this work of mine to my husband, Amandeep Singh, for his love, motivation and support towards anything and everything that I wish to accomplish.

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1. INTRODUCTION

1.1. Background

Construction industry is growing day by day, with the ever-increasing need for infrastructure. This growing need gives way to the competitiveness in the industry. Due to which demand for building more with less resources and better quality is much more than ever before.

Construction industry's performance is measured most of the times, in terms of timely completion, within budget and little emphasis is given to the customer satisfaction and continuous improvement. Poor communication, misrepresentation of information, onsite errors, poor collaboration are among the major problems which make construction project vulnerable to overruns, reworks and adversarial relations, creating the need for better management.

Construction management is largely divided into two different approaches: 1) Project management, which deals with the interaction of activities; and 2) Operations management which works with each activity individually. "Lean construction believes in combining both; effort on individual tasks and their interaction leading to better performance outcomes" (Paez, Salem, Solomon, & Ash, 2005). It encourages building products with little possible waste (non-value adding activities), variability and increased value to the customers.

Lean concept originated in manufacturing and was developed by Taiichii Ohno and Eiji Toyoda in 1950's. It focuses on reducing the non-value adding activities termed waste, thereby maximizing the value by improving the process itself. (Womack, Jones, & Roos, The Machine That Changed The World , 1990).

Lean construction identifies flow of work like a task completed by one team and then being handed off to next team as equivalent to manufacturing industry's flow of product in the production line. It is important to understand the construction as a production system in order to successfully adapt from manufacturing.

Last Planner System(LPS) is one of the methods, developed by Glenn Ballard and Gregory Howell, as construction production control and planning system to reduce the workflow uncertainty by creating a hierarchy of work plans. It reduces the transfer of error and its effects from the one activity to the next activity. To successfully implement LPS in today's complex construction setting, more reliable work plans and accurate sequencing is needed.

Construction process becomes more comparable to manufacturing when using Prefabrication, the concept of manufacturing building components offsite and assembling them on-site. As the units are being made offsite beforehand, their tolerance for error is close to zero to avoid clashes with other structure systems. This raises the demand for better sequencing and greater level of certainties in the construction workflow. These elements of prefabrication encourage the environment of pull system, which is one of the core principles of Lean.

Building Information Modeling (BIM) with its ability to provide computer simulated building models, containing detailed information, can immensely facilitate the creation of more reliable workflow. It provides visual perspective to design and construction sequence, reduced errors and clashes in the workflow and generates shop drawings with greater detail. It has the ability to improve Lean's LPS and facilitate more accurate prefabrication.

Integrating BIM and prefabrication with Lean's Last Planner system have the potential to result in reliable work flow and, faster and better quality end product needed to update Lean's Last Planner System to today's construction industry needs.

1.2. Need Statement

1.2.1. Need to Improve Selection for Sound Activities

One of the widely used Lean construction tool is Last Planner System that is used as scheduling tool to reduce flow variability, and uncertainty in the planning process, acting as a production and planning control system**.** The four levels of planning of LPS 1) Master schedule 2) Phase schedule 3) Look Ahead Schedule 4) Weekly Work Plan focus on moving only those activities to the next level which are considered sound. Soundness of activities depends upon seven preconditions: (Koskela, 1999)

1. "Construction design; correct plans, drafts and specification are present
2. Components and materials are present
3. Workers are present
4. Equipment and machinery are present
5. Sufficient space so the task can be executed
6. Connecting works, previous activities must be completed
7. External conditions must be in order."

"These preconditions are only taken into consideration only once and little effort is done to check if the preconditions itself has changed or not which can affect the soundness of the activities". As (Lindhard & Wandahl, 2011) explains changes in design are expected as customer/client may not be able to visualize the end product. It identifies the need for 3D tools which can help in defining criteria and thereby reducing the number of changes. A 3D tool will be able to assess the soundness of the activities in a better way.

1.2.2. Need to Automate Clash Detection

Clash detection is important for checking soundness of activities for LPS so that only those activities which are without any constraints are moved to the next level creating a reliable workflow, automating it with the help of a 3D tool will vastly improve it by making it faster and more accurate.

"This would be nearly impossible to achieve with traditional 2D CAD technologies, where even if drawings are overlaid on each other, they do not always make it easier for the user to identify where the clash would be in a 3D space". (Dave, Koskela, Kiviniemi, Tzortzopoulos, & Owen, 2013).

1.2.3. Need for More Reliable Master Schedule

LPS's foundation schedule is Master schedule, its reliability is utmost important as the other plans are made based on it. "One of the major limitation of Master schedule is its focus on estimated duration and interrelationships of activities but no consideration for constraints and much needed buffer/slacks". (Lindhard & Wandahl, 2013). This is easier to estimate when construction process can be studied by using computer simulations.

1.2.4. Implementation Challenges

(Dave, Hamalainen, Juho-Pekka, & Koskela, 2015) identifies some of the implementation challenges of LPS:

- Lack of standardized flow of reporting between shorter planning functions such as weekly and daily planning to long range plans like phase and master plans,
- Inability to deploy collaborative approach
- Lack of recognition of information systems.

- Difficulty in tracking and monitoring the impact of identified constraints on workflow reliability before execution.
- Information is not aggregated or synchronized by any system.
- Production control is mainly done manually so the information does not naturally flow from higher level plans (master plans and phase) to lower level (look-ahead and weekly work) and vice versa.

It identifies the need to update LPS to reflect the practical and currents needs of the construction industry**.** Information system is needed to improve collection so that focus can be shifted to planning and scheduling activities rather than collecting information in the collaborative meetings. Integrating BIM models containing detailed and updated information can be beneficial. (Dave, Hamalainen, Juho-Pekka, & Koskela, 2015)

1.2.5. Reduce Variability in Construction Process

Prefabrication manufactures building components offsite and assemble them onsite much like a product in the manufacturing industry. The prefab building units require tighter tolerance to avoid conflicts onsite. The assembly requires the components to be on site just in time so that there is little need for storage and less clutter on site creating a pull system. "Higher precision tolerances would contribute to leaner processes as they arguably reduce variability and the resultant waste from the construction process as well as generally diminish the losses due to deviations from target values." (Taguchi, 1993).

A reliable workflow to efficiently manage the prefabrication's pull system and 3D tool for much more accurate building components can reduce the variability in the construction process.

Lean construction's Last Planner System (LPS) provides a production planning and control system but in today's complex and fast paced construction environment, the absence of the automation of this system makes it less efficient. There is a need to integrate modern practices like building information modeling and prefabrication with Lean's LPS to make production planning process smooth, more visualized, and fast paced.

It is significant to understand their use and form a framework to achieve their combined potential effectively, resulting in a leaner environment.

1.3. Objectives

The main objective of the research is to integrate Last Planner System with Building Information Modeling and Prefabrication to boost the Lean principle environment.

- To document the use and important factors relating to Lean construction and Last Planner System (LPS).
- To document the use and important factors relating to Prefabrication and BIM in construction projects.
- To analyze the integrated use.
- To propose a framework to integrate all three to achieve Leaner environment.

1.4. Scope

The scope of the study is limited to evaluation of use of Building information modeling for both prefabrication and LPS to improve Lean construction environment in the current construction management process and proposing a framework for the same. Due to time constraints and various others, a case study implementation in the industry is not covered in the current study instead a follow-up survey is performed by sending the proposed framework and summary report along with questionnaire to same set of respondents in order to find out their opinion.

1.5. Methodology

In order to achieve the research objectives listed above, a systematic methodology is used for this study. This methodology contains several steps: (1) Preliminary literature study, (2) Research need identification, (3) Data collection, (4) Data analysis, (5) Proposed framework, (6) follow-up survey, and (7) Recommendations, as illustrated in Figure 1. While each of these steps are listed below again with its main focuses, more detailed explanation for several of these steps can be found below Figure 1.

- ***Preliminary Literature study*** – Study current use of Lean, BIM and prefabrication.
- ***Research Need Identification*** **–** Based on current practices, its challenges and possible area of improvement.
- ***Data collection*** – This was attained through literature review, online survey using questionnaire.
- ***Data analysis***– An analysis of the collected data to find potential to integrate.
- ***Proposed framework*** - Based on data evaluation, an integrated framework is proposed.
- ***Follow-up survey questionnaire -*** The proposed framework, along with the summary report of the initial survey is send to respondents.
- ***Conclusion and Recommendations***

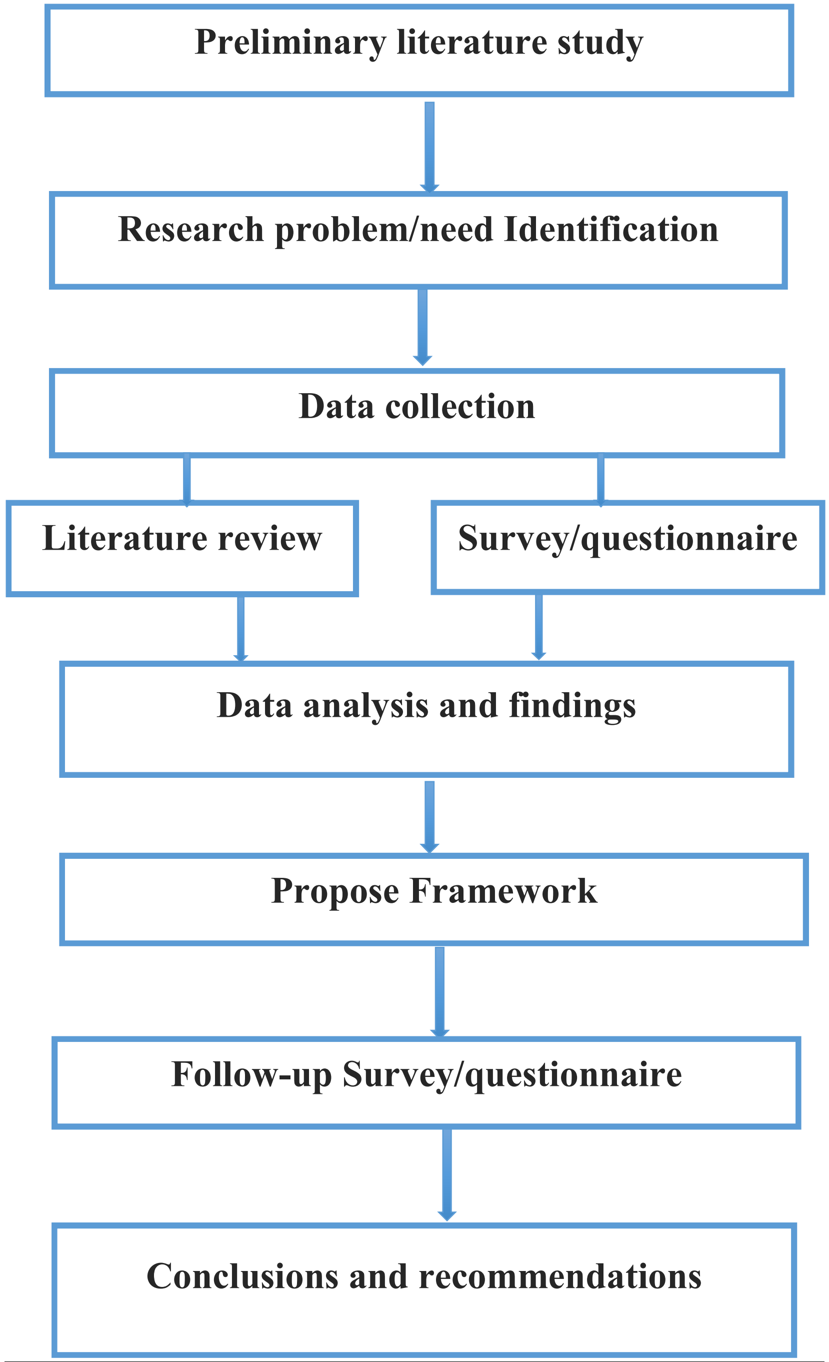

Figure 1. Methodology

1.5.1. Literature Review

The primary sources for the literature review consisted, for the most part, of journals and research articles about the Lean, BIM and prefabrication and integration. Other sources included books, official market reports, published conference proceedings and online sources. The purpose of the literature review was to understand Lean and its Last Planner System, Prefabrication and BIM and how their integration could result in a more efficient and lean system.

The majority of the articles and journals were accessed from the online libraries of North Dakota State University and its other resources available at the library. Attention was paid to the authenticity of the sources and academic contents, in respect to articles and websites referred during the literature study.

1.5.2. Data Collection

The data was collected through an online survey. The questionnaire was developed and approved by the Institutional Review Board at North Dakota State University (NDSU).

The questionnaire had total of 35 questions formulated to know the awareness and experience of using Lean, BIM, Prefabrication and their integration. The questions were divided into 6 sections: (1) Section I: Information Sheet, (2) Section II: Respondent's Background (3) Section III: Lean principles (4) Section IV: Building Information Modeling, (5) Section V: Prefabrication (6) Section VI: Integration. In addition to this, participants were also asked to mention any additional comments that they thought were relevant and significant to the study.

1.5.3. Data Analysis

The data that were gathered using the online survey during was used to draw inferences. The following steps were used:

- Survey responses were described using statistics either numerically or graphically.
- Inferences were made keeping in mind the objective of the study.
- Then based on these inferences framework is proposed and conclusions were made

1.5.4. Proposed Framework

Finally, based on the data collected through literature review and via online survey analysis results, a framework is proposed to integrate Lean/tools with BIM and Prefabrication to further the Lean environment by providing an efficient building production system.

1.5.5. Follow-up Survey Questionnaire

The proposed framework and the summary report of the initial survey are send to respondents, along with the follow-up questionnaire.

This questionnaire consisted total of 15 questions, which were formulated to find out the respondents opinion about the proposed framework. The questions were asked both corresponding to different phases of the proposed framework and about the framework as whole.

In addition to this, participants were also asked to mention any additional comments that they thought were relevant.

1.6. Thesis Organization

This thesis is organized into five chapters.

Chapter 1 Background contains introductory information Building Information Modeling and Prefabrication and how they can make a leaner construction environment, when integrated with Lean tools such as Last Planner System (LPS). The need statement is formulated to explain the significance of the research. Objectives, scope are designed to provide a direction and the methodology is outlined to achieve those objectives. Chapter 2 Literature review is targeted to understand the concept and the characteristics of Lean/tools, BIM and Prefabrication. Their extent of integration and the potential to integrate them to further enhance their use. This is achieved through the review of previous research articles, reports. Chapter 3 Survey results and analysis contains the information collected via online survey and inferences made from the results. Significant findings that are relevant to the objective of the study are listed at the end of the chapter. Chapter4 Proposed Framework is for the integration of Lean's Last Planner System with BIM and Prefabrication. All the phases of the framework are explained along with the advantages and purpose for integration at every phase. Chapter 6 Follow-up Survey outlines the construction of the questionnaire and the findings from the follow-up survey. At the end of thesis, Chapter 7 Conclusion is providing the summary of the study and explaining necessary conclusions. The recommendations for future work are also provided at the end of this chapter.

2. LITERATURE REVIEW

2.1. Lean Philosophy

Toyota Corporation of Japan first introduced Lean Philosophy as the manufacturing system termed as Toyota Production System (TPS). The origin of lean thinking is the elimination of waste. Eiji Toyoda and Taichi Ohno, the creators of Toyota Production System, along with their research team, studied the craft and mass production system at Toyota and recognized that there were activities that did not contributed any value to the productivity and hence associated the term waste or Muda (Japanese word for waste) with them. Elimination of these non-value adding activities is the core of Lean philosophy. The team identified following wastes in the system. (Womack, Jones, & Roos, The Machine That Changed The World , 1990)

- Muda of Overproducing
- Muda of Waiting (waiting time/Queue time)
- Muda of Transportation
- Muda of Over processing (waste in work itself)
- Muda of Inventory (having unnecessary stock/material on hand)
- Muda of Motion (using unnecessary motion)
- Muda of Rejection (waste of rejected production, quality issues)
- Muda of Human potential (labor, workforce)

2.1.1. Lean Principles

Lean concepts dwell on 5 basic principles namely Value, Value stream, Flow, Pull, Perfection. All the lean concepts and tools have been formulated by keeping in my mind these principles. (Womack & Jones, Lean Thinking: Banish Waste and Create Wealth in Your Corporation , 1996) explains these principles as follows:

- Specify value from the standpoint of customer. Identify value in terms of product i.e. resources, costs etc. and in terms of construction process.
- Identify all the steps in the value stream, steps needed to create a product meeting the customer needs and eliminating whenever possible those steps which are non-value adding to the process.
- Make the value-adding activities laid out in a sequence so that there is a continuous flow towards the final product. Business flow includes project information like specifications, contracts, plans etc., jobsite flow and supply flow
- As flow is introduced, create an environment of pull system from the next upstream activity.
- As value is specified, value streams are identified, wasted steps are removed, and flow and pull are introduced, improve continuously by following the same principles repeatedly, until a state of perfection is reached in which perfect value is created with no waste.

