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Title: Interaction between Lean Construction and Construction Industrialization

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______________________________________________________

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Lean construction and construction industrialization have been the focus of the construction industry in recent decades. Lean construction has been shown to reduce waste and uncertainty, and construction industrialization has a positive effect on improving efficiency and safety. Research on lean construction shows that lean construction practices are recognized by researchers and businesses, and bring benefits to construction projects. However, there is limited evidence in the industry that lean construction has sufficient potential in the context of evolving processes and methodologies. This research explores the relationship between lean construction and construction industrialization, and whether they reinforce each other to provide added benefit. The research identifies and quantifies the value, waste, and impact factors of lean construction practices and construction industrialization methods through a literature review, survey, and interviews. The results of the literature review and online survey were used to assess 14 lean construction practices and four construction industrialization methods, along with their value and waste. Interviews were used to validate the results of the literature review and survey. The research incorporates the Plan-Do-Check-Act (PDCA) concept, applies it to construction, and classifies lean construction. Finally, an improved combined construction process was developed to optimize the shortcomings of their respective applications. The contribution of this research to knowledge is an attempt to combine the application of lean construction practices and construction industrialization methods for better performance by demonstrating six aspects associated with construction projects. Appropriate application of the combined methods can increase the value they bring relative to separate implementation. The research attempts to explore the performance of the combined methods using different measurement dimensions. In this study, value and waste goals, project success factors, and employee factors are discussed.

Interaction between Lean Construction and Construction Industrialization

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries.  My signature below authorizes release of my thesis to any reader upon request.

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Qichang Dai, Author

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# DEDICATION

My highest gratitude to my father Xiaolin Dai and my mother Li Liu for their infinite love and support.

# 1 INTRODUCTION

## 1.1 Background

The concepts of lean thinking and construction industrialization have initial beginnings within the architecture-engineering-construction (AEC) industry. Project cost, quality, schedule and safety have been the primary focus of the AEC industry. Lean Construction developed from lean thinking in the automotive industry and is gradually being applied to projects in the AEC industry (Pestana, 2016). Lean construction attempts to fundamentally change the production method. It requires enterprises to slowly change from traditional production to lean production (Pestana, 2016).

Construction industrialization, represented by prefabricated buildings, is also expected to make gains in the industry. One of the problems encountered in the implementation of construction industrialization is the high cost. Effective management is one of many ways to solve the high cost of industrialized construction. According to Zimina (2012), the cost of rework, repeated work, and misunderstanding of information during construction accounts for approximately 30% of the total cost. Hosseini (2012) pointed out that construction efficiency is negatively affected by internal waste factors. Construction industrialization aims to improve construction performance and reduce construction waste (Liu, 2020). Researchers provide more discussion on project duration, cost, quality, control, safety and workflow. Rüßmann (2015) pointed out that Industry 4.0, also known as the Fourth Industrial Revolution, means fundamental changes in manufacturing, management, economy and productivity. Lasi (2014) stated that the concept of Industry 4.0 includes autonomously controlled and digitalized smart factories, cyber-physical systems (CPS), decentralized self-organization, and personalized product and service development. It is still to be determined whether lean construction can bring added value to the development of construction industrialization value under Industry 4.0.

## 1.2 Terminology

This section provides a list of definitions for terms used in this research study. These terms originate from the Lean Enterprise Institute (2008).

**Value:** The inherent worth of a product is judged by the customer and reflected in its selling price and market demand. The added values proposed by Saraf (2013) are as follows:

1. Project duration
2. Cost
3. Safety
4. Efficiency
5. Engineering quality

**Waste:** Any activity that consumes resources but creates no value for the customer.

In the traditional definition, there are seven types of waste in engineering: overproduction, waiting, unnecessary transportation, over-processing, excess inventory, excess motion, and defects. Formoso (2011) identified "making-do" as the eighth type of waste in lean construction. Hosseini (2012) proposed that underutilized skills and talent should be included as waste in the construction field. Underutilized skills and talent is included as the eighth type of waste in the present research because it is typically associated with the construction industry. However, making-do is not included in the research because it is usually associated with the manufacturing industry. The wastes attributed to construction industrialization are the same as listed above. The definitions of waste introduced by Ray (2006) are as follows:

1. **Overproduction:** Making more products earlier or faster than is required by the next process step; a typical example is a work in process inventory
2. **Waiting:** Idle time created while waiting for items that are not immediately available, such as waiting for information, tools, or materials
3. **Transportation:** Moving work over short or long distances without adding value; a typical example is inefficient material flow within the plant or yard
4. **Over-Processing:** Work processes or materials that add no value to the product from the customer's viewpoint, such as extra rich design or batching chemical usage
5. **Inventory:** Inventory in excess of the minimum needs of the next transforming step, such as work in process waiting to move to the next step
6. **Motion:** Any movement of people or machines that are not value added; typical examples are checking, counting, and measuring
7. **Defects:** Products that do not meet customer specifications, such as design or drawing errors
8. **Underutilized Skills and Talent:** The waste of not using employees' mental, creative, and physical abilities, such as lack of engagement, and slow to react

# 2 Literature Review

## 2.1 Introduction

In this chapter, the definitions of lean construction and construction industrialization are clarified. Lean construction practices and construction industrialization methods used in this study are also identified and categorized. In addition, through an analysis of lean construction and construction industrialization literature, a summary table is provided to further differentiate practices and methods. Finally, papers used in this research are summarized to introduce the present knowledge and gaps related to the topic.