2.1.2. Lean in Construction

The Construction Industry Institute defines Lean construction as

"Lean construction is 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".

The Lean concept, inspired from manufacturing industry, is complimentary to construction in spite of the implementation challenges due to some fundamental differences between these two industries. Construction is Project-based production system, which is characterized by jumbled flow, process segments loosely linked and uniqueness of the project whereas manufacturing is product based production system. (Ballard & Howell, What Kind of production is construction?, 1998). (Diekmann, Krewedl, Balonick, Stewart, & Won, 2004) outline the other difference which is construction is managed and controlled by individuals working on the project like workers, project managers where as in manufacturing system is controlled by configuring the production line.

One of the challenges mentioned by (Dave, Koskela, Kiviniemi, Tzortzopoulos, & Owen, 2013) "is called 'making do'; Starting construction before designs are finalized is a common example of this practice, leading to decreased efficiency and effectiveness of the whole process". They further explain that collaboration across stages of construction and the supply chain, and the application of improved planning and production control towards eliminating "making do", are two examples that can help reduce the challenges of Lean implementation.

"The most important determinants of construction are supposed to be workflow reliability and labor flow, but lean construction has changed the traditional view of the project as transformation, and embraces the concept of flow and value generation. It shares the same objectives of lean production like cycle time reduction, elimination of waste, and variability reduction". (Aziz & Hafez, 2013).

It is evident that construction, in order to effectively adapt Lean principles should understand construction of buildings as production of buildings focusing on reducing variability in the workflow.

2.1.3. Lean Construction Tools/techniques

Various tools/techniques have been identified for lean construction however as new developments and studies include more with time. (Salem o. , Solomon, Genaidy, & Luegring, 2005) Stated following tools/techniques.

- Last Planner system addresses flow variability.
- Increased Visualization addresses transparency
- 5s Process (**S**ort, **S**traighten, **S**tandardize**,** **S**hine, **S**ustain) addresses transparency
- Daily Huddle meetings addresses continuous improvement
- First Run Studies address continuous improvement
- Fail-safe for quality and safety address process variability

(McGrawHill Construction, Dassault Systems, 2013) SmartMarket Report survey sample consisted of two groups: McGrawHill Construction contractors and Lean Construction Institute members and when asked about using construction specific lean approaches 30% used Last Planner System and 36% used Pull Planning, which is one step in Last Planner System.

2.2. Last Planner System

In the organization, top-level management plans keeping in mind the entire project and frame objectives and constraints governing it. Lower level planning processes decides means for achieving those objectives. Ultimately, someone (individual or group) decides what physical, specific work has to be done the next day. That type of plans has been called "assignments". The person or group that produces assignments is called the "Last Planner". (Ballard & Howell, Implementing Lean construction:Stabilizing Workflow, 1994). Last planner is last in the chain of production as the outputs results in the final production.

The Last Planner System was developed by Glen Ballard and Gregory Howell as a production planning and control system to assist in smoothing variations in construction work flow, developing planning foresight, and reducing uncertainty in construction operations. (Ballard & Howell, 1998). "'Control' here means causing a desired future rather than identifying variances between plan and actual." (Ballard G. , Lean Project Delivery system, 2000a).

It compromises of four levels of planning processes:

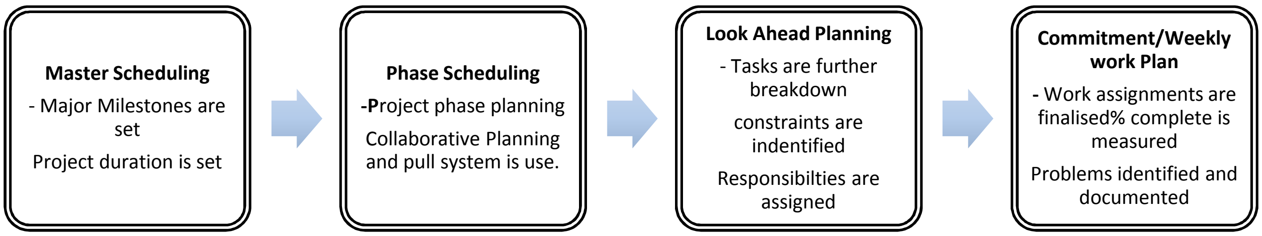

Figure 2. Last Planner System

Master schedule: It contains milestones and major activities. It serves as the foundation or guiding tool for the rest of the levels of planning. The duration of the phases is determined and the detail level is low at this point. In order to become more reliable, master schedule requires development of more studied Critical Path Method (CPM) with responses from those responsible for the particular work.

A Phase pull Schedule (PPS): It is developed, describing milestones deliverables, execution plan and the tasks. It determines the sequence of the tasks by organizing them in a pull system; by starting from the end of the phase and working its way back. During the Phase scheduling the detail level is increased.

It is important that all the team members agree on the planned hand-off between the activities including timing and sequence. It should also have the confident of all the members regarding work flow, resource availability and the identified lead times.

Look-ahead Plan: Activities in the pull phase schedule establish tasks in the Look-ahead Plan (LAP), each week. It is generally 6 weeks long but can range from 3-12 weeks depending upon the duration and complexity of the project. Tasks can be further subdivided in to subtasks, which are linked to LAP and hand-off between them can be established here.

Various functions of look-ahead process explained by (Ballard G. H., 2000) are as follows:

- Shape work flow sequence and rate
- Match work flow and capacity
- Decompose master schedule activities into work packages
- Develop detail methods for executing
- Maintain a backlog of ready work
- Update and revise higher-level schedules as needed.

Activities enter LAP ahead of their execution, from their they are moved week by week in the order of their constraint removal until they are allowed to enter into workable backlog

"The objective is to maintain a backlog of sound work, ready to be performed, with assurance that everything in workable backlog is indeed workable" (Koskela, 1999).

The soundness of activities depends upon seven preconditions:

- Construction design; correct plans, drafts and specification are present
- Components and materials are present
- Workers are present
- Equipment and machinery are present
- Sufficient space so the task can be executed
- Connecting works, previous activities must be completed
- External conditions must be in order. (Koskela, 1999)

These preconditions are only taken into consideration only once and little effort is done to check if the preconditions itself has changed, which can affect the soundness of the activities previously judged to be sound. (Lindhard & Wandahl, 2011)

Weekly Work Plan: WWP includes those tasks that are completely ready to be performed, clear off all the constraints and the required resources are available or will be available when needed. Tasks that are in full confidence of the team that they can be completed within time are assigned in WWP. The tasks are breakdown to the level that their completion time on WWP is usually of the size of a day or so. Inspections are also included when they are prerequisites for the next tasks.

"Percent Plan Complete (PPC) is used to measure the effectiveness of the schedule. It is the number of planned activities completed divided by the total number of planned activities, expressed as a percentage." (Ballard G. H., 2000) Higher PPC corresponds to doing more of the right work with given resources, i.e. to higher productivity and progress but then focus is only on quantity not quality.

Analysis of non-conformances can then lead back to root causes, so improvement can be made in future. In order to achieve better quality, a detailed root cause analysis and continuous improvement is significant.

2.2.1. Should-Can-Will-Do

The Last planners make commitments (WILL) to doing what SHOULD be done, keeping in mind the constraints (CAN) and finally are able to do the planned. This give the ability to select assignments that are actually workable and not just pushed downstream the production line to meet the schedules, which is usually done in traditional practice. "To be able to look ahead and prescreening tasks for constraints, help the production unit to improve productivity also.” (Ballard & Howell, Implementing Lean construction:Stabilizing Workflow, 1994)

2.2.2. Benefits of Last Planner System

Some of the major benefits outlined by (Dave, Hamalainen, Juho-Pekka, & Koskela, 2015) and (Brady, Patricia, & Rooke, 2011) are:

- Tackling variability, ensuring task availability and compressing duration
- Smooth production flow
- Improving flow, making waste visible and continuous improvement
- Building collaboration and trust amongst project participants
- Supply chain integration

2.3. Building Information Modeling

National Institute of Building Sciences (NIBS) describes BIM as:

"A digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward. (Defined as existing from earliest conception to demolition)”

The glossary of the BIM handbook defines BIM as “a verb or adjective phrase to describe tools, processes, and technologies that are facilitated by digital machine-readable documentation about a building, its performance, its planning, its construction, and later its operation.”

“Building information modeling (BIM) is a digital representation of the building process to facilitate exchange and interoperability of information in digital format”. (Hartmann, Meervald, Vossebeld, & Adriansse, 2012)

(Kymmell, 2008) Suggest that's BIM is a project based simulation consisting of the 3D models of the project components with links to all the required information connected with the project's planning, construction or operation, and decommissioning.

Simulation here means single coordinated and integrated entity containing all required information to plan and construct a building project.

2.3.1. Project Models

Model is a visualization/graphic image of an actual project, the type and level of detail with which a model is required to be made depends solely upon its purpose/need of visualization and the ability to understand it. The purpose of the simulation will define its specifications and this in turn is dependent upon the phase of project and the estimated schedule. As there is varied level of information available at different phases of its life cycle that increases with time, the model can also be detailed along the life cycle of the project.

2.3.2. Types of Models

There are different types of BIM models depending upon the level of details and the purpose of the model which can range from conceptual study, design analysis, clash detection, constructability analysis, sequencing, communication, resource information to developing shop drawings for execution and for post construction uses like root cause analysis, reasons for variability or for building maintenance. Various types are as follows (Kymmell, 2008):

- Conceptual model or schematic model
- Design Model
- Construction model
- Shop drawing model
- Detailing model

- As-built model
- Operations and maintenance model

2.3.3. Benefits of BIM

BIM has a wide range of benefits that can leverage construction projects, depending upon the scale and complexity of the project. Some of the most prevalent benefits are as follows:

- Better performing design team –
    - The models reinforce the assessments made during the structural and design analysis in the design phase.
    - Accurate Visualization
- Organize the project, schedule and budget -
    - Helps with clash detection in construction phase and in reducing RFIs or change orders. Construction sequencing, resource planning and procurement schedules are easier to manage with the information contained in the models.
- Reducing waste and rework –
    - BIM enable the project to be studied in detail before the construction begins and detects errors at early stages It improves the coordination between project participants and the team member. It reduces the chances of costly reworks on-site by detecting them off-site and making project teams proactive.
- Managing greater project complexity

    - As the construction projects are becoming more and more complex and large scale, early collaboration of various teams is important to facilitate early inputs from various teams.
- Working with compressed project schedules
    - BIM facilitates faster delivery of projects, which is very important in current social and economic pressures.
- Integrated project delivery
- Generation of more accurate 2D drawings
- Better estimates during design phase
- Increased building performance and quality
- Integration with facility operation and management systems

(Autodesk, 2011) (Bryde, Broquetas, & Volm, 2013) (Eastman, Teicholz, Sacks, & Liston, 2008)

2.4. Prefabrication

Prefabrication is the assembly of buildings or their components at a location other than the building site. The method controls construction costs by economizing on time, wages, and materials. Prefabricated units may include doors, stairs, window walls, wall panels, floor panels, roof trusses, room-sized components, and even entire buildings. (Encyclopedia Britannica)

Merriam – Webster defines prefabrication – “To fabricate the parts of at a factory so that construction consists mainly of assembling and uniting standardized parts”.

2.4.1. Benefits of Prefabrication

(Tam, Tam, Zeng, & Ng, 2007) In the article titled "Towards the adoption of prefabrication in construction" used seven benefits of applying prefabrication for conducting the survey, which were identified by many researchers:

- Frozen design at the early design for better adoption of prefabrication;
- Better supervision on improving the quality of prefabricated products;
- Reduce overall construction costs;
- Shorten construction time;
- Environmental performance improved for waste minimization;
- Integrity on the building design and construction; and
- Aesthetic issues on the building.

(Cowels & Warner, 2013) survey lists 11 benefits of using prefabrication in which 50% of respondents ranked reducing time to project completion as the most significant benefit of prefabrication to project success. Other benefits were as follows:

- Reducing time to project completion
- Reducing construction cost
- Increasing profit margins
- Competitive advantage
- Overall improvement to worker safety
- Improvements in quality
- Reducing rework
- Reducing material waste
- Reducing the need for skilled labor on the job site

- Reducing change orders
- Ease of recruiting skilled employees for work in a shop environment compared to the field.

Among all these benefits identified reduced project construction time, reducing rework, reducing change order, quality improvements, in particular are consistent with Lean principles as they essentially reduce non-value adding activities (waste) in the construction process. These very factors can be enhanced when prefabrication is done using Building Information Modeling.

These complimentary aspects of Lean, BIM and Prefabrication should be the focus when integrating to achieve more capable system.

2.4.2. Challenges Towards Using Prefabrication

- Need for early decision making, which is challenge even with traditional construction methods.
- Need for more collaborative planning. All the trade partner should be coordinating well to avoid clashes while assembling on-site.
- Need for more skilled labor at prefabrication shop
- Logistics of moving prefab components to the site

BIM can help lessen two of the major challenges early decisions making and more collaboration. BIM's visualization is beneficial in making early decisions and visualization in 3D space enable clash detection more efficiently, improving the overall quality of prefabrication.

(McGrawHill Construction, 2011) Surveyed non-users of prefabrication/modularization on projects 46% of them said

- Architect did not design prefab/modular into project. BIM can play an integral part by giving architects ability to design with more accuracy.

- 34% said project type was not applicable and not being familiar with the prefabrication process was a reason for not using prefab.
- Owner does not want prefabricated/modular elements.
- 20% of non-users think availability of local prefab shop is a challenge
- Concern about quality of components/ structure
- 11% feels the availability of trained workforce is limited
- Only 10% think that prefabrication costs too much.

Survey explains that once the challenges like early design commitment and logistics are overcome, the owners report that multiple benefits can be achieved in addition to schedule and cost improvements, such as increased safety, waste reduction and overcoming skilled workforce shortages.

2.4.3. Factors Driving Demand for Prefabrication

A survey results titled: Prefabrication and Modularization in Construction published by FMI Corporation in 2013 suggest that for mechanical and electrical contractors, the largest factor driving demand for prefabrication is the need to improve productivity. It also listed Lean construction as one of the driving factors. It is interested to note that as Lean construction focuses on reducing waste and making construction flow a pull system by allowing the items to be available only when they are needed much like prefabrication components delivered to the site when they are ready to be assembled.

Other factor driving demand was technological improvements like BIM allowing more prefabrication. These demand driving factors for prefabrication clearly states the potential to integrate Prefabrication, Lean and BIM.

(McGrawHill Construction, 2011) Report on prefabrication lists current drivers to use of prefabrication/modularization segregating it by players.

- 92% of contractors, 70% of engineers and 68% of architects believe improved productivity as the major driver for the use. This means reduction in project schedules and budget. Owners report project schedule reductions of 10% to 30% resulting from off-site work.
- Competitive advantage (85%) and generating greater ROI (70%) are stronger drivers for contractors than they are for architects and engineers.

2.5. Integration of BIM, Prefabrication and Lean

In McGraw-Hill Construction's Prefabrication and Modularization: Increasing productivity in the Construction Industry report that on traditional healthcare projects with onsite fabrication, metals waste average 15% to 25% of total recycled materials. On healthcare projects employing lean principles with BIM-enabled prefabrication, metals waste average only 5% to 10% of total recycled materials.

At the $340-million, 1.3-millionsquare- foot University of Kentucky Patient Care Facility in Lexington, crews used BIM and lean construction to facilitate the installation of 1.2 million pounds of prefabricated sheet metal in six months. Nineteen miles of 3-inch to 6-inch conduit was also installed in six months, and the subcontractor, Gaylor Electric, bent all pieces off-site. (McGrawHill Construction, 2011).

In another examples of BIM enabled prefabrication and Lean: a major player in California healthcare projects, DPR, performed drywall detailing on one of its hospital projects, the Sutter Health Castro Valley Clinic.

With fully coordinated BIM spool sheets created from 3D model, DPR's drywall team was able to install all of the hospital's post and panel construction before the walls went in. That meant they could also install the MEP equipment before the walls went in, too, eliminating opportunities for costly rework. (Yoders, 2014)

"BIM provides the capability for contractors to input component details directly, including 3D geometry, material specifications, finishing requirements, delivery sequence, and timing, etc. before and during the fabrication process. Coordination of subcontractors' activities and designs constitutes a large part of a contractor' s added - value to a project". (Eastman, Teicholz, Sacks, & Liston, 2008).

- All of the above mentioned integration instances although the focus was to follow lean principle of reducing non-value adding activities or waste, no particular Lean tool was used.
- (Bhatla & Leite, 2012) integrated BIM coordination meetings with Last Planner System but no emphasis on integrating progressive BIM models and prefabrication with particular lean tool, specifically Last Planner System.
- Using an appropriate Lean tool like Last Planner System to integrate with BIM could potentially result in an efficient building production system.

2.6. Problems/gaps Identified and Potential to Integrate

(Lindhard & Wandahl, 2011) identified that LPS can be upgraded further if

- LPS's ability to handle soundness of the activities is improved
- Focus on quality of end product rather than just finishing it on time.

A central element in LPS is the making ready process, which secures that all preconditions are removed. When all preconditions are removed the assignment is moved to a workable backlog, from here the sound assignments are later moved to the Weekly Work plan. (Lindhard & Wandahl, 2011) . Soundness of the activities can be greatly improved, if the activities and their sequence could be visualized to study.

Integration with BIM can cover this gap as it helps in selecting more sound assignments/activities by checking the connecting works in 3D space and resource availability from the information contained in the BIM models. With the use of BIM, soundness of the activities is more certain and they can then be moved to next level with more confidence.

(Dave, Koskela, Kiviniemi, Tzortzopoulos, & Owen, 2013) suggests that integration of also automates the whole system making it more reliable and robust.

BIM not just improves the scheduling of the project but with reduced rework, it improves the quality of the end product.

(Dave, Hamalainen, Juho-Pekka, & Koskela, 2015) explored the recurrent problems in LPS implementation. They observed five companies from a LPS implementation perspective, four from the UK and one from Finland. All five were large size main contractors that were familiar with Lean Construction principles and had prior experience in implementing LPS on their projects. Problems identified included:

- Absence of systematic constraint analysis for individual activities. It is only prepared for the whole plan.
- PPC, progress and non-compliance reports were being made but no focus on root cause analysis or continuous improvement,
- Less collaborative approach in making plans,
- Information flow from short-term plans (WWP, Look-ahead plans) to long term plans (Phase, master plans) for the use of tracking and monitoring.

- Not all elements of LPS were deployed

These problems could be reduced if LPS is integrated with BIM, it creates a system where the models get updated throughout the duration of the projects making it easier to track back and look for non-compliance, analysis the root causes and use that feedback for future projects and not just rely on PPC reports.

BIM models with the information integrated within them provides for the easy information flow between various levels of schedules.

The BIM models containing varied levels of details integrated at various level of Last Planner System could create standardize system and may promote implementation of all the elements of LPS not just parts of it.

Lean being a concept adapted from manufacturing has many attributes, which are not fully adjustable to construction industry. Prefabrication enables to manufacture buildings components offsite and assemble them onsite much like a product in the manufacturing industry. It creates a pull system, which is one of the Lean principle and a step in Last Planner system, as the assembly requires the components to be on site just in time for the assembly.

The building units require tighter tolerance so as to avoid conflicts onsite, which makes the construction process more standardized and less susceptible to waste (reworks, quality issues). These tighter tolerances and reliable design could be achieved if integrated with BIM.

It is evident from the literature that there are numerous instances where Lean and its tools can benefit from integrating with BIM and Prefabrication resulting in an enhanced system.

3. SURVEY DATA AND ANALYSIS

The survey was conducted via Internet to over 60 firms, which consisted of mix of contractors, architectural firms out of which 10 firms completed the survey.

Questionnaire was divided into six sections including information sheet for respondents, organization background, Lean principles, Building Information Modeling (BIM) application, Prefabrication and the Integration. Questionnaire contained total of 35 questions with few questions on a 10-point ranking scale and in addition to that participants were also asked to make comments that were significant in their knowledge but were not covered in the questionnaire.

3.1. Descriptive Statistics and Analysis of Survey

The following information includes the details for background information of the respondents:

1. Organization type

Participants were asked about their organization type to know the respondents' distribution. As seen is Figure: 3; The majority of the participants were contractors, six comprising of 60% of the total respondents. This reflects contractors' interest in the area of research much more than owner, architect or CM/PM.

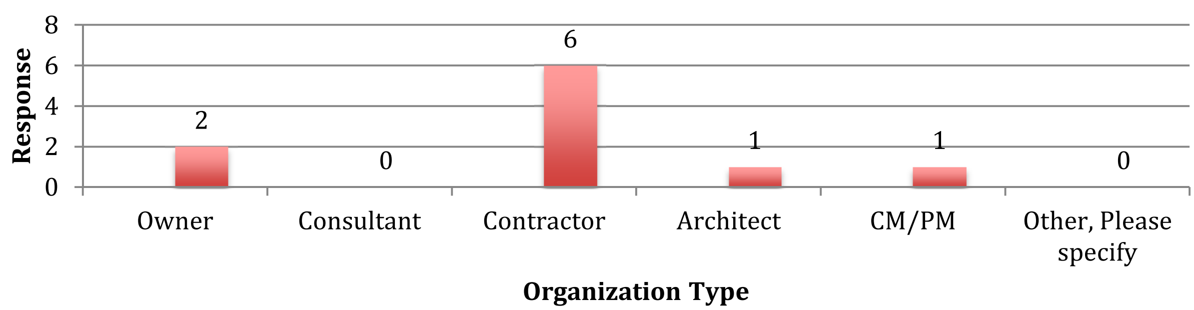

Figure 3. Organization Type

2. Annual Volume of work

Respondents were asked to answer the question open ended using Units of Million dollar. Responses ranged from 20 million dollars to 800 Million dollars with one respondent answering 7 Billion per year as a company combined. This range of volume of work helps us in learning the scale of work respondents would have managed.

3. Job Position types

As seen in Figure 4, eight of the total respondents were at the managerial position and rest of the two was entry level and technical staff each. This suggests that majority of responses would reflect concerns at the management level.

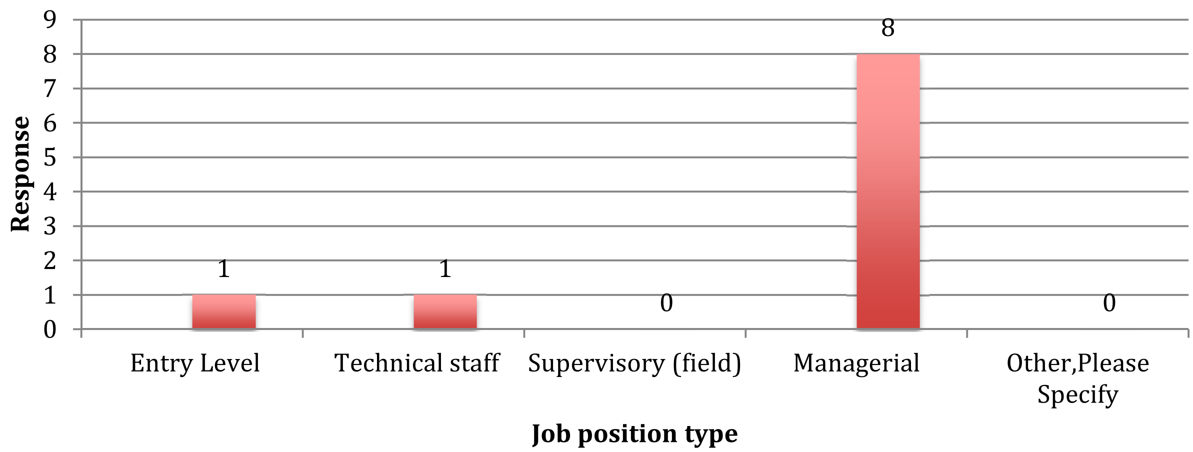

Figure 4. Job Position Type

4. Years of experience

As seen in figure 5, Five out of ten respondents had 16 or more years of experience followed by 11-15 years of experience and 3-5 years of experience both had two respondents each. Only one of the total respondents had 0-2year experience. Majority of the respondents were highly experienced in their field, which reflects the reliability of the responses.

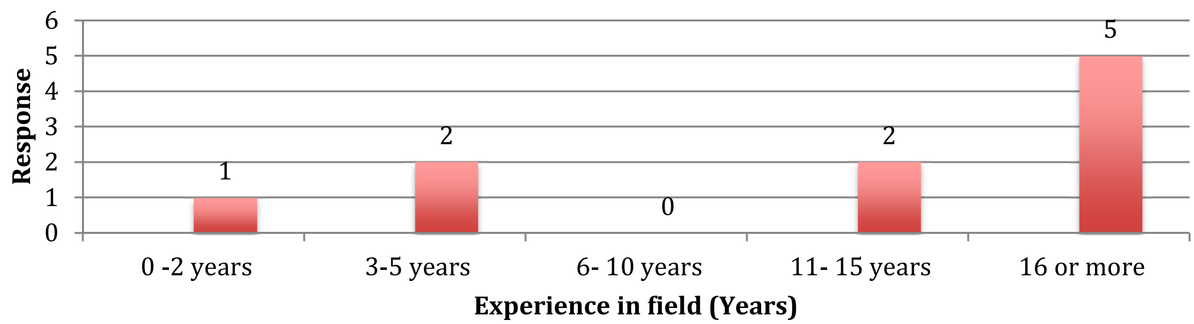

Figure 5. Years of Experience in Field

The following information includes the responses related to Lean Principles:

Participants were asked to answer either Yes or No about the use of Lean principles in their organization. Eight out of ten (80%) said yes they are using Lean within their organization and two of them said NO. Thus making the total number of respondents for the section eight.

1. Experience Level

As seen in figure 6, three of the respondents had 3-4 years of experience followed by 1-2 year and >5 year with each having two. Only one respondent had 2- 3 years of experience.

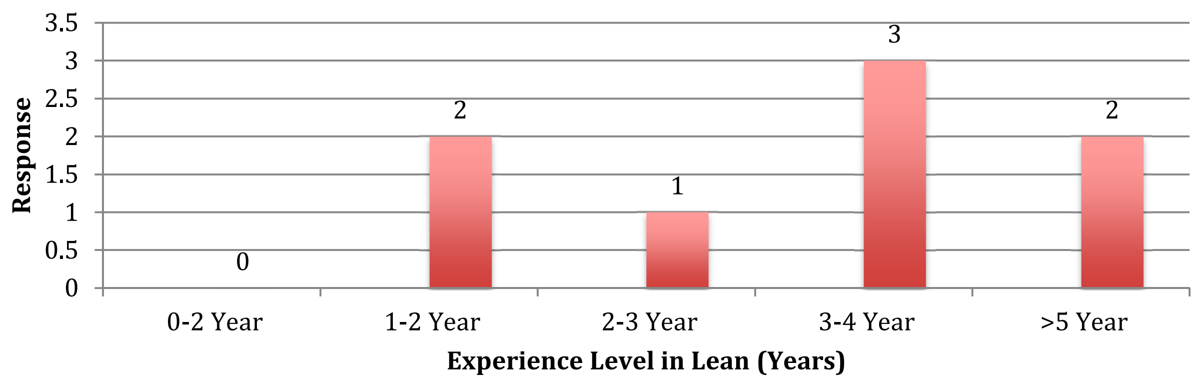

Figure 6. Years of Experience in Lean

2. Skill Level

As seen in figure 7, majority of the respondents, four out of eight, had moderate skill level in using lean principles. Three of them had advanced skill level and only one was a beginner. None of the respondents had lean skill at the expert levels.

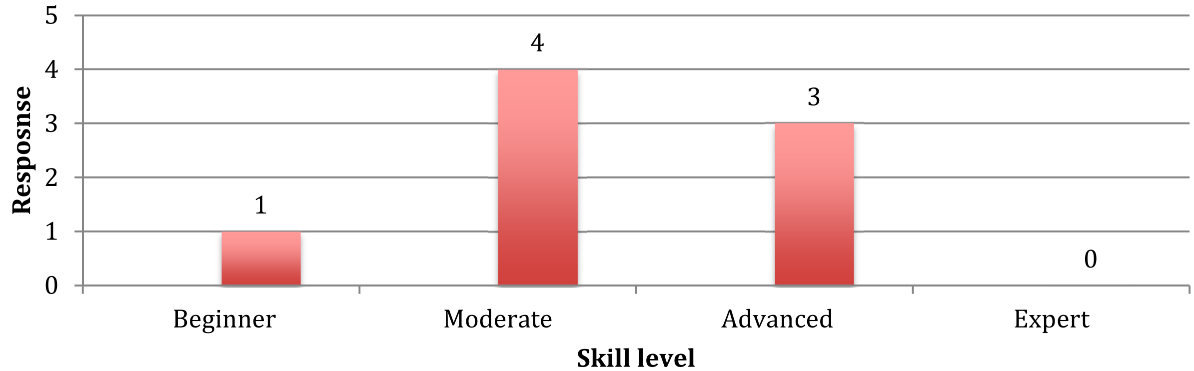

Figure 7. Skill Level in Lean

Bulk of the respondents have been using Lean for more than three years with moderate to advance level of skill, which tells their reasonable understanding of Lean concepts.

3. Reasons for using Lean

For this question participants were asked to answer based on a 10-point ranking scale 1 being the least and 10 the most important reason for using Lean within the organization. To understand the responses for all the ranking questions in the survey, following numerical measures were used:

- Measure of central tendency by calculating weighted mean value.
- Measure of Variability by calculating Standard deviation (SD) and Co- efficient of variation (CV)

As seen in Figure 8, for Improved co-ordination respondents replied with the value of 9, followed closely by Improved workflow and efficiency with both having mean values of 8.67. then Increased collaboration, better schedule performance, cost performance and lastly reduce waste was ranked.

"Mean values being the measure for central tendency provide only partial description of a quantitative data set. The description is incomplete without a measure of variability". (Mclave & Sincich, 2013). The standard deviation (SD) provides us with measure of variability and is calculated as $s = \sqrt{s^2}$ Where s^2 is the variance, for n measurements variance is equal to the sum of the squared deviations from the mean, divided by (n-1). SD provides us with distribution of responses, how far the individual responses vary or deviate from the mean value.

Coefficient Variance (CV) is also a measure of variability its higher value indicates higher variability in the responses. CV = SD/Mean

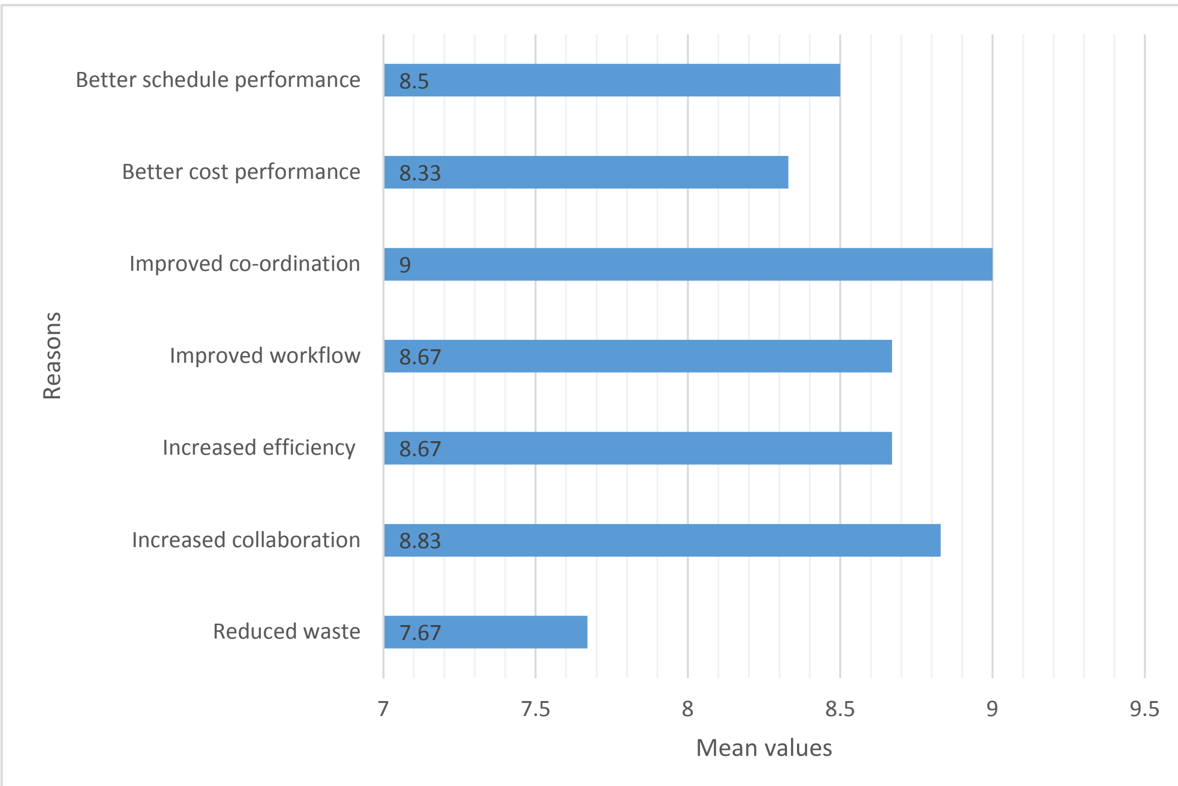

Figure 8. Reasons for Using Lean

Table 1

Numerical Measures For Lean

Reasons	Mean	St. Dev.	Estimated St. Error	Coefficient Variance (CV)
Reduced waste	7.67	2.07	0.846	0.27
Increased collaboration	8.83	2.4	0.98	0.28
Increased efficiency	8.67	1.97	0.805	0.23
Improved workflow	8.67	1.97	0.805	0.23
Improved co-ordination	9	2	0.817	0.23
Better cost performance	8.33	1.97	0.805	0.24
Better schedule performance	8.5	1.97	0.805	0.24

Considering not just mean but also SD, CV and estimated std. error, we can infer that improved coordination and workflow, and increased efficiency are the primary reasons for using Lean principles. The results help in comprehending that improvement of these factors will be most favorable for Lean environment.