## 2.2 Lean Construction

Koskela (1992) first introduced the lean thinking of the manufacturing industry into the construction industry, and defined it through a report at the first International Group of Lean Construction (IGLC) conference. The concept of lean construction comes from lean production (LP). Lean production originates from Toyota's production system. In short, it is a large-scale and standardized production method. After nearly 30 years of development, the basic theoretical framework system of lean production has been preliminarily formed and applied to manufacturing on a large scale. With the continuous development of large-scale and complex construction projects, researchers began to consider applying lean production to the construction industry, which is called lean construction. Ballard (2003) defines lean construction as a method to minimize waste and a production tool to maximize investment value. The most important characteristics of lean construction are that it attaches great importance to the needs of customers, tries to continuously improve the project, and coordinates all departments to achieve the goal. Another characteristic is that, while manufacturing is performed by mobile products and fixed personnel, construction is performed by mobile personnel and fixed products. It is not feasible to simply equate lean production with lean construction. The characteristics of each project must be considered, such as scale, budget, and site conditions to improve the construction process.

Yahya (2011) pointed out through research that the lean principles can be applied to rapid construction, which can shorten the waiting time of a project. Bertram (2019) proposed minimizing waste and optimizing production through a reasonable construction process and improved construction module. Nahmens (2009) pointed out that the industry should improve lean production tools, pay more attention to sustainable modular housing, and realize the ideal sustainable building. Bajjou (2018) believes that lean construction should continue to optimize the construction process, improve the quality of construction, and provide products and services that meet the needs of the owner. It can be seen that lean construction is based on lean thinking. The realization of lean construction in the future needs to verify the feasibility of theory and practice.

## 2.3 Lean Construction Practices

Babalola (2019) reviewed 102 documents published between 1996 and 2018 and ultimately identified 32 different lean practices. Babalola classifies Lean Construction practices (LCPs) into four categories based on key operations: Design and Engineering Practices (DEPs); (ii) Planning and Control Practices (PCPs); (iii) Construction and Site Management Practices (CMPs); and (iv) Health and Safety Management Practices (HSMPs). As LCPs may be grouped into multiple categories (Babalola 2019), there is some overlap in the different categories identified in the present research. Lean construction practices are divided into two parts: Planning and Control Practices (PCPs) and Construction and Site Management Practices (CMPs). The two groups of practices are illustrated in Figure 2.1, and each of the practices within the two groups is described/defined in detail below.

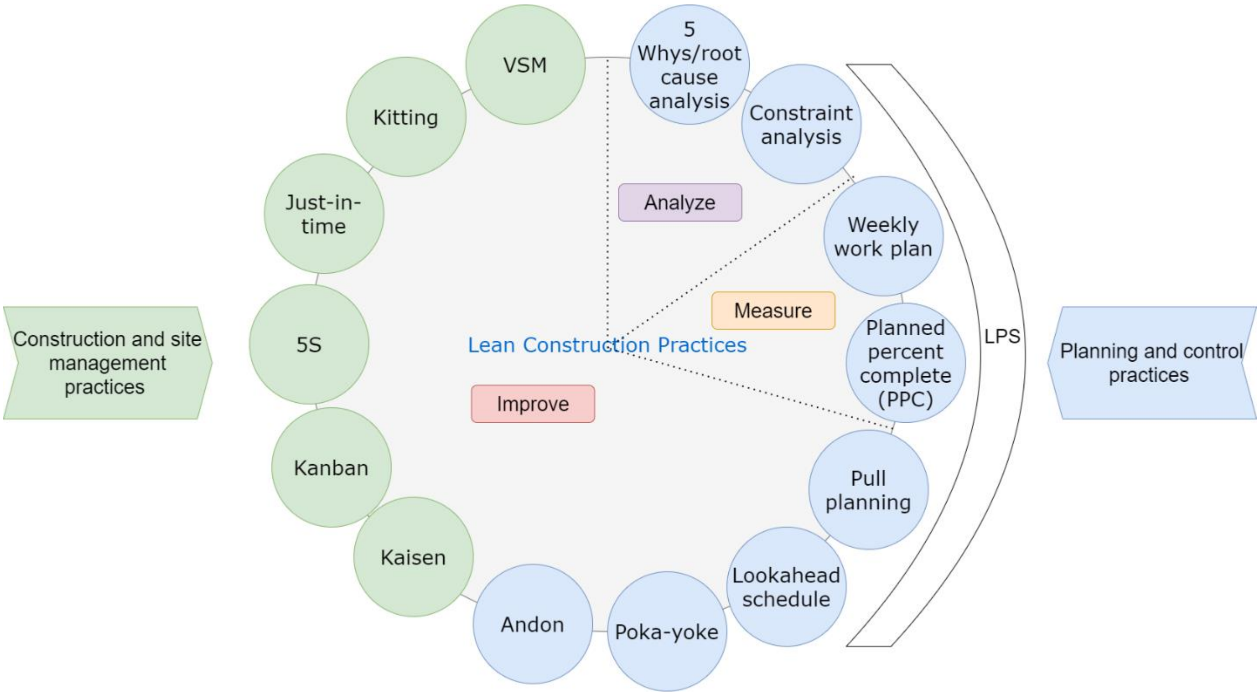


Figure 2.1 Lean Construction Practices

### 2.3.1 Planning and Control Practices (PCPS)

Listed below are eight lean practices that support strategic decision-making during construction planning and control. Babalola (2019) pointed out that some of these practices are well-implemented in the construction industry by inferring the number of published papers that identify the practice.

According to the Lean Construction Institute (LCI), the Last Planner® system (LPS) is a planning, monitoring, and control system that follows lean construction principles. LPS is designed to facilitate dialogue between trade foremen and project managers at the appropriate level of detail and before problems become serious enough to enable the planning process and workflow reliability. LPS practices remove constraints during the execution review plan, especially the collaborative planning phase, and verify commitments made, ultimately ensuring that those commitments are firm, timely, and unambiguous. Ballard (2016) describes the composition of LPS, which includes pull planning, constraint analysis, look-ahead schedule, weekly work plan and planned percent complete. The methods that make up LPS are considered separately in this research as lean construction practices used alone.