4. Lean tools used

Respondents were asked to select from the various Lean tools stated and they could select any number of tools they were using. As seen in Figure 9, Last planner system was selected by most of the respondents – seven. Value stream mapping, 5S and Just-In-Time (JIT) all three were used by four of the respondents. One of the respondents mentioned other tool, Target Value Design that was not listed.

Respondent's answers indicate Last Planner system as the most adopted lean tools by construction organizations. In reflection upon these results, improving Last Planner System will be most beneficial for the users.

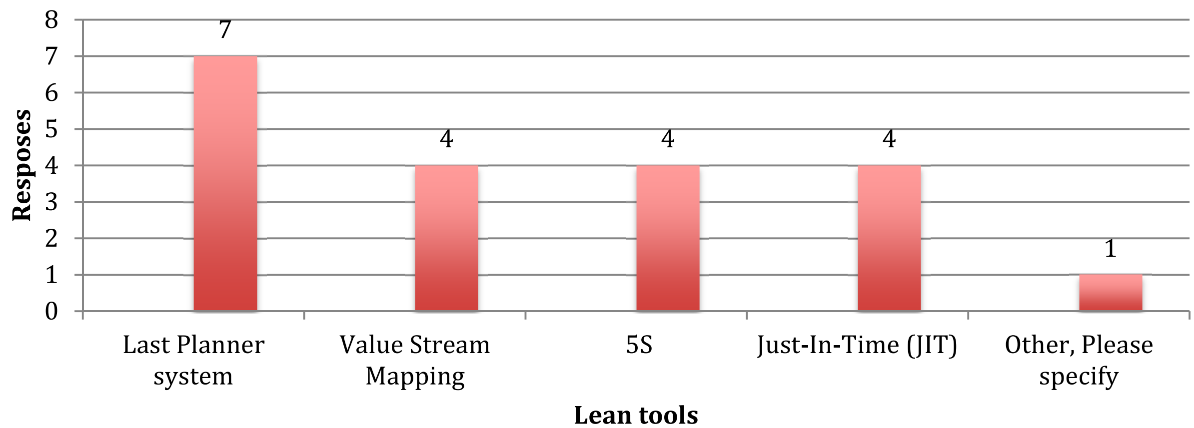

Figure 9. Lean Tools Used

5. Implementation of the tool

For this question participants were given the option to answer open ended. Various responses were:

- Use of multiparty contract to align risk/reward of major participants and then help them implement lean concepts successfully.
- Use of integrated Form of Agreement with shared risk/reward structure to optimize the whole not the part of the projects.
- Implementing lean tools project by project,

- Organization working at the project level in each of the district locations in the country, by supporting a specific project team first and then growing it organically from there.

The responses pointed out a vital characteristic, the need to find a structured way to use and promote Lean tools at both organization level and project level, and among the various participants.

The following information includes responses related BIM:

Participants were asked to answer either Yes or No about the use of BIM in their organization. Eight out of ten (80%) said yes they are using BIM within their organization and two of them said NO. Thus making the total number of respondents for the section eight.

1. Software used

Respondents were asked to select the BIM product/software being used by them. Three of them were using Autodesk Revit. As seen in figure 10, two respondents used Autodesk Navisworks followed by Google Sketch-Up, which was used by one of the 8 respondents. Two of the respondents mention other software not listed.

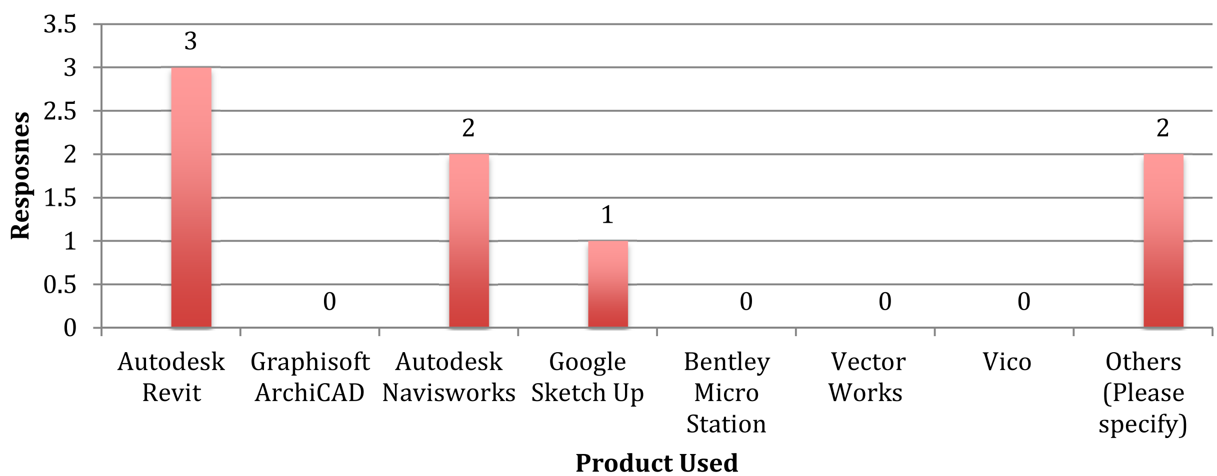

Figure 10. BIM Product Use

2. Experience Level

As seen in figure 11, Majority of the respondents, five out of eight had more than 5 years of experience using BIM while each of the other three respondents had 0-2 year, 1-2 year and 2-3 year of experience.

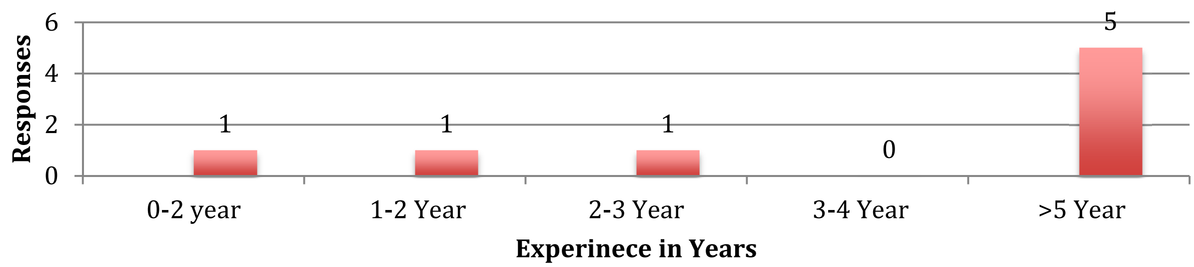

Figure 11. Years of Experience in BIM

3. Skill Level

As seen in Figure 12, three of the respondents are Beginners, two of them moderate and two of them advanced and only of the respondents was at the expert skill level for the use of BIM.

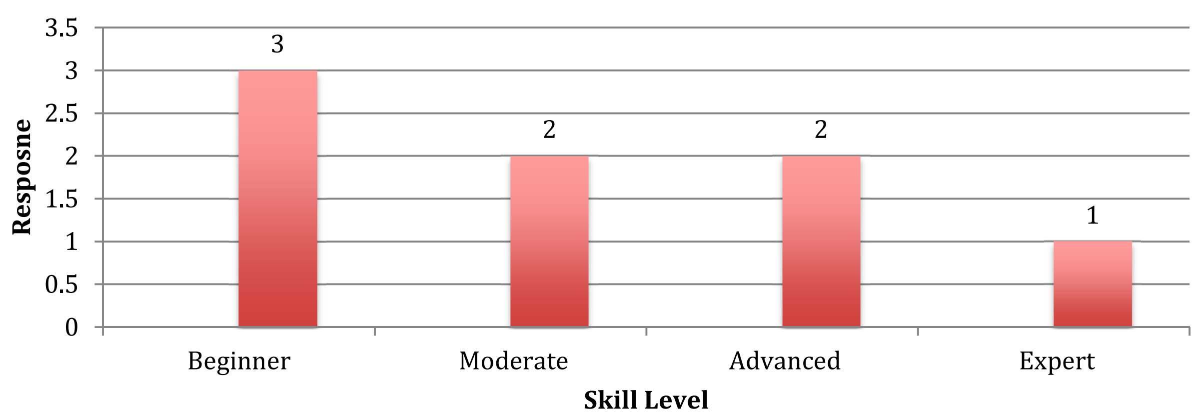

Figure 12. Skill Level in BIM

The experience level suggested that respondents have been suing BIM for a reasonable amount of time with a moderate level of skills. This tells that respondents understood the practical benefits and challenges related to BIM use.

4. Percentage of projects on which organization is using BIM

As seen in figure 13, majority of the respondents, four used BIM on the projects moderately (15% to 30%) within their organization. Two out of total respondents used BIM lightly and one each for heavy use (31% to 60%) and very strong (> 60 %).

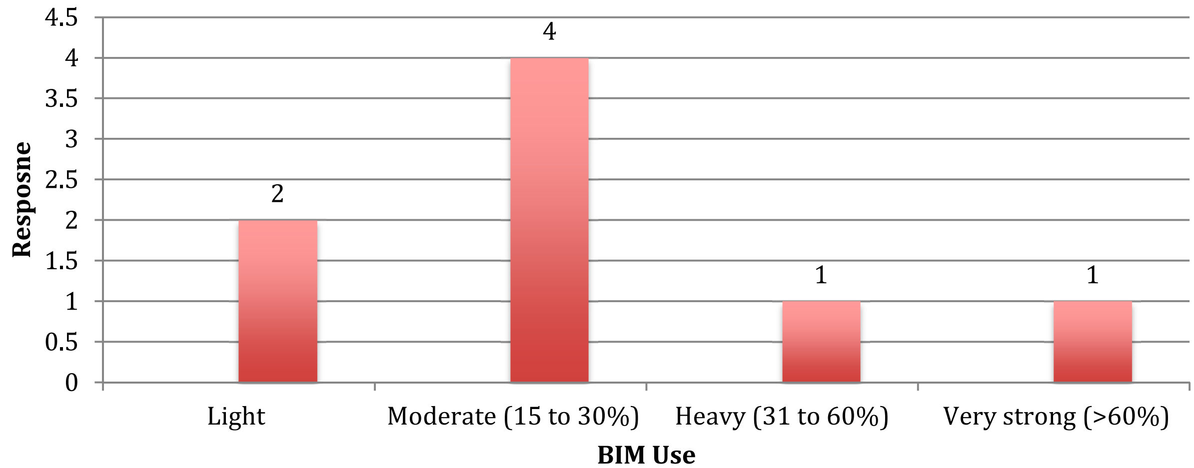

Figure 13. Percentage of Projects with BIM Use

5. Reason for using BIM

For this question participants were asked to answer based on a 10-point ranking scale 1 being the least and 10 the most important reason for using BIM within the organization.

As seen figure 14, Faster MEP clash detection (Mean Value = 8.5, CV= .244) and increased collaboration (Mean value 8.17, CV = .224) were considered main reason for using BIM followed by increased productivity.

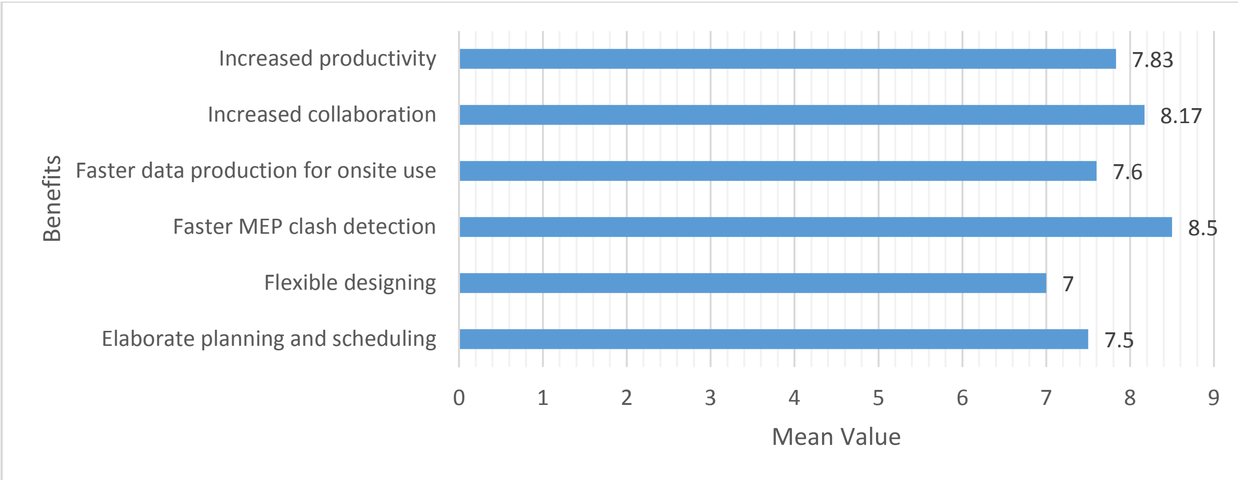

Figure 14. Reasons for Using BIM

Table 2

Numerical Measures For BIM

Reasons	Mean	St. Dev	St. Error	Coefficient Variance (CV)
Elaborate planning and scheduling	7.5	2.59	0.819	0.346
Flexible designing	7	2.53	0.8	0.362
Faster MEP clash detection	8.5	2.07	0.655	0.244
Faster data production for onsite use	7.6	2.3	0.728	0.303
Increased collaboration	8.17	1.83	0.579	0.224
Increased productivity	7.83	1.72	0.544	0.22

Understanding from literature review, need for collaboration and faster MEP clash detection is significant when using Lean's LPS as they are important in realizing a more robust workable backlog. MEP clash detection also plays significant role in prefabrication, as strong clash detection system will save both time and money, by preventing reworks at site while assembling prefab units with other building components.

This result is significant as it tells that if integrated BIM has the ability to improve both Lean's LPS and Prefabrication.

6. Phase of construction for BIM use

Respondents were able to check all the options that applied. As seen in figure 15, Planning and scheduling, and Construction phase of the project is when most of the respondents used BIM followed by design phase with 6 of the respondents using it. Only one of the respondent used BIM post construction.

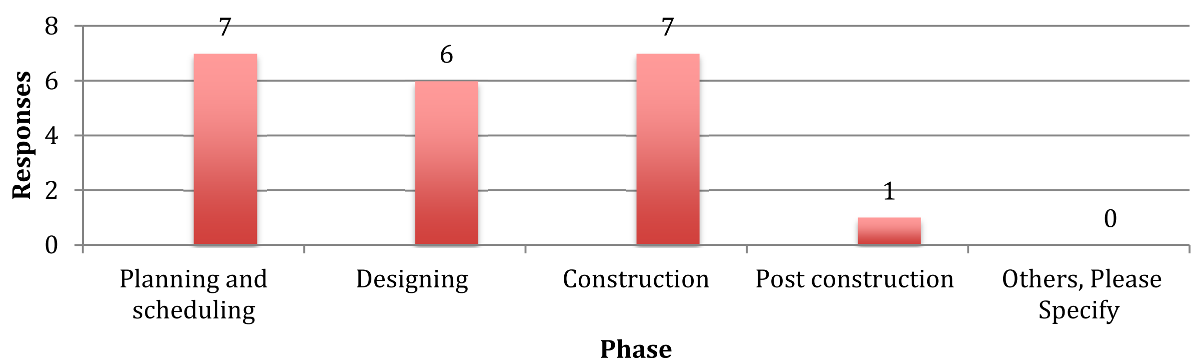

Figure 15. Project Phase for BIM Use

The importance of this question was to understand whether the respondents were using BIM throughout the project cycle or not. The answers show that while most of them used for planning and construction phase, not much of them used BIM's potential in post construction phase. This tells us that while integrating attention should be paid throughout the project cycle.

7. Challenges while implementing BIM

As seen in figure 16, high initial investment and BIM not being used by every trade were among the main challenge faced while implementing BIM followed by high cost for training and resistance from employees. Only one respondent felt the interoperability issue is a challenge to implement BIM.

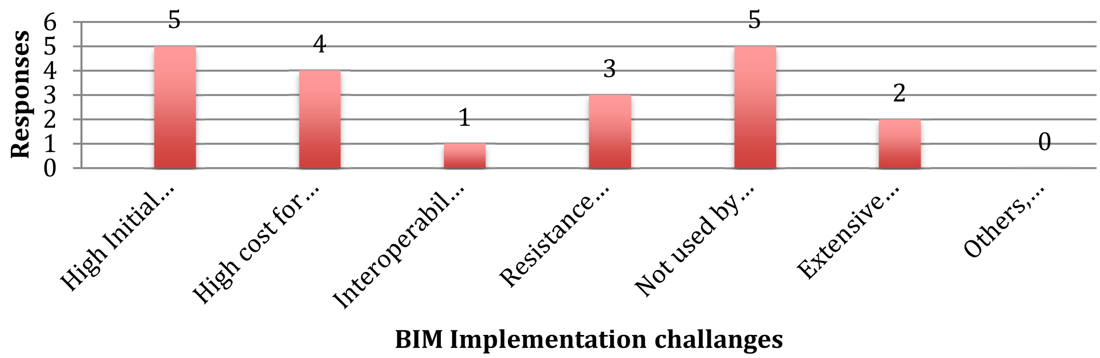

Figure 16. BIM Implementation Challenges

This information is important as it helps to understand that when attempting to integrate, the attention should be paid to offset these challenges as it would lead to more accepted integration.

The following information includes responses related to prefabrication:

Participants were asked to answer either Yes or No about the use of Prefabrication in their organization. Ten out of ten (100%) said yes they are using Prefabrication within their organization. Thus making the total number of respondents for the section ten.

1. Experience level

As seen in Figure 17, Majority of the respondents had more than 5 years of experience in performing prefabrication followed by 3-4year experience with two respondents and 0- 1 year and 1-2 year each with one respondent.

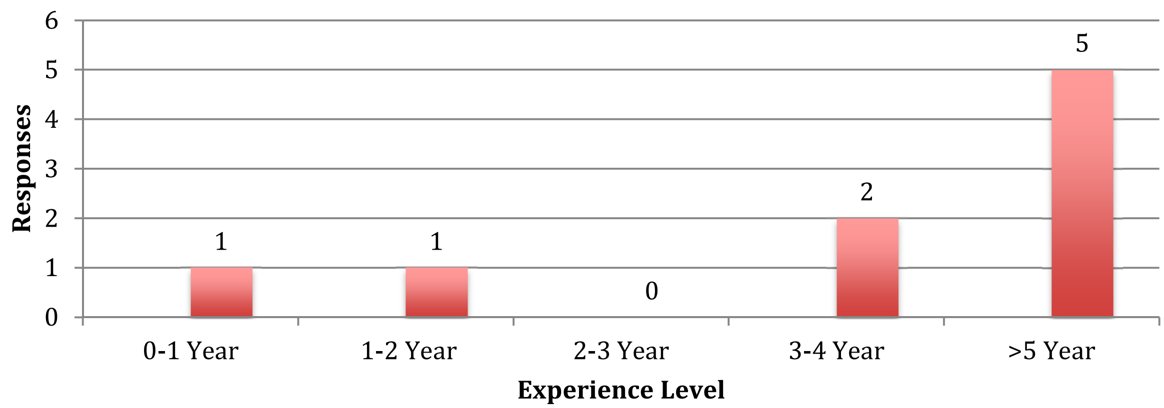

Figure 17. Experience Level in Prefabrication

2. Skill Level

Majority of the respondents i.e. four had moderate skill level for prefabrication. Three of them had advanced skill level and two of them had beginner skill level.

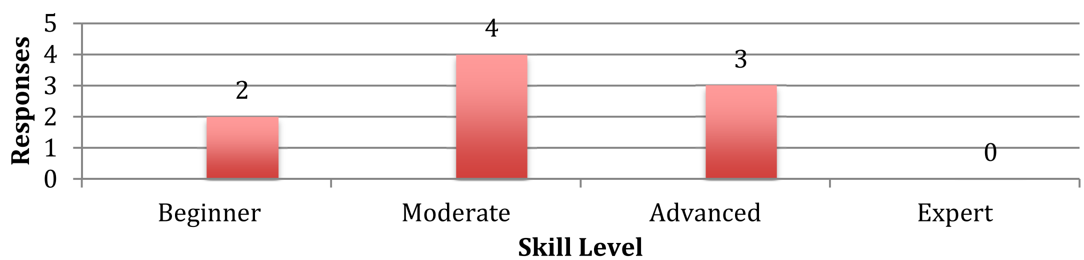

Figure 18. Skill Level for Prefabrication

The fact that respondents for this section had great experience (Figure 17) with moderate to advanced level of skill (Figure 18) and were using prefabrication for moderate percentage of projects (figure 19), provides the information that respondents understood the use of prefabrication decently to make practical suggestions.

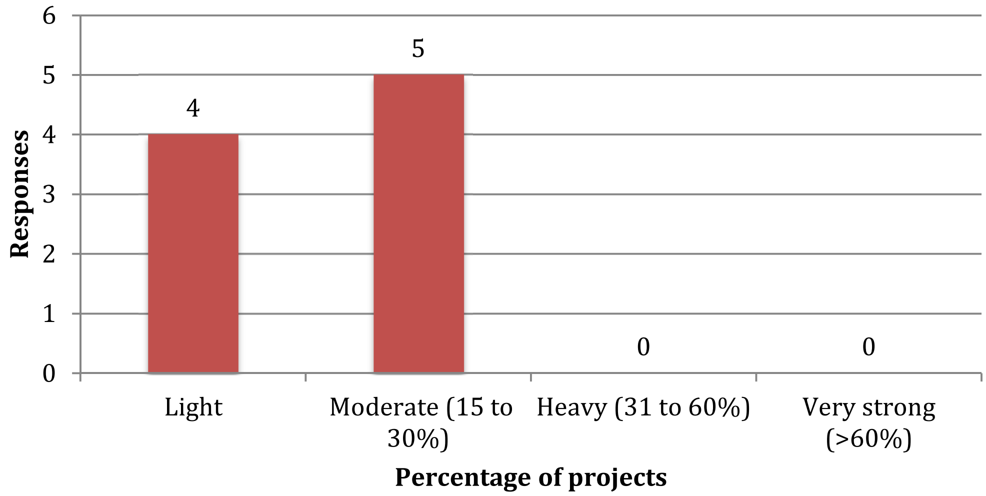

Figure 19. Percentage of Projects Using Prefabrication

3. Benefits of using Prefabrication

For this question participants were asked to answer based on a 10-point ranking scale 1 being the least and 10 the most important benefits of using prefabrication.

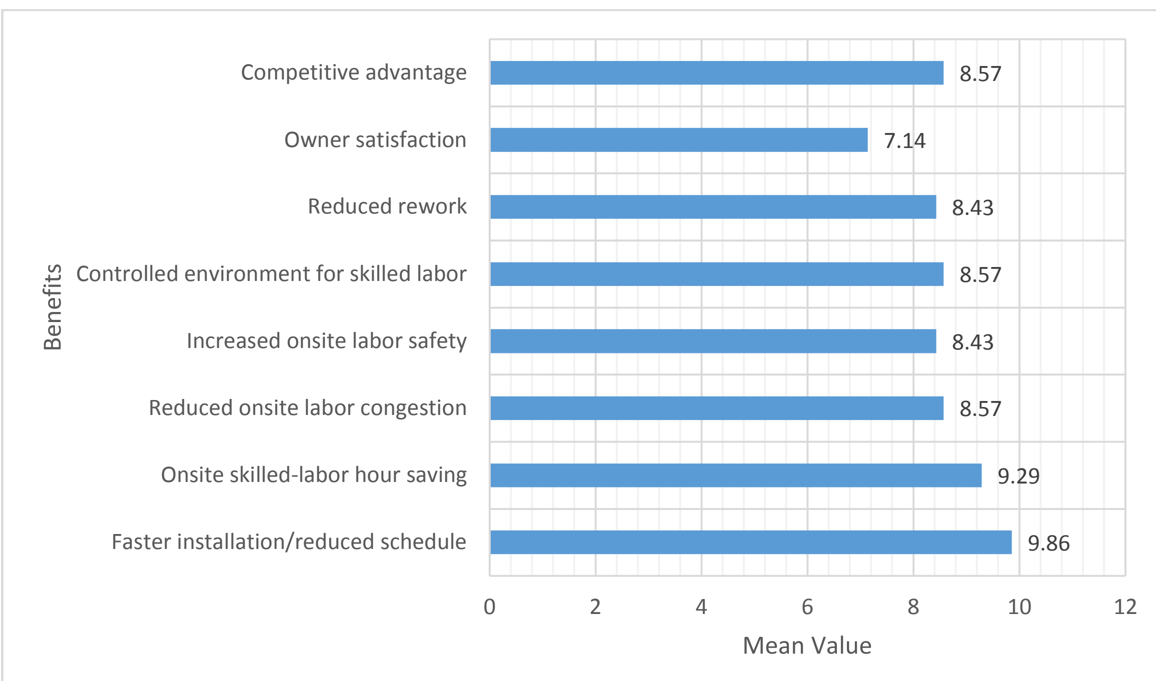

Figure 20. Benefits of Using Prefabrication

Table 3

Numerical Measure For Prefabrication

Benefits	Mean	St. Dev	St. Error	Coefficient Variance (CV)
Faster installation/reduced schedule	9.86	0.38	0.144	0.039
Onsite skilled-labor hour saving	9.29	1.11	0.42	0.12
Reduced onsite labor congestion	8.57	1.62	0.613	0.19
Increased onsite labor safety	8.43	1.27	0.48	0.151
Controlled environment for skilled labor	8.57	1.13	0.428	0.132
Reduced rework	8.43	1.81	0.685	0.215
Owner satisfaction	7.14	1.68	0.635	0.236
Competitive advantage	8.57	1.62	0.613	0.19

As seen in figure 20, faster installation/reduced schedule had the mean value of 9.86 with least of SD .38 and CV 0.039 making it the most significant benefit of using prefabrication, followed by onsite skilled-labor hour saving with mean value of 9.29, reduced onsite labor congestion, competitive advantage reduced rework and controlled environment for labor.

Respondents believed that faster installation resulting in reduced schedule i.e. production of building in a faster and controlled environment was the major benefits of prefabrication provides the information that it can be fairly integrated with other production control system used in construction.

4. Challenges faced during Prefabrication

As seen in figure 21, most the respondents felt that need for more collaboration is the main challenge faced during prefabrication, followed by higher initial cost and need for more skilled trades.

It can be understood that there is a need to bring together a system that would enable organizations to be more collaborative into their prefabrication process.

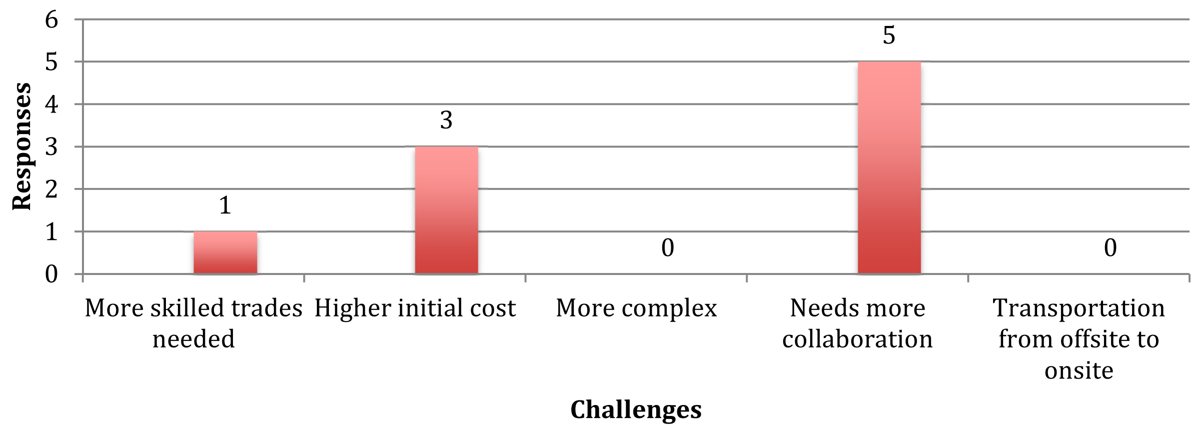

Figure 21. Challenges Faced During Prefabrication

The following information includes responses related to Integration:

Participants were asked to answer either Yes or No about the use of Integration in their organization. Nine of the respondents answered to this section. Out of which 5 of them said yes, thus the total number of respondents for this section is 5.

1. Project Phase in which BIM is used to prefabricate

As seen in figure 22, most of the respondents used BIM to prefabricate in pre-construction phase and design phase. None of them used in construction phase.

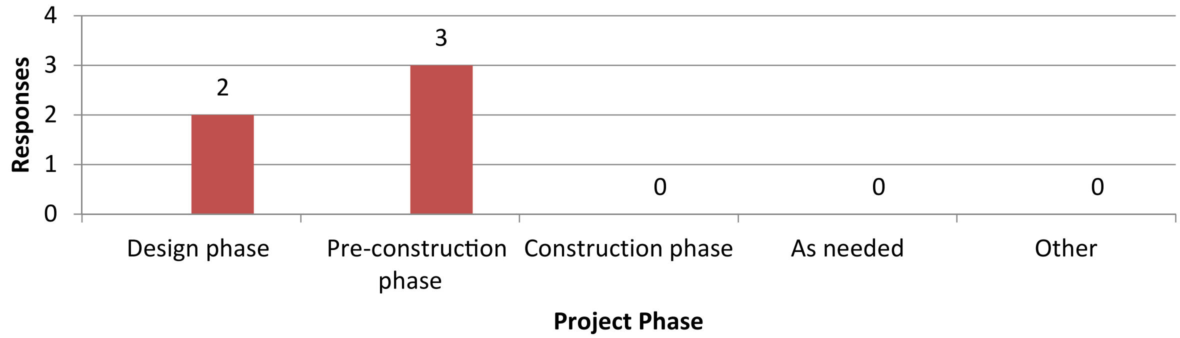

Figure 22. Project Phase in which Integrated

2. Benefits of integrating BIM with prefabrication

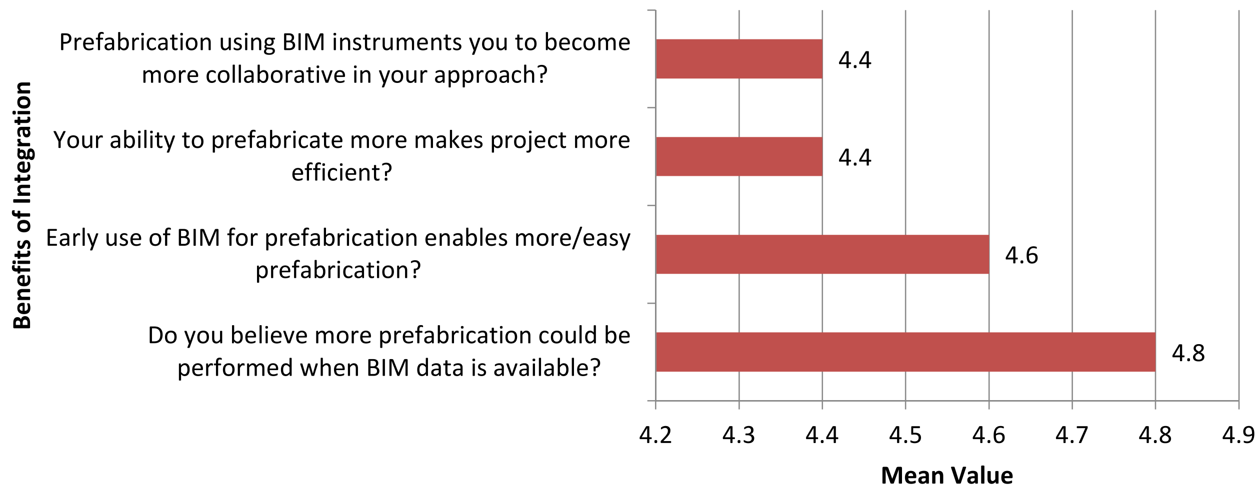

Figure 23. Benefits of Integrating BIM with Prefabrication

For this question respondents were asked to answer on a 5-point scale ranging from strongly agree to strongly disagree. The main purpose of asking respondents this question was to gather whether integrating BIM and Prefabrication resulted in being lean even when they are not following consciously and if so, then possibly using a lean tool specific to construction will generate a structured integration.