1) **Pull planning:** Orderly planning the various parts of the work, and formulating detailed work plans through scientific methods, including master planning, stage planning, forward planning, and weekly planning.
2) **Constraint analysis:** An integral part of the LPS that is applied as a proactive approach to problem-solving as a team. Project performance can be directly improved by removing key constraints in the overall system performance of the production process (Shen, 2005).
3) **Look-ahead schedule:** A short-term schedule usually developed in weekly team meetings where the team evaluates what it "can" do in the next 6 to 8 weeks. The goal is for the team to determine constraints, assign responsibilities, and commit to resolving the constraints before they affect the activity.
4) **Weekly work plan based on reliable commitments:** Tactical team collaboration to plan each day's work, conditions for handoff and acceptance, and sequencing and synchronizing the next week's work. The point of maximum progressive elaboration is to create reliable work plans.
5) **Planned Percent Complete (PPC):** A basic measure of how well the planning system is working – calculated as the "number of promises/activities completed on the day stated" divided by the "total number of promises/activities made/planned for the week".

6) **5 Whys/root cause analysis:** A process used to find the exact reason that causes a given problem by asking a sequence of "Why" questions.
7) **Andon:** A system designed to alert operators and managers of problems in real-time so that corrective measures can be taken immediately.
8) **Poka-yoke (mistake-proofing):** A way of designing a product or system to eliminate the possibility of mistakes and, hence, avoid defective products or services.

### 2.3.2 Construction and Site Management Practices (CSMPs)

Babalola (2019) described Construction and Site Management Practices (CSMPs) as practices that facilitate the proper management, organization and coordination of site activities and processes during the construction phase of project delivery. Types of CSMPs are described below:

1) **Kanban:** A project management technique that uses tools such as billboards or signs to document and streamline the various steps in processes.
2) **Kaizen:** Continuous improvement.
3) **5S Housekeeping:** A set of five techniques to improve housekeeping in a workplace: Sort, Set in order, Shine, Standardize, Sustain.
4) **Just-in-time:** An inventory management approach designed to eliminate waste by "receiving goods only as they [are needed] for production processes."
5) **Value Stream Mapping (VSM):** A visual tool that helps individuals visually see and understand a given process rather than simply looking at results.
6) **Kitting:** A process in which individually separate, but related, items are grouped, packaged, and supplied together as one unit before delivering them to

the particular place for installation, thus assembling a complete “kit” of parts required for the installation.

### 2.3.3 Table Classification

For the purposes of this research study, the lean construction practices are organized into five categories according to their characteristics. As shown in the Table 2.1, the Target stage is used to indicate the stage at which the technology is expected to work, such as analysis, measurement, and improvement. Value target and Waste target reveal specific areas of technical value and waste sources. Site or Office indicates the usual location of technology application. Finally, the Value Category represents which practice is used for a specific classification of the application.

Table 2.1 Characteristics of Lean Construction Practices

| Lean Techniques | Lean Technique Characteristics | | | | |
|---|---|---|---|---|---|
| | Target stage | Value target | Waste target | Site or Office | Value Category |
| Pull planning | Improve | Efficient | N/A | Office | Organization/planning /info flow |
| Constraint analysis | Analysis | Communicate | N/A | Office | Client focus |
| Look-ahead schedule | Improve | Information transfer | N/A | Office | Organization/planning /info flow |
| Weekly work plan | Measure | Efficient | N/A | Office | Organization/planning /info flow |
| Planned Percent Complete | Measure | Communicate | N/A | Office | Material flow & pull |
| 5 Whys | Analysis | Construction Quality | N/A | Office | Quality |
| Andon | Improve | Information transfer | N/A | Site | Organization/planning /info flow |
| Poka-yoke | Improve | Construction Quality | Rework | Site | Quality |
| Kanban | Improve | Time | N/A | Site | Material flow & pull |
| Kaisen | Improve | Development | N/A | Site | Continuous improvement |
| 5S | Improve | Safety | N/A | Site | Client focus |
| Just-in-time | Improve | Efficient | N/A | Site | Material flow & pull |
| Value Stream Mapping | Improve | N/A | Misunderstand | Office | Material flow & pull |
| Kitting | Improve | N/A | Space utilization | Site | Waste consciousness |

### 2.3.4 Plan-Do-Check-Act Cycle

The Plan-Do-Check-Act (PDCA) cycle originated in a lecture given by Dr. W. Edwards Deming in Japan in 1950 (Moen 2006). The Five-Phased Project Management Methodology originated from the PDCA cycle. Realyvásquez-Vargas (2018) defines the PDCA phases as:

a) Plan: In this phase, improvement opportunities are identified, and later priorities are assigned to them. Likewise, the current situation of the process to be analyzed is defined through consistent data, the problem causes are determined, and possible solutions are proposed to solve it.

b) Do: This phase is intended to implement the action plan, and select and document the information. Also, unexpected events, learned lessons, and acquired knowledge must be considered.

c) Check: In this step, the results of the actions implemented in the previous step are analyzed. A before-and-after comparison is performed to verify whether there were improvements and if the established objectives were achieved. To accomplish this, several graphical support tools, such as a Pareto chart or Ishikawa diagram, can be used.

d) Act: This phase consists of developing methods aimed at standardizing the improvements (in the case when the objectives had been reached). In addition, the proof is repeated to obtain new data and re-test the improvement (only if data are insufficient or circumstances have changed), or the project is abandoned and a new project is started from the first stage (in the case when the implemented actions did not yield effective improvements).

### 2.3.5 Lean Six Sigma Method

The Lean Six Sigma method proposed by Atmaca (2013) is used in this research to indicate the application stage of lean construction practices, where five project phases are defined as follows:

1) **Define:** Clearly and accurately define the goals of the project from a business or client perspective
2) **Measure:** Gather accurate, meaningful, and reliable data about a problem to be solved or a process to improve
3) **Analyze:** Determine how accurately the process performed and identify any reasons for non-conforming performance
4) **Improve:** Solve problems and improve processes
5) **Control:** Ensure that improvements transition successfully from project teams to business processes and will be the new normal operating model

Atmaca (2013) mentioned that the purpose of definition and measurement is to identify problems. In the definition stage, managers need to determine the project goals and boundaries, and communicate with project participants promptly to align the goals of all parties. During the measurement phase, the team should define detailed processes and validate the systems used to collect data, identify problems, or process data. The present research focuses on the construction of the project, therefore "definition" is not included in this research because it is a part of the design.

Atmaca (2013) states that the analysis phase is the phase where the work team analyzes the data to discover the root cause of a problem. Teams may need to go through more than one round of data collection and statistical analysis to understand the full issue. During this phase, the work team identifies the source of the problem or waste, and sets out several solutions that can be achieved to solve the problem or eliminate the waste.

According to Atmaca (2013), the improvement phase is the implementation of problem-specific solutions, and the improvements are made in the control phase. The improvement phase may require complete changes to the previous solution or only minor adjustments. In extreme cases, it may be necessary to coordinate the interests of all parties and change a part of the design. The work team then tests the solution to ensure successful implementation. The control phase includes updating systems or procedures that require improvement and retraining operators and users. Similar to the definition, "control" was not included in the present research study because it is a part of project maintenance.

In the present study, "define" corresponds to the ACT phase, to identify urgent problems or focused value (or waste); "measure" and "analyze" correspond to the PLAN phase to identify solutions to problems; "improve" and DO correspond to the value-enhancing process or specific problem solution; and "control" corresponds to the CHECK phase and is used as a method to ensure the successful implementation of the program.

### 2.3.6 Value and Waste Categories

Value and waste can be defined in different ways depending on the perspective of the person or organization receiving the value or incurring the waste. Hofacker (2008) defines several value and waste categories as shown in Table 2.2.

Table 2.2 Value and Waste Target Descriptions (Hofacker, 2008)

| Type of Value or Waste | No. | Value/Waste Target |
|---|---|---|
| Client Focus (Value) | 1. | Client focus, in terms of sales, marketing and strategy focus, detecting what is value for the client (and how well is this perceivable by the visitor) |
| | 2. | Regular client communication and flexibility to adapt to change requests |
| | 3. | Project flexibility and communication between project-designers and construction management (during execution) |
| | 4. | Cleanliness of the construction site (5S), orderliness, client-focus through cleanness and project-visualization in the engineer's offices |
| Waste Consciousness (Waste) | 5. | Waste of construction materials: detection of waste and consciousness on site |
| | 6. | Actions, knowledge, and incentives to eliminate waste (overproduction, waiting time, unnecessary transport, rework, etc.) |
| | 7. | Disposal (waste) management (recycling, and separation of construction disposal) |
| | 8. | Space utilization: how efficient is the space utilized (e.g., materials located in clearly dedicated areas, small parts stored in an orderly manner, and as few spaces utilized as possible) |
| | 9. | Wasted time (transportation time reduction, waiting time, usage of equipment and transport standardizations) |
| Quality (Value) | 10. | Regular quality control of construction materials (e.g., certification of concrete -strength control) |
| | 11. | General quality certification existing for the project/company (e.g., ISO certified) |
| | 12. | Visually perceived quality of the construction execution (variability to standard) |
| | 13. | Safety on the construction site |
| | 14. | Root cause analysis for rework executed (5W) |
| | 15. | Standardization of processes |
| | 16. | Visual management systems (clear signs, self-explaining and quality controlling systems) |
| | 17. | Degree of mechanization (technical machining) to obtain a standard quality & performance, facilitating smooth and efficient construction processes |
| Material flow & pull (Value) | 18. | Kanban card system (existence and well operated) |
| | 19. | Just-In-Time (JIT) concepts applied (measurable, e.g., in the amount of stock, where stocks > 1 week indicates no JIT) |
| | 20. | Use of ready-mixed concrete and efficient material flow on the construction site (e.g., manual in situ concrete = 0) |

| | | |
|---|---|---|
| | 21. | Ordering system and time to get main material (concrete, steel, bricks) from suppliers (1 day = very good, 1 week = ok, > 2 weeks = bad) |
| | 22. | Use of transportation support systems (crane) integrating horizontal and vertical transportation, and standardization of transport (e.g., standard pallets) |
| Organization/ planning/info flow (Value) | 23. | How is the top management aware of, convinced by, and supporting of the application of lean construction? |
| | 24. | Motivation and self-responsibility of employees (are there actions or methods to promote this?) |
| | 25. | Multi-functional teams (how flexible are the employees to work in different work areas?) |
| | 26. | Last Planner System applied with daily hurdle meetings. (or classical structural production planning) |
| | 27. | Communication tools (e.g., Andon applied) |
| | 28. | Is there a vertical and horizontal information system applied |
| Continuous improvement, Kaizen (Value) | 29. | How is the company striving for perfection, and how is a learning process from project to project applied? |
| | 30. | Is there continuous education for the employees (e.g., quality, further specialization, and lean) |

## 2.4 Construction Industrialization

The concept of construction industrialization originated in World War II. Due to the shortage of housing and labor, construction industrialization in Europe increased, and prefabricated buildings developed with the support of the government. Construction industrialization includes three basic characteristics: design standardization, component prefabrication, and process mechanization. Li (2017) proposed that construction industrialization is the future of the industry. Through industrialized manufacturing, transportation, installation, and scientific management, the low efficiency traditional industrial production mode can be replaced (Li, 2017). Construction industrialization emphasizes off-site or on-site prefabrication, which improves process stability and product standardization, and ensures reliable construction progress (Liu, 2020). The management of construction industrialization is mainly reflected in the supply chain and assembly. Therefore, the key to the success of the construction industrialization project is whether the efficient management of the supply chain and construction plan can be realized; the emergence of lean construction provides a possible solution.