Respondents felt that using prefabrication and BIM makes them more collaborative and efficient, which is the core to the lean concept.

As seen in figure 23, for "Do you believe more prefabrication could be performed when BIM data is available? Respondents replied with mean value of 4.8, next is "early use of BIM for prefabrication enables more/ easy prefabrication respondent replied with mean value of 4.6, followed by "your ability to prefabricate more makes project more efficient" and prefabrication using BIM instruments you to become more collaborative in your approach" with mean value of 4.4.

3.2. Analysis and Significant Findings from the Survey

The analysis was done by using the scores assigned to each factor by the respondents and then the ranking, in terms of their criticality as perceived by the respondents, was done by use of Relative Importance Index (RII), which was computed using equation (1) (Somiah, 2015) (Aziz R. , 2013) (Enshassi, 2009) and the results of the analysis are presented in Table 4 to Table 6. RII was used for the analysis because it best fits the purpose of this study.

$$RII = \sum W \;/\; (A * N)$$

Where:

W – is the weight given to each factor by the respondents and ranges from 1 to 10,

A – is the highest weight (i.e. 10 in this case) and; N – is the total number of respondents.

Table 4

Relative Importance Index For Lean Factors

Lean factors	RII	Rank
Reduced waste	0.8125	6
Increased collaboration	0.9	2
Increased efficiency	0.8625	4
Improved workflow	0.8625	4
Improved co-ordination	0.925	1
Better cost performance	0.8125	6
Better schedule performance	0.875	3

For the lean factors, the respondents perceived that among all the mentioned factors, improved coordination is the most important reason for using Lean concepts in the work with RII of 0.925 followed by increased collaboration with RII of 0.9 and then better schedule performance with RII of 0.875.

Table 5

Relative Importance Index For BIM Factors

BIM factors	RII	Rank
Elaborate planning and scheduling	0.7875	5
Flexible designing	0.7125	6
Faster MEP clash detection	0.85	2
Faster data production for onsite use	0.8	4
Increased collaboration	0.8625	1
Increased productivity	0.8125	3

Among the various BIM factors, respondents believed that increased collaboration is the most important reason for the using BIM applications with RII of .8625 followed by faster MEP clash detection with RII of .85.

Table 6

Relative Importance Index For Prefabrication Factors

Prefabrication factors	RII	Rank
Faster installation/reduced schedule	0.989	1
Onsite skilled-labor hour saving	0.9112	2
Reduced onsite labor congestion	0.8778	3
Increased onsite labor safety	0.8445	6
Controlled environment for skilled labor	0.8667	5
Reduced rework	0.8778	3
Owner satisfaction	0.7223	8
Competitive advantage	0.8334	7

For the use of prefabrication respondents considered faster installation/reduced schedule the major benefit of using prefabrication with RII of .989.

The following table 7 lists the key findings and the corresponding potential for integration of Lean, BIM and prefabrication from the analysis of the data collected.

Table 7

Key Findings

Findings	Potential for Integration
Key Findings for Lean Use	
Improved coordination and workflow, increased efficiency and increased collaboration were the primary reasons that the respondents were using Lean.	It is more useful to find ways to be more coordinated with smooth workflows in order to encourage the use of Lean.
Last Planner System is the most widely used tool by respondents.	It is appropriate to find ways to further improve/upgrade the tool.
Implementation of tool(s) Respondents used multiparty contract, integrated form of agreement to align risk/reward of major participants and to implement lean successfully. Starting at the project level with one team and then progressing.	There is a potential to find a systematized way to use lean/tools, which can be adopted by various trade participants throughout the project cycle not just for selected phases.
Key Findings for BIM	
Increased collaboration and faster MEP clash detection were perceived as two of the most important reasons to use BIM applications.	Clash detection is significant when developing reliable workflow; important consideration for both Lean and Prefabrication preventing costly rework. It suggests potential to integrate.
Most of the respondents used BIM for planning and construction phase, while not much of them used BIM's potential in post construction phase.	When integrating, attention should be paid to the use throughout the project cycle
Implementation High Initial investment and not used by every trade were considered the major implementation challenge for BIM.	

Table 7 *Key Findings (continued)*

Key Findings for Prefabrication	
Faster installation or reduced schedule is a major reason for using prefabrication.	Faster Installation equals increased efficiency, which is core to Lean.
Implementation More collaboration is the main challenge faced during prefabrication, followed by higher initial cost and need for more skilled trades.	Need for a system to be more collaborative, which is one of the main focus of Lean and major benefit of using BIM. It suggests potential to integrate.
Key Findings- Opinion on Integration	
Respondents ranked high for the ability to be more collaborative and efficient	Suggests preference for Lean environment, as these are the essential principles of Lean, whether or not pursuing Lean actively.

4. PROPOSED FRAMEWORK

A framework is proposed for integrating BIM and prefabrication using Lean's Last Planner System to recognize their combined potential, making the construction environment leaner. Lean's Last Planner system with Look-ahead detail (Ballard G. H., 2000) was used as the foundation for the framework.

The proposed framework for BIM integration with last planner System is explained with figure 24:

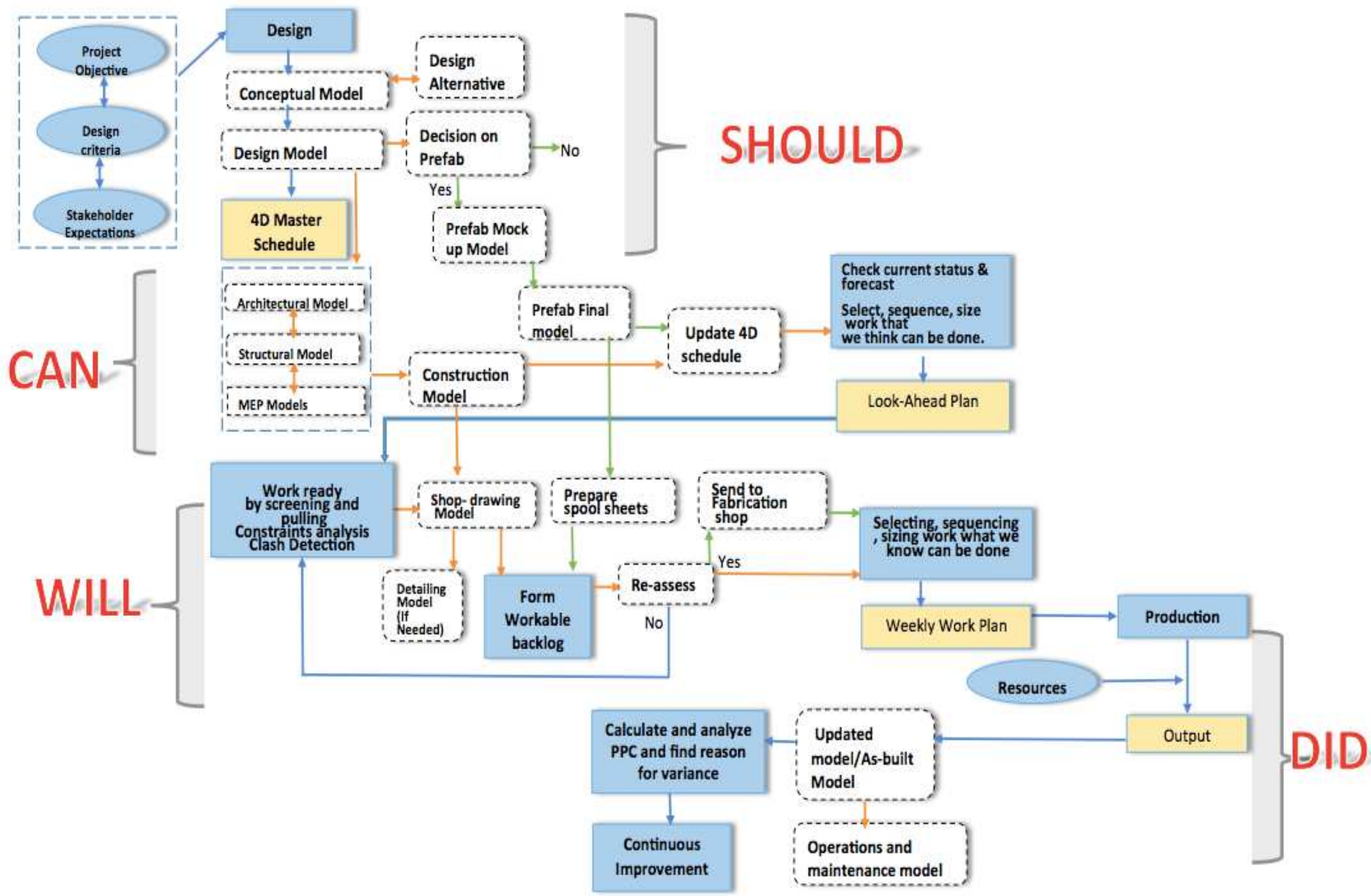

Figure 24. BIM Integration with Last Planner System

PHASE I: A Master schedule, which is a breakdown of activities in their logical sequence is prepared. It dictates the 'SHOULD' part of the system.

- Project objectives, stakeholder expectations and other related information is used as foundation for design.
- Work break down structure is set keeping in mind the lead times.

BIM Integration at Phase I: Conceptual/ schematic model for design development is used to visualize the design concept in 3D.

In the traditional LPS design development is done manually with help of 2D drawings, using 3D model will provide much more information and important visualization.

It will allow considering lead times, corresponding buffers and the constraints at the master plan level because it would be necessary to use this information to develop BIM model elements.

Purpose of the model at this phase of project cycle is conceptual development and Level of Detail (LOD) is low for two reasons as the information available is fundamental and other details like structure, MEP are not required at this phase.

Once the conceptual model is worked out, designers can now move up to the next level, which is design model. It contains detailed design elements of the project keeping in mind the budget and resources. Once the design model is set, the information contained in it provides the ability to make informed decision on prefabrication. If there are considerable components that can be prefabricated a mock up model for those components is made at this phase.

Advantages of BIM Integration at Phase I

- Designers can analyze and discuss among team members by visualizing various possible design alternatives.
- More informed breakdown of activities and eventually the master schedule.
- Design model serves as communication tool. MEP and structural consultants can use this model as foundation
- Easy and structured flow of information via models, which helps in making knowledgeable decisions at early stages.

By visualizing the project in computer simulations schedulers would better understand the logical sequences of activities, its constructability and will be able to breakdown the required work more effectively and formulate the Master schedule. By linking the design model with the schedule, made using tools like Microsoft project, a 4D master schedule is the output at phase I.

PHASE II: Look-ahead plan is prepared in which potential assignments for coming weeks are listed and it dictates the 'CAN' part of the system.

The look- ahead plans can have a varying range depending upon the project characteristics. (Ballard G. H., 2000) explains "The vehicle for the look ahead process is a schedule of potential assignments for the next 3 to 12 weeks. The range for the look-ahead process is decided based on project characteristics, the reliability of the planning system, and the lead times for acquiring information, materials, labor, and equipment".

BIM Integration at Phase II: Design model moves to the LOD of architectural model containing more detailed information of the elements of the projects. Mechanical, Engineering and Plumbing (MEP) and structural models are prepared using the detailed architectural model. Both Structural and MEP models will be developed either by a team of architects and trade contractors or solely by trade contractors as the level of detail in these models require expert knowledge. These models are prepared simultaneously and finally transition into construction model usually developed with the help of contractor and sub contractors.

Originally at this stage of LPS, current status of the resources is analyzed and forecasts are made for their future availability to help select, sequence and size the work. This is all done by gathering information manually.

By using BIM models, potential future assignments could be selected in more efficient sequence and size, accounting various constraints like resource requirement and lead times, which was otherwise done manually using 2D drawings.

Advantages of BIM Integration at Phase II:

- Detailed constructability analysis,
- Efficient sequence and sizing as all the required information is in one system- BIM models would develop simultaneously as changes required due to any structural or MEP requirements, budget/cost analysis, resource availability would automatically be reflected in architectural and construction model.
- Updated master schedule - Spontaneous flow of information from higher levels of planning (Look-ahead Plan) to lower level of planning (Master Schedule)

Prefabrication at Phase II:

With BIM models providing so much detail about sizing and sequencing at this phase, strict tolerances required for prefabrication can be managed and it is easier to make decisions like ‘What to prefabricate’, ‘When to prefabricate’ and ‘How to prefabricate’.

- Mock up model for prefabrication is used to discuss with various stakeholders and adjust design details accordingly. Once the architectural details are finalized, a final prefabrication model is generated.
- The prefab components can then be selected, sequenced and sized for them to be put on Look-ahead plan.

PHASE III: Weekly Work plan (WWP) which dictate the 'WILL' part of the system is developed.

- Work is made ready by using a pull system, which essentially is demand driven i.e. only activities called sound activities, which the last planner is willing to commit on doing and clear of constraints, are made ready to enter the Weekly Work Plan (WWP).
- The activities, which are not yet, ready to be executed but are clear of any constraints and clashes are kept in workable backlog.
- When activities are in the workable backlog waiting to be moved to WWP their soundness should be reassessed repeatedly as the preconditions to determine the soundness might have changed since then and the previously sound activity might not be a workable now.

BIM Integration at Phase III: Shop drawings are generated using the BIM construction models, which are then used on site.

A detailing model as the name suggest, is used to visualize certain portion of the project with higher level of detailing. They can be built outside the BIM. It can also be used for analyzing prefabrication details.

Prefabrication at Phase III: Spool sheets are prepared and send to prefabrication shop only for those sound activities that are ready to move to workable backlog. This prevents the chances of unnecessary inventory of prefabricating components that are still away from installation at the site.

Advantages of BIM Integration at Phase III:

- Automated constraints analysis is possible using BIM models.
- Once the workable backlog is formed, it can be reassessed at the later time using the BIM models and if there is any change, those particular activities could go through constraint analysis again before moving back to workable backlog.

PHASE IV: This is the production phase which dictates the 'DID' part of the system.

Activities move from WWP into the production cycle and are performed with the required resources made available at the time only when they were actually needed.

Lean believes is continuous improvement, keeping this in mind LPS calculates Percent Plan Complete (PPC) after the production. PPC is number of planned activities completed divided by the total number of planned activities, expressed as a percentage." PPC becomes the standard against which control is exercised at the production unit level, being derivative from an extremely complex set of directives: project schedules, execution strategies, budget unit rates, etc." (Ballard G. H., 2000).

PPC helps in finding the variance between planned and actually completed. It's important to realize this variance and find its reason so that in future those mistakes can be avoided and the continuous improvement can be achieved.

BIM Integration at Phase IV: A properly updated BIM model becomes the As-built model, which can then be used more effectively for performance analysis. Proper protocol is necessary to update the model, as the project develops so as to get an accurate As-built model at the end of the project.

AIA as a part of its digital practice documents published document G202-2013 *Project Building Information Modeling Protocol in June 2013.* It can be customized to fit the user's specifications. (American Institute of Architects, 2013). It is important to assign the party(s), which is responsible for developing model before the start in order to prevent any liability issues later.