### 2.4.1 Construction Industrialization Methods

Gibb (1999) mentioned that the more defined off-site prefabrication methods are prefabrication, pre-assembly and modularization. Isaac (2016) pointed out that for most production work, modularization, prefabrication and preassembly are usually done off-site. In contrast to construction industrialization, artisanship is considered a traditional construction method in which the work is performed manually and takes place on the construction site (without the application of lean construction or construction industrialization) (Liu 2020). The following methods (illustrated in Figure 2.2) are identified as the methods of construction industrialization in this research.

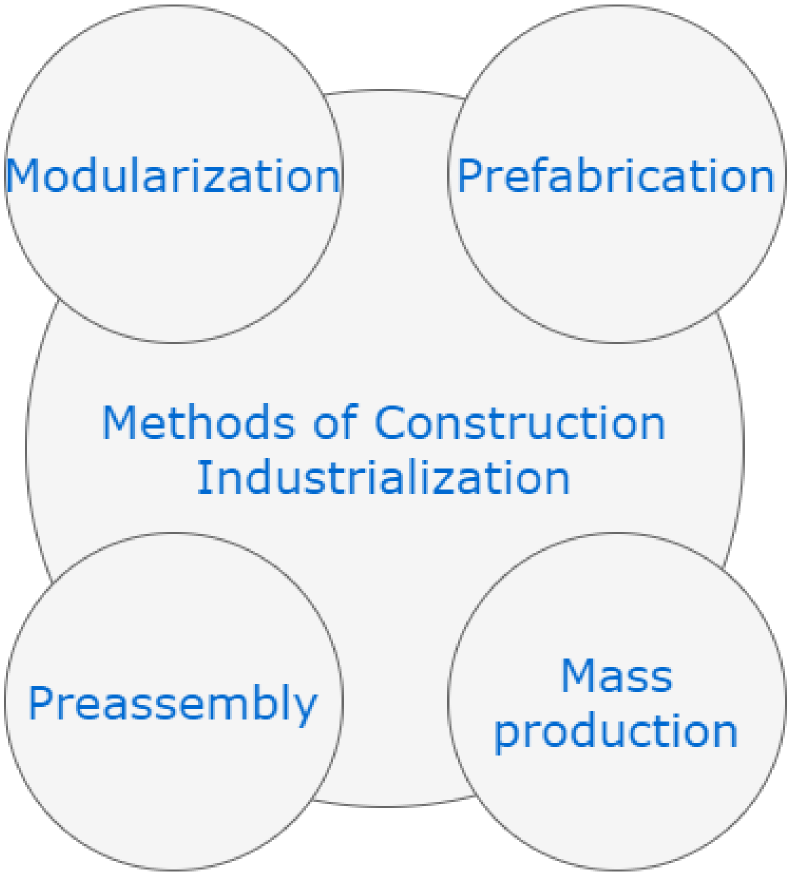


Figure 2.2 Construction Industrialization Methods

1) **Modularization:** Also known as modular construction, modularization includes work that is performed off-site and entails the assembly of large components and areas of a completed project. For building construction, modularization commonly refers to the process of constructing buildings off-site using the same raw materials designed and applied in a specific factory.
2) **Single-trade Prefabrication:** The process that constitutes the construction of a single building component in an off-site, condition-controlled environment concurrently with construction of the building structure and on-site work.
3) **Multi-trade prefabrication:** The process that comprises the simultaneous construction of multiple building components in an off-site, condition-controlled environment alongside building structures and on-site work.
4) **Preassembly:** The process of joining together various materials, prefabricated components and/or equipment off-site for subsequent installation as subunits.
5) **Mass production:** Also known as flow production or repeated flow production, mass production refers to the production of a large number of standardized products on a production line. Mass production overlaps in the concepts of lean construction and construction industrialization. Poppendieck (2011) mentioned that the concept of lean production comes from mass production. In the present research, mass production is classified under methods of construction industrialization.

### 2.4.2 Table Classification

The industrialized construction methods can be divided into seven categories according to the characteristics of the construction industrialization methods. The categories and their characteristics are shown in Table 2.3. In the table: "Where produced" is used to indicate the place where the method occurs, such as in a factory, on the site, or offsite; "Where assembled" reveals where the related components are assembled, such as in a factory, on the site, or offsite; "How installed" shows the type of components, such as assembly, module, and individual components; "Manufacturing " indicates the application of technology from two aspects (number and size); "Produced by" shows the way the components are produced, such as by a human or by a machine; and "Influence of human behavior/Error" indicates the extent in which the method is influenced by and involves humans (low, moderate, or high influence).