Prefabrication at Phase IV: Prefabricating units are delivered to the site only when they are required to be installed at the site and the final output is realized.

Advantages of BIM at Phase IV:

- The As-built model can be used as learning reference for future project, which helps in improving continually.
- Models can be used for post-production/construction phase of the project cycle in operations and maintenance of the project.

Coordination Meetings: Coordination meetings are highly recommended at every phase in Last Planner system for continuous improvement. Participants of the meeting should include but is not limited to:

- Designer(s)/Architect
  - BIM modeler(s)
  - Scheduler(s)
- Engineer
  - Structural consultants/their assigned representative
  - MEP consultants/their assigned representative

    - BIM modeler(s)
- General Contractor(s)
    - With sub-contractor(s)/representatives
- Specialty contractor (Prefabricators)
- Assigned Field supervisor
- Foreman (Last Planner)

All the participants of the meeting should make a commitment to attend all the planning/coordination meetings in the future as well.

Recommended Checklist

Each participant at the meeting should be prepared to provide the necessary information depending upon the phase of the project. Checklists provided below are not exhaustive, as it can vary depending upon the complexity and purpose of providing these is to put forward the idea.

Table 8

Checklist for Designer/Architect

Required Information	
Updated models	
Changes/expected changes	
Reason/causes for design changes	
Trade-contractors affected by the changes	
Clashes detected/responsible party for the model/when were they informed	
Expected change in resource requirement	
Other suggestions/concerns	

Table 9

Checklist for Engineer/consultants

Required Information	
Updated models	
Changes/Expected changes	
Reasons/causes for changes	
Trade-partners affected by the changes	
Clashes detected/responsible party for the model/when were they informed	
Expected change in resource requirement	
Other suggestions/concerns	

Table 10

Checklist for GC/Sub/Specialty

Required Information	
Construct-ability issues	
Resource requirement	
Current availability of resources	
Future requirements	
Other Suggestions/concerns	

Table 11

Checklist for Field Supervisor

Required Information	
Site constraints	
Current status of work	
Prerequisite for future work	
Other suggestions/concerns	

Table 12

Checklist for Foreman

Required Information	
Current status	
Resource requirements for next assignment	
Other suggestions/concerns	

5. FOLLOW-UP SURVEY FOR PROPOSED FRAMEWORK

A follow-up questionnaire was developed with the purpose of attaining outlook of the proposed framework and valuable suggestions for future study. It was performed by sending out the survey to same set of respondents as in the preceding survey.

The questionnaire consisted of questions, which were divided corresponding to each phase of the proposed framework, related information along with the graphics. Respondents were asked to rate the on the scale of 1 to 5 with 1 being least beneficial and 5 being the most beneficial for BIM integrated Lean environment. Respondents were also asked to make any valuable comments that were otherwise not covered.

In addition to the follow-up questionnaire, a brief summary report was prepared that consisted of information about the study, the key findings from the preceding survey and the proposed framework. This summary report was also sent along the follow-up questionnaire so as to provide the respondents with adequate information.

The survey was conducted via Internet and total of three responses were received. Due to the incompleteness of the responses only two responses could be used. In order to have additional feedback for the proposed framework, author also contacted additional respondents via phone but unable to find any responses.

5.1. Findings From Follow-up Survey

Background Information: The three respondents worked on managerial positions and the organization types consisted of owner, contractor and one that worked both as general contractor as well as construction manager. They had experience ranging from 11- 16 years. This was important because, the background situate the responses within context.

Phase I: Respondents were asked to rate the attributes of Phase I of the proposed framework on the scale of 1 to 5 with 1 being the least beneficial and 5 being the most beneficial.

Table 13

Proposed Framework Phase I Feedback

Question	1	2	3	4	5	Total
Design development using BIM models	0	1	0	0	1	2
Visualization of design	0	0	0	1	1	2
Master Schedule linked with 3D design model	0	1	0	1	0	2
Early decision on prefabrication using design BIM model	0	0	0	1	1	2
Model used as communication tool (Information flow)	0	0	0	0	2	2

From Table 13 it is evident that respondents believed that in phase I of the proposed framework models are used as an effective communication tool and that early decision on prefabrication can be made.

Phase II: Respondents were asked to rate the attributes of Phase II of the proposed framework on the scale of 1 to 5 with 1 being the least beneficial and 5 being the most beneficial.

Table 14

Proposed Framework Phase II Feedback

Question	1	2	3	4	5	Total
Simultaneous development of architectural, MEP, structural models	0	0	0	2	0	2
Efficient sequencing of work assignments using construction BIM models	0	0	0	1	1	2
Forecasting the need for resources using BIM models	0	1	0	1	0	2
Prefab mock up model to analyze prefab components discretely	0	0	1	1	0	2
Spontaneous flow of information	0	0	0	0	2	2

From Table 14 it is evident that respondents believed in phase II of the proposed framework provided spontaneous flow of information among the phases and that it was possible to make efficient sequencing of work assignments.

Phase III: Respondents were asked to rate the attributes of Phase III.

Table 15

Proposed Framework Phase III Feedback

Question	1	2	3	4	5	Total
Automated constraint analysis using BIM models	0	0	2	0	0	2
2D Shop-drawings generation using 3D BIM models	0	0	0	2	0	2
Formation of workable backlog using BIM models	0	0	0	1	1	2
Reassessment of workable backlog	0	0	0	2	0	2
Generation of Spool sheets for prefabrication using BIM models	0	0	0	0	2	2

Table 15 provides us the information regarding Phase III. Respondents gave higher rating to most attributes like generation of spool sheets, formation and reassessment of workable backlog in the proposed framework.

Phase IV: Respondents were asked to rate the attributes of Phase III.

Table 16

Proposed Framework Phase IV Feedback

Question	1	2	3	4	5	Total
Updated BIM model/As-built model	0	0	1	0	0	1
Post construction use of BIM model	0	0	1	0	0	1
Detailed performance analysis using BIM model	0	0	1	0	0	1
Continuous Improvement using BIM model as reference	0	0	0	2	0	1

Respondents gave higher rating to the attribute that continuous improvement can be done suing BIM model as a reference in the phase IV of the proposed framework.

Respondents were asked to rate the influence of proposed framework in the Lean environment. (Table 17) to which the responses yielded lower ratings.

Table 17

Feedback for Lean Environment

Question	1	2	3	4	5	Total
Beneficial in improving traditional Last Planner System	1	0	1	0	0	2
Beneficial in improving overall Lean Principle environment		0	2	0	0	2

The respondents were subsequently asked to mention the reasons open ended. Though the attributes of the framework yielded optimal ratings but the influence in over all Lean environment received lower ratings, one of the respondents believed that the communication of the framework to the team is challenging.

6. CONCLUSION

Integration of Lean's Last Planner System with BIM and prefabrication, by using it as means to use and coordinate progressive BIM models, has a potential to create an efficient production control and planning system. The objective of the research was to propose a framework to integrate Lean, Building Information Modeling and Prefabrication, with potential to result in a Leaner environment, which was done by studying the current use of all the three Lean, Building Information Modeling and prefabrication and their possibility to integrate and by performing online survey.

The purpose of the survey was to find out the key benefits and implementation challenges, lean tool(s) used most widely and the prospective of integrating them to further enhance Lean environment. The results provided information that Lean's LPS is the most widely used Lean construction tool. It needed more reliability in workflows with ability to exchange information automatically not manually, automate clash detection and improve performance reporting.

Survey results also suggested that increased collaboration and faster MEP clash detection are the main reasons for using BIM, Prefabrication's ability to faster installation resulting in reduced schedule is considered its major benefit. These are very significant advantages for improving LPS when making reliable Look-ahead plans and feasible workable backlogs as well as for quality prefabrication. All these factors were the motivation while proposing a framework for integration.

The proposed framework is divided into four phases corresponding to hierarchal levels of work plans of LPS. BIM models with appropriate Level of Detail (LoD) are integrated at each phase, starting from conceptual model to design and MEP models to shop drawings and finally

As-built model, providing visualization to the flow and work plans. Prefabrication encouraged a pull system, Lean's core principle, with the need for tighter tolerances and structured schedules. Prefabrication also benefitted from improved clash detection.

The follow-up survey provided vital feedback regarding the attributes of the various phases of the proposed framework. The corresponding attributes of each phase of the proposed BIM integrated LPS framework does have encouraging improvement in work flows, visualization, information communication and performance reporting but the framework needs further study in terms of communication as entire system to the project team.

6.1. Recommendations for Future Work

- Future work can be directed towards studying various ways to communicate the proposed framework among various teams in a particular project.
- Other lean tools apart from Last Planner System like 5s, First-run studies and Fail safe for quality can tested with BIM or prefabrication.
- Future work can also be directed towards using BIM driven prefabrication in lean environment for one particular type of building like hospitals, housing etc., preferably buildings which have repetitive building components.
- The proposed framework could be studied keeping in mind a particular type of construction contract/ agreement, to analyze if contract clauses make any significant difference in the outcome of using the framework.

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APPENDIX A. LEAN AND BIM INTERACTIONS

Principal area	Principle	Column key
Flow process	**Reduce variability**	
	Get quality right the first time (reduce product variability)	A
	Focus on improving upstream flow variability (reduce production variability)	B
	Reduce cycle times	
	Reduce production cycle durations	C
	Reduce inventory	D
	Reduce batch sizes (strive for single piece flow)	E
	Increase flexibility	
	Reduce changeover times	F
	Use multiskilled teams	G
	Select an appropriate production control approach	
	Use pull systems	H
	Level the production	I
	Standardize	J
	Institute continuous improvement	K
	Use visual management	
	Visualize production methods	L
	Visualize production process	M
	Design the production system for flow and value	
	Simplify	N
	Use parallel processing	O
	Use only reliable technology	P
	Ensure the capability of the production system	Q
Value generation process	**Ensure comprehensive requirement capture**	R
	Focus on concept selection	S
	Ensure requirement flow down	T
	Verify and validate	U
Problem solving	**Go and see for yourself**	V
	Decide by consensus, consider all options	W
Developing partners	**Cultivate an extended network of partners**	X

Figure A1. Lean Principles

Source - (Dave, Koskela, Kiviniemi, Tzortzopoulos, & Owen, 2013)

Stage	Functional area and function	Row key
Design	**Visualization of form**	
	Aesthetic and functional evaluation	1
	Rapid generation of multiple design alternatives	2
	Reuse of model data for predictive analyses	
	Predictive analysis of performance	3
	Automated cost estimation	4
	Evaluation of conformance to program/client value	5
	Maintenance of information and design model integrity	
	Single information source	6
	Automated clash checking	7
	Automated generation of drawings and documents	8
Design and fabrication detailing	**Collaboration in design and construction**	
	Multiuser editing of a single discipline model	9
	Multiuser viewing of merged or separate multidiscipline models	10
Preconstruction and construction	**Rapid generation and evaluation of construction plan alternatives**	
	Automated generation of construction tasks	11
	Construction process simulation	12
	4D visualization of construction schedules	13
	Online/electronic object-based communication	
	Visualizations of process status	14
	Online communication of product and process information	15
	Computer-controlled fabrication	16
	Integration with project partner (supply chain) databases	17
	Provision of context for status data collection on site/off site	18

Figure A2. BIM Functionalities

Source (Dave, Koskela, Kiviniemi, Tzortzopoulos, & Owen, 2013)

		Lean principles																							
		Reduce variability		Reduce cycle times		Reduce batch sizes	Increase flexibility		Select an appropriate production control approach		Standardize	Institute continuous improvement	Use visual management		Design the production system for flow and value				Ensure comprehensive requirements capture	Focus on concept selection	Ensure requirements flow down	Verify and validate	Go and see for yourself	Decide by consensus consider all options	Cultivate an extended network of partners
BIM functionality		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
Visualization of form	**1**	1,2													3				4		11	5	6	4	
Rapid generation of design alternatives	**2**	1		22									7	7		8									
Reuse of model data for predictive analyses	**3**	9	9	22			51												1	16		5			
	4		10	12												8				16		5			
	5	1,2	1	12															1	1	1	5			
Maintenance of information and design model integrity	**6**	11	11																		11				
	7	12	12	22																		12			
Automated generation of drawings and documents	**8**	11		22	(52)	53											54	54							
Collaboration in design and construction	**9**			23						36						36									
	10	2,13		24				33											43		56	46		49	
Rapid generation and evaluation of multiple construction plan alternatives	**11**	14		25	(29)		31								(41)										
	12		15	25	(29)					37					(41)					44		47			
	13	2	40	25	(29)						17		40	40		40						47		49	
Online/ electronic object-based communication	**14**		29	26	30	30			34					34			(42)					47	48		
	15	18		26	30	30			34		38		38	34			(42)				45			49	
	16	19		27			32																		
	17		20	28					35								(42)								50
	18		21		30	30			34			39					(42)					47	48		

Figure A3. Interaction Matrix of Lean Principles and BIM Functionalities

Source (Dave, Koskela, Kiviniemi, Tzortzopoulos, & Owen, 2013) For detailed explanation of Interaction matrix please refer the source document

APPENDIX B. QUESTIONNAIRE

SECTION 1 – INFORMATION SHEET

Study Title: *"Practice of Building Information Modeling (BIM) and Prefabrication: A boost to Lean Principles environment"*

Researcher: Manisha Goyal

Email: Manisha.goyal@ndsu.edu

Program: Construction Management

Dept. University: Construction Management & Engineering Department / North Dakota State University (NDSU), Fargo.

Project Supervisor: Dr. Jerry Gao

Email: Jerry.Gao@ndsu.edu

Dear Participant,

You are being invited to take part in a study being conducted in the program of construction management at the North Dakota State University, Fargo, North Dakota. This survey is voluntary and anonymous*. The purpose of this study is to focus on Lean Construction and to investigate various tools/technological advancements like Building Information Modeling and Prefabrication, which encourage developing the environment favorable to Lean principles

Depending upon your responses, some questions may be skipped and the survey should take approximately 10-20 minutes to complete.

Thank you for participating in this survey and, your assistance is greatly appreciated.

*Frequently Asked Question and Answers for this survey:

Do I have to participate in this survey?

It is up to you to decide whether or not to take part and you are free to withdraw at any time. Your participation will help us provide valuable input to the study

Will the information provided in the survey be kept confidential?

All information collected for this study will be kept strictly confidential and full anonymity of participants will be ensured during the collection, storage and publication of research materials in accordance with North Dakota State University policies and procedures

What will happen to the results of the research study?

The results will be used in a graduate level M.S. Thesis and related publications.

Contact for Further Information

If you have any concerns about the way in which the study has been conducted or about research subjects' rights or to file a complaint regarding the research, you may contact the project supervisor or researcher (contact details above) or NDSU Human Research Protection Office, +1.701.231.8908, or ndsu.irb@ndsu.edu.