Table 2.3 Characteristics of Construction Industrialization

| Production Methods | Production Method Characteristics | | | | | | |
|---|---|---|---|---|---|---|---|
| | Where produced | Where assembled | How installed | Manufacturing scale (number) | Manufacturing scale (Size) | Produced by | Influence of human behavior/Error |
| Modularization | Factory | Factory | Assembly/module | Medium/large | Medium/large | Human/machine | Moderate |
| Single-trade Prefabrication | Offsite | Site/offsite | Individual components | Small/medium | Small | Human | High |
| Multi-trade prefabrication | Offsite | Site/offsite | Individual components | Large | Medium/large | Human | High |
| Pre-assembly | Offsite | Site/offsite | Assembly/module | Medium/large | Medium/large | Human/machine | Moderate |
| Mass production | Factory | Site/offsite | Individual components | Large | Large | Machine | Low |
| Artisanship | Site | Site | Individual components | Small | Small | Human | High |

## 2.5 Literature Review Summary

This chapter presents more clearly what is known about lean construction and construction industrialization from previous research. It illustrates the gap in knowledge that is addressed in the present study.

Table 2.4 gives a summary of lean construction. Table 2.5 gives a summary of construction industrialization. The tables provide the title, objectives, methods, and conclusions of pertinent literature related to lean construction and construction industrialization, respectively.

Table 2.4 Summary of Lean Construction Literature Review

| Author | Title | Objectives | Methodology | Conclusions |
|---|---|---|---|---|
| Pestana (2016) | Multi-Criteria Risk Mapping Using lean tools for the Architecture | Find solutions that combine lean implementation and risk mapping to create risk-based mitigation solutions in construction management. | Literature review, case study projects, interviews, observation, and archival records. | The method of combining lean tools and methods with risk management tools is proposed, which can be used to improve the construction activities in AEC industry. |
| Zimina (2012) | Target Value design (TVD): Using collaboration and a lean approach to reduce construction cost | Whether TVD is the same as the current practice and whether the TVD system has practical significance. | Action research, observation, interviews. | TVD is fundamentally different from contract and cost management technologies in management concepts and implementation, and the system application of target value design can make the final cost of the project 15% lower than the market cost on average. |
| Hamzeh (2021) | Lean Construction 4.0: Exploring the Challenges of Development in the AEC Industry | Identify research needs and discuss the role of lean construction in facing the challenge of using Industry 4.0 in the AEC industry. | Literature review | The paper expounded on the future needs of the AEC industry for the principles of lean construction 4.0 and proposed that maintaining the triad of people, technology, and processes is an important step in responding to the fourth industrial revolution. |
| Bajjou (2018) | The Potential Effectiveness of Lean Construction Principles in Reducing Construction Process Waste: An Input-Output Model | Try to clarify the main conceptual basis of lean construction by proposing a model of the lean construction concept, and establishing an interaction between the main principles of the concept and all waste sources. | Survey, literature review, archival records. | An input-output model showing the principles of lean construction is provided, and nine principles have been determined based on this, namely customer-centricity, supply, continuous improvement, elimination of waste, personnel participation, planning and scheduling, quality, standardization and transparency. Then verify the actual relationship between these principles and different sources of waste. |
| Koskela (1992) | Application of the New Production Philosophy to Construction | Try to find the impact of new product concepts on construction. | Literature review, analysis and synthesis. | The author identified a principle that can improve the efficiency of the process, and believes that the improvement of flow |

| | | | | |
|---|---|---|---|---|
| | | | | activities should mainly focus on reducing or eliminating flow activities to make conversion activities more effective. |
| Yahya (2011) | Review on Lean Principles for Rapid Construction | Determine the standards for rapid construction projects, evaluate the lean principles of the rapid construction process, and identify the benefits and key success factors of identifying the lean principles in the rapid construction process. | Literature review, case review, analysis and synthesis. | Standards for stable work processes can be achieved by applying lean principles to the construction process, and rapid construction can be achieved by eliminating waste as the basic principle. |
| Hosseini (2012) | Implementing Lean Construction Theory into Construction Process Waste Management | Describe various construction process wastes by assessing the amount of construction process waste, and explain the lean construction principles for waste reduction accordingly. | Literature review, case review, analysis and synthesis, archival records. | The researchers proposed a method to apply lean production principles to reduce waste in the construction process and believe that these principles have great potential in improving the construction process and reducing waste generation. |
| Nahmens (2009) | An Empirical Examination of the Relationship between Lean Construction and Safety in the Industrialized Housing Industry | Determine the prevalence of lean construction, find the potential impact of specific concepts used in lean construction, continuous improvement (CI) on safety results, and show the safety results of an industry-wide survey of industrialized residential contractors. | Literature review, survey, analysis and synthesis. | The incident rate of lean construction projects is much lower than that of non-lean projects. By using at least one lean process, construction safety can be significantly improved. |
| Salem (2006) | Lean Construction: From Theory to Implementation | Try to find the possible benefits of lean principles to the project and propose more effective tools for lean construction. | Literature review, case review, analysis and synthesis. | The implementation of lean construction keeps the project below budget, reduces the construction period, increases the satisfaction of subcontractors and GC, and reduces the incidence of accidents. A self-assessment tool that can be used to track the improvement of any project is proposed. |

Table 2.5 Summary of Construction Industrialization Literature Review

| Authors | Title | Objectives | Methodology | Conclusions |
|---|---|---|---|---|
| Liu (2020) | Construction Worker and Equipment Energy Consumption for Offsite Precast Concrete | Find building components that can be produced off-site in the factory to replace the on-site construction process. Analyze the difference in energy consumption of workers during construction on-site and off-site, and the difference between on-site and off-site energy expenditures of the project. | Literature review, survey, data analysis, | The paper provided a basic calculation of the energy consumed by the off-site precast concrete process and defined the levels of automation (LOA) in the construction industry. |
| Bertram (2019) | Modular Construction: From Projects to Products | Quantify the potential benefits of modular buildings, explore possible challenges, and focus on the broad and sustainable impact of modular buildings. | Data analysis, archival records. | Modular buildings can achieve construction cost savings of more than 20% for real estate companies. Two important reasons for using modular buildings are the demand for real estate and the availability and relative cost of skilled construction labor. |
| Li (2017) | A Research on Development of Construction Industrialization based on BIM Technology under the Background of Industry 4.0 | A comparative analysis based on the mechanism and development path of the Industry 4.0 production mode; expounds on the current difficulties faced by construction industrialization and proposes a new production pattern. | Literature review, analysis and synthesis. | Continuously improving specifications and construction standards, and increasing research and development (R&D) investment are conducive to the development of construction industrialization. |
| Bertelsen (2003) | Complexity–Construction in a new Perspective | Try to find more effective construction methods for complex projects. | Literature review, analysis and synthesis. | Complex construction projects can improve efficiency through management methods such as organization, planning, and process control. |

### 2.5.1 Literature Review Overview

Figure 2.3 presents a summary of previous articles, including topics related to lean construction and construction industrialization, along with the authors who published research related to each topic.