1. I have read this information sheet and wish to participate in this research. (Please note a negative response will end the survey)
    a. Yes. Please continue the survey on the next page (Part II).
    b. No. Please explain why? ____
    ____

SECTION 2: BACKGROUND

1. Please indicate your organization type?

a) Owner
b) Consultant
c) Contractor
d) Architect
e) CM/PM
f) Other, please specify _____________________________

2. What is the annual volume of work performed? Units – Million dollar
____

3. Please indicate the estimated percentage of total work in following categories?

a) Commercial - __
b) Residential - __
c) Institutional - __
d) Industrial- __
e) Heavy Construction __
f) Other, please specify _____________________________

4. Please indicate your job position type?

a) Entry Level
b) Technical staff
c) Supervisory (field)
d) Managerial
e) Other, Please Specify_______________________________

5. How many years of experience do you have in your field?

a) 0 -2 years
b) 3 – 5 years
c) 6 – 10 years
d) 11 – 15 years
e) 16 or more

SECTION 3: LEAN PRINCIPLES

6. Does your organization generally follow Lean Principles?

Yes
No

If yes, please continue and if No go to section 4 question 12

7. Please indicate your experience level with Lean?

a) <1 Year
b) > 1-2 Year
c) > 2-3 Year
d) > 3-4 Year
e) >5 Year

8. How will you best describe the skill level for the use of Lean?

a) Beginner
b) Moderate
c) Advanced
d) Expert

9. Please rank the reasons for using Lean within your organization?
(Scale on 1 to 10 where 1 – Least beneficial and 10 = Most beneficial)

	1	2	3	4	5	6	7	8	9	10
Reduced waste	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Increased collaboration	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Increased efficiency	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Improved workflow	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Improved co-ordination	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Better cost performance										
Better schedule performance										

10. Please specify the Lean tool(s) used? Check all that apply

f) Last Planner system
g) Value Stream Mapping
h) 5S
i) Just-In-Time (JIT)
j) Other, please specify

____

11. Please describe briefly how do you implement the above-mentioned tool in your organization?

____
____
____

SECTION 4: BIM APPLICATION

12. Do you use Building Information Modeling (BIM) for projects?

Yes_ Continue

No_ Go to section 5 question 20

13. Please specify the software (product used)?

a) Autodesk Revit
b) Graphisoft ArchiCAD
c) Autodesk Navisworks
d) Google Sketch Up
e) Bentley Micro Station
f) Vector Works
g) Vico
h) Others (Please specify)

14. Please indicate your experience level with BIM?

a) <1 Year
b) > 1-2 Year
c) > 2-3 Year
d) > 3-4 Year
e) >5 Year

15. How will you best describe the skill level for the use of BIM?

a) Beginner
b) Moderate
c) Advanced
d) Expert

16. Please indicate percentage of projects on which your organization is using BIM?

a) Light (<15%)
b) Moderate (15 to 30%)
c) Heavy (31 to 60%)
d) Very strong (>60%)

17. Please rank the reason for using BIM within your organization?
(Scale on 1 to 10 where 1 – Least beneficial and 10 = Most beneficial) make a table

Reasons	1	2	3	4	5	6	7	8	9	10
Elaborate planning and scheduling	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Flexible designing	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Faster MEP clash detection	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Faster data production for onsite use	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Increased collaboration	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Increased productivity	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

18. What phase(s) of construction BIM is used? Please check all that apply.

a) Planning and scheduling
b) Designing
c) Construction
d) Post construction
e) Others, Please Specify

____

19. Please specify the challenges you experience while implementing BIM? Check all that apply.

a) High Initial Investment
b) High cost for training
c) Interoperability issues
d) Resistance for employees
e) Not used by every trade
f) Extensive collaboration
g) Others, Please Specify

____

SECTION 5: PREFABRICATION

20. Do you use prefabrication in your organization?

Yes _ Continue

No _ Go to section 6 question 31

21. Please indicate your experience level with prefabrication?

a) <1 Year
b) > 1-2 Year
c) > 2-3 Year
d) > 3-4 Year
e) >5 Year

22. How will you best describe the skill level for the use of prefabrication?

a) Beginner
b) Moderate
c) Advanced
d) Expert

23. Please indicate percentage of project work accomplished by using prefabrication?

a) Light (<15%)
b) Moderate (15 to 30%)
c) Heavy (31 to 60%)
d) Very strong (>60%)

24. Please rank the benefits of prefabrication most important to project success?
(Scale on 1 to 10 where 1 – Least beneficial and 10 = Most beneficial)

Benefits	1	2	3	4	5	6	7	8	9	10
Faster installation/reduced schedule	☐ ☐	☐	☐	☐	☐	☐	☐	☐		☐
Onsite skilled-labor hour saving	☐ ☐	☐	☐	☐	☐	☐	☐	☐		☐
Reduced onsite labor congestion	☐ ☐	☐	☐	☐	☐	☐	☐	☐		☐
Increased onsite labor safety	☐ ☐	☐	☐	☐	☐	☐	☐	☐		☐
Controlled environment for skilled labor	☐ ☐	☐	☐	☐	☐	☐	☐	☐		☐
Reduced rework	☐ ☐	☐	☐	☐	☐	☐	☐	☐		☐
Owner satisfaction	☐ ☐	☐	☐	☐	☐	☐	☐	☐		☐
Competitive advantage	☐ ☐	☐	☐	☐	☐	☐	☐	☐		☐

25. Do you own your own prefabrication facilities?

a) In-house
b) Outsourced
c) Both

26. What phase of the project do you plan for prefabrication?

a) Design phase
b) Pre-construction phase
c) Construction phase
d) As needed
e) Other

27. How do you decide which components to prefabricate?

a) Pre-planning

b) Owner requested assemblies only
c) Availability of prefabrication facility
d) Other (Please specify) ________________________________

28. Please indicate the challenges faced during prefabrication?

a) More skilled trades needed
b) Higher initial cost
c) More complex
d) Needs more collaboration
e) Transportation from offsite to onsite

29. How often do you experience clash between prefab unit and other system/structures?

a) Never
b) Rarely
c) Occasionally
d) Regularly
e) Don't know

30. What are the causes for the clashes?

____
____
____

SECTION 6: INTEGRATION OF BIM AND PREFABRICATION

31. Do you use BIM data for prefabrication and/or installation?

Yes _Continue
No_ Go to question 35

32. How helpful is BIM to your ability to prefabricate?

a) Very helpful
b) Helpful
c) Little

33. During what phase of project is BIM used for prefabrication decisions?

a) Design phase
b) Pre-construction phase
c) Construction phase

d) As needed
e) Other

34. Please respond to the probable benefits of integrating BIM with Prefabrication.

	Benefits	Strongly agree	Agree	Uncertain	Disagree	Strongly disagree
1.	**Do you believe more prefabrication could be performed when BIM data is available?**	☐	☐	☐	☐	☐
2.	**Early use of BIM for prefabrication enables more/easy prefabrication?**	☐ ☐	☐ ☐	☐ ☐	☐ ☐	☐ ☐
3.	**Your ability to prefabricate more makes project more efficient?**	☐	☐	☐	☐	☐
4.	**Prefabrication using BIM instruments you to become more collaborative in your approach?**					

35. Your comments please:

____

____

____

APPENDIX C: FOLLOW-UP SURVEY QUESTIONNAIRE

Study Title: *"Integration of Building Information Modeling (BIM) and Prefabrication: A boost to Lean Principles environment"*

Researchers: Manisha Goyal, Dr. Jerry Gao (supervisor)
Email: Manisha.goyal@ndsu.edu ; Jerry.Gao@ndsu.edu
Dept. /University: Construction Management & Engineering Department / North Dakota State University (NDSU), Fargo.

Dear Participant,

You are invited to take part in a follow-up study being conducted in the program of construction management at the North Dakota State University, Fargo, North Dakota. This survey is seeking your comments on the proposed framework to integrate BIM and prefabrication with Last Planner System. The framework is developed using the previous survey results done by the same researchers and surveyee groups (you). As you might still remember, the previous study was focused on Lean Construction and to investigate various tools/technological advancements like Building Information Modeling and Prefabrication, which when integrated would encourage developing the environment favorable to Lean principles. The summary report for the proposed framework based on previous survey is provided along with this survey. This follow-up is just to perform an additional survey on the proposed framework. Of course this survey is also voluntary and anonymous*; however, depending upon your responses, the survey should take only approximately 10-20 minutes to complete, and your opinions are so valuable to the construction industry.

Thank you for participating in this survey. Your assistance is greatly appreciated.

*Frequently Asked Question and Answers for this survey:

Do I have to participate in this survey?
It is up to you to decide whether or not to take part and you are free to withdraw at any time. Your participation will help us provide valuable input to the study.

Will the information provided in the survey be kept confidential?
All information collected for this study will be kept strictly confidential and full anonymity of participants will be ensured during the collection, storage and publication of research materials in accordance with North Dakota State University policies and procedures.

What will happen to the results of the research study?
The results will be used in a graduate level M.S. Thesis and related publications.

Contact for Further Information
If you have any concerns about the way in which the study has been conducted or about research subjects' rights or to file a complaint regarding the research, you may contact the project supervisor or researcher (contact details above) or NDSU Human Research Protection Office, +1.701.231.8908, or ndsu.irb@ndsu.edu.

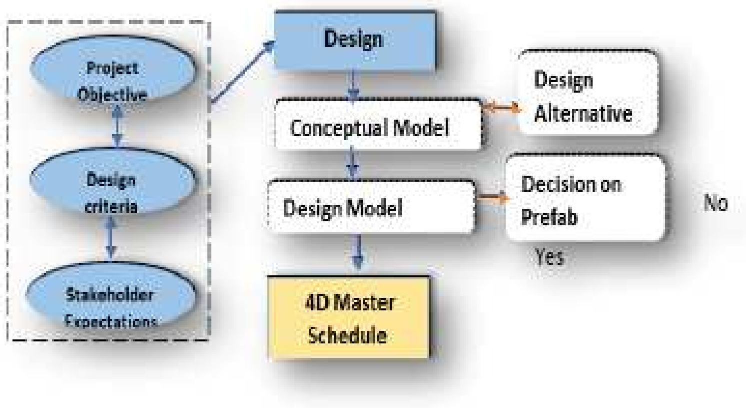
Background Information

Question 1. Please indicate your organization type?
a) Owner ___ b) Consultant ____c) Contractor____ d) Architect ___ e) CM/PM ___ f) Other, please specify ___________________________

Question 2. Please indicate your job position type?
a) Entry Level ___ b) Technical staff ___ c) Supervisory (field) ___ d) Managerial ___ e) Other, please Specify___________________________

Question 3. How many years of experience do you have in your field?
a) 0 -2 years ___ b) 3 – 5 years ___ c) 6 – 10 years d) 11 – 15 years ___ d) 16 or more___

Questions 4 through 10 are about the key features of the proposed framework. Please rate them on the scale of 1 to 5 with 1 being the least and 5 being the most beneficial for BIM integrated Lean environment.
Questions are divided corresponding to each phase; its related graphic and brief description is provided for your understanding.



Phase -I

Design is finalized keeping in mind the project objectives, design criteria and stakeholder's expectations and then a master schedule is prepared.

- To help finalize the design, BIM conceptual model is used to analyze design alternatives leading to final design model.
- When this 3D design model is linked with master schedule, a 4D master schedule is prepared.
- The information contained in these BIM models provides with the ability to make relatively early decision on prefabrication.

Benefits of Integration

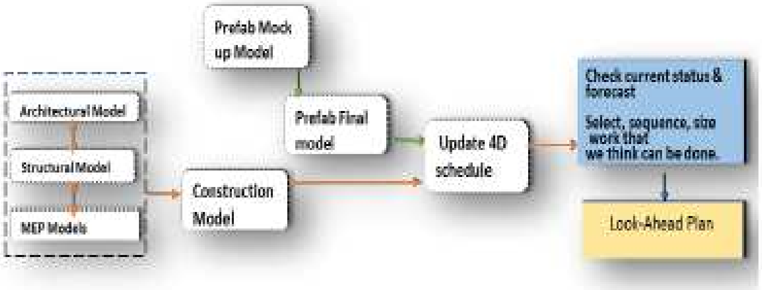
Integrating BIM at the master schedule level, which is the foundation for all the other levels of planning, allows considering lead times, corresponding buffers and realizing constraints at the early stages of planning. Information contained in BIM models help make knowledgeable decisions at early stages

Question 4.

Features	1	2	3	4	5
Design development using BIM models					
Visualization of design					
Master Schedule linked with 3D design model					
Early decision on prefabrication using design BIM model					
Model used as communication tool (Information flow)					

Question 5. Please mention any suggestions or comments about the proposed framework at phase I?

-



Phase - II

Look- ahead plan is prepared in which potential assignments for coming weeks are listed.

- Using the design model; Architectural, MEP and structural BIM models are prepared simultaneously at this phase, which leads to construction model.
- All these models develop simultaneously and the changes in one would be reflected in the others, creating spontaneous flow of information.
- Prefabrication mock up model is used to adjust the design details which leads to final prefab model.
- After this level of planning schedule is updated to reflect any changes.

<u>Benefits of Integration</u>

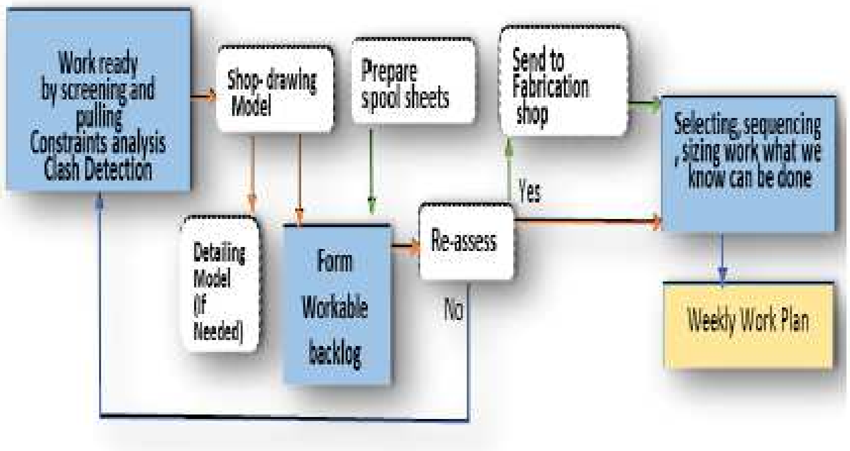
By using BIM models, potential future assignments could be selected in more efficient sequence and size, accounting various constraints like resource requirement and lead times, which was otherwise done manually using 2D drawings.

Question 6.

Features	1	2	3	4	5
Simultaneous development of architectural, MEP and structural models					
Efficient sequencing of work assignments using construction BIM models					
Forecasting the need for resources using BIM models					
Prefab mock up model to analyze prefab components discretely					
Spontaneous flow of information					

Question 7. Please mention any suggestions or concerns about the framework at phase II?

____



Question 8.

Features	1	2	3	4	5
Automated constraint analysis using BIM models					
2D Shop-drawings generation using 3D BIM models					
Formation of workable backlog using BIM models					
Reassessment of workable backlog					
Generation of Spool sheets for prefabrication using BIM models					

Question 9. Please mention any suggestions or concerns about the framework at phase III?

-

____

____

____

Phase - III

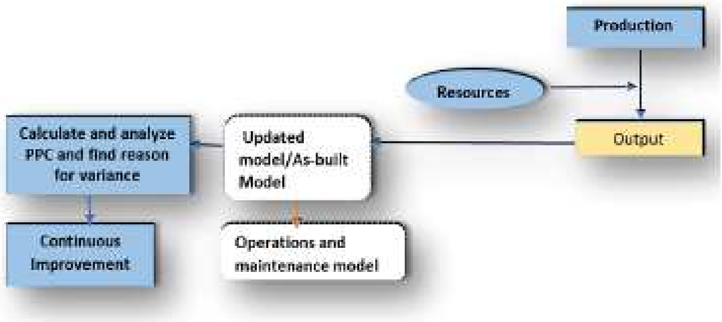
Weekly Work Plan is developed.

- All the constraints, which were accounted in phase II, are removed and a workable backlog of activities, free of any constraints is formed.
- Shop drawings are generated using the BIM construction model prepared at phase II, which are then used on-site.
- Spool sheets for prefabrication are generated from final prefab model and are then sent to fabrication shop, after reassessing the workable backlog.
- Last Planners commit to performing work by pulling activities into a Weekly Work Plan.

<u>Benefits of integration.</u>

Automated constraints analysis is possible using BIM models.

Once the workable backlog is formed, it can be reassessed at the later time using the BIM models and if there is any change, those particular activities could go through constraint analysis again before moving back to workable backlog.



Phase - IV

Work planned in the phase III moves into production and the output is realized using the required resources.

- At the end of the project, an accurately updated BIM model becomes the As-built model.

Benefits of Integration

The updated model could enable more effective performance analysis and also be used for post construction operations and maintenance activities.
The As-built BIM models can also be used as learning reference for future projects, which helps in improving continuously.

Question 10.

Features	1	2	3	4	5
Updated BIM model/As-built model					
Post construction use of BIM model					
Detailed performance analysis using BIM model					
Continuous Improvement using BIM model as reference					

Question 11. Please mention any suggestions or concerns about the framework at this phase?

-

For questions 9 -11, please rate on the scale of 1 to 5 with 1 being the least and 5 being the most.

Question 12. Please rate how helpful the proposed framework could be for the following?

	1	**2**	**3**	**4**	**5**
For developing more reliable work plans					
For performing faster constraint analysis					
For developing sound Workable Backlog					
To Last Planners (Last in the chain, e.g. Foremen) for making commitment to perform work					
In performance analysis (root- cause analysis, variance and PPC calculations)?					

Question 13. Please rate the likelihood for the use of proposed framework?

	1	2	3	4	5
Use of framework within your organization					
Recommend use of framework among trade partners					

Question 14. Please rate how beneficial the proposed framework could be for the following?

	1	2	3	4	5
Beneficial in improving traditional Last Planner System					
Beneficial in improving overall Lean Principle environment					

Question 15. Please mention any other comments you would like to suggest.