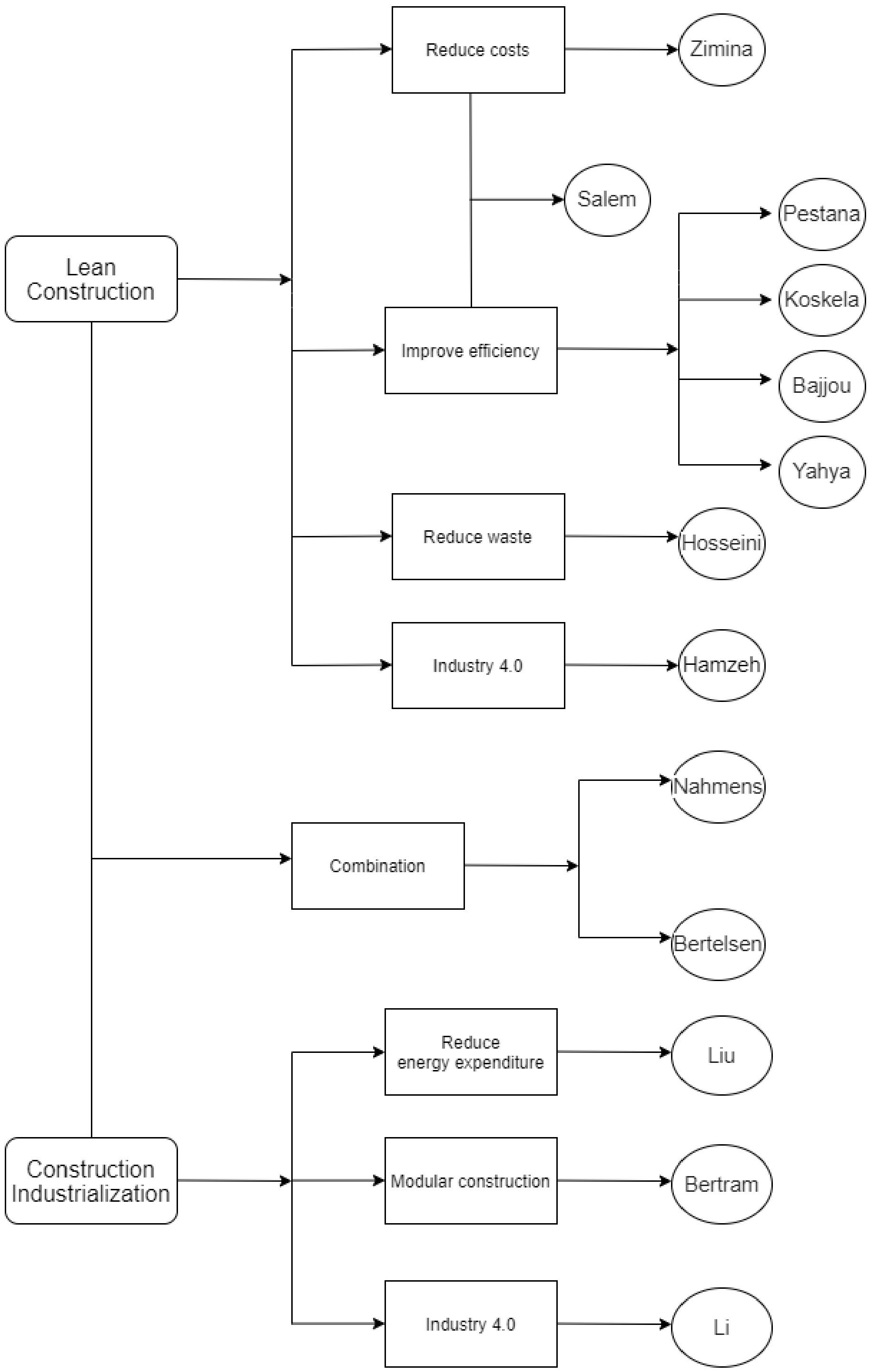


Figure 2.3 Literature Review Overview Diagram

### 2.5.2 Research Gap

Bertelsen (2003) believed that the coordination brought by lean construction can be used to solve large-scale and complex projects. Salem (2006) presented a case study of construction project implementation under specific lean construction factors and proposed a simple and understandable lean measurement tool suitable for new projects. Hosseini (2012) studied a discrete event simulation method based on lean thinking, determined the waste of any form of the construction process, and proposed that the construction process has high optimization potential. Compared with the projects without lean construction, the projects with lean construction have significantly lower injury incidence, which shows that lean construction can not only reduce waste and improve efficiency, but also improve safety on the construction site. Lean construction has been proven to reduce waste and uncertainty. Past research on the lean construction process shows that lean construction has been recognized by researchers and industry organizations, and has indeed brought benefits to construction projects. However, the arrival of Industry 4.0 puts forward higher requirements for lean construction (Hamzeh, 2021). There is insufficient evidence in the industry to show that lean construction has sufficient potential in the context of continuously evolving processes and methods. The review of previous literature on lean construction and construction industrialization, reveals that there a lack of references to practice-based integration of lean construction and construction industrialization on projects. Further research is needed to determine how lean construction can benefit construction industrialization processes and methods.

# 3 METHODOLOGY

## 3.1 Introduction

The research aims to explore lean construction and construction industrialization, and the added value of implementing lean construction and construction industrialization together on projects. As mentioned previously, lean construction and construction industrialization have been proven to have positive effects on projects including, but not limited to, improving value and reducing waste. The current research focuses on the factors affecting the two methods, the impacts of their combined use on projects, and further developments to improve the processes.

## 3.2 Research Questions and Hypotheses

### 3.2.1 Research Questions

Based on the existing research and outstanding gaps in knowledge, the following questions with respect to lean construction and construction industrialization remain to be answered:

**1)** Can values generated by lean construction and construction industrialization be measured?

**2)** Will the amount and type of value generated vary by work trade?

**3)** What are the factors that affect the value?

**4)** Can the degree and frequency of factors be measured?

**5)** Does lean construction fit in with construction industrialization on projects?

**6)** Are there combinations of lean construction and construction industrialization methods that increase the value of a project?

### 3.2.2 Research Hypotheses

For this research, it is assumed that the parallel use of lean construction and construction industrialization will promote each other, especially in terms of safety, quality, and efficiency. For this reason, the corresponding lean construction and construction industrialization practices/methods used on the construction site are further validated with data obtained through an online survey and project interviews.

In response to the research questions, it is assumed that the lean construction practices used on construction projects are:

- Pull planning
- Constraint analysis
- Look-ahead schedule
- Weekly work plan based on reliable commitments
- Planned Percent Complete (PPC)
- 5 Whys/root cause analysis
- 5S
- Andon
- Just-in-time
- Kaizen
- Kanban
- Poka-yoke
- Kitting
- Value stream mapping (VSM)

Similarly, the construction industrialization methods used on projects are assumed to be:

- Modularization
- Prefabrication
- Preassembly
- Mass production

The practices and methods mentioned above are used in the research for measuring whether a project can be classified as a lean construction project and/or a construction industrialization project. The practices and methods are derived from published papers and have been widely used throughout the industry. All of the construction methods listed above are from published literature.

It is assumed that the added value of these methods can be measured (Research Question #1) because their value has been identified in previous literature. Similarly, it is assumed that these values can be quantified (Research Question #2) because they have been quantified by different methods in previous research. With respect to Research Question #3, the amount of these values may change depending on the type of project, such as residential buildings, roads, and industrial facilities. Lean construction practices are implemented differently, in terms of when, where, and for what purpose, than construction industrialization methods. For Research Question #4, it is assumed that the factors are divided into internal and external factors because these two types of factors are commonly used as the main factors affecting construction. A unique assumption within the research is that lean construction and construction industrialization can improve each other (Research Question #5) because both methods have a positive effect on the project when implemented on their own. Lastly, for Research Question #6, it may be the case that an improved process that combines lean construction and construction industrialization can be developed because the combination of lean construction and construction industrialization provides a more suitable process than when they are implemented separately.

### 3.2.3 Research Goal and Objective

The overarching goals of this research are to find the degree of fit between lean construction and construction industrialization on projects, and to further develop the construction process to improve project performance. To further study the above questions, the following objectives are the core of this research:

1. Determine lean construction practices and construction industrialization methods commonly used on construction projects
2. Identify types of added value and waste present on construction projects
3. Develop metrics for value and waste
4. Determine the factors that affect value and waste on construction projects
5. Identify the factors that influence the combination of the two methods
6. Identify construction project characteristics and develop a process that involves the combination of the two methods to increase the amount of value added to construction projects

In order to conduct the study to further explore the value of implementing lean construction along with construction industrialization, specific study tasks were undertaken to meet the study objectives. The tasks conducted for each objective are as follows:

For Research Question #1:

1) Determine lean construction practices and construction industrialization methods
    - Conduct a review of relevant literature
    - Collect data on evaluation criteria using an online survey and construction site interviews

- Statistical analysis of data collected

For Research Question #2:

1) Identify work trades
    - Conduct a review of relevant literature
    - Collect data on work trades using an online survey and construction site interviews
2) Determine factors that influence the combination of the two methods
    - Conduct a review of relevant literature
    - Conduct further interviews based on the linked-out survey feedback

For Research Question #3:

1) Identify values and wastes
    - Conduct a review of relevant literature
2) Develop metrics for value and waste
    - Collect data on potential metrics using an online survey and construction site interviews
    - Statistical analysis of data collected

For Research Question #4:

1) Determine the factors that affect value and waste on construction projects
    - Conduct a review of relevant literature
    - Collect data on potential factors using an online survey and construction site interviews
2) Develop metrics for the influencing factors

- Collect data on potential metrics using an online survey and construction site interviews
- Statistical analysis of data collected

For Research Question #5:

1) Identify the factors that influence the combination of the two methods
    - Conduct interviews of workers on construction sites
    - Collect data on potential factors using an online survey and construction site interviews

For Research Question #6:

1) Summarize the collected data and analyze
    - Review and analyze the data collected from the online survey and construction site interviews

Figure 3.1 shows the three specific aims of the study. Aim #1 is to identify the basic concepts and foundational knowledge about lean construction and construction industrialization, as well as the values and wastes that have been identified to date. Aim #2 is related to the factors that affect value and waste, and metrics that can be used to measure the factors. Aim #3 focuses on the combination of lean construction and construction industrialization, specifically to investigate the impacts of the combination, identify project characteristics, and develop a process that provides the benefits of using the combination.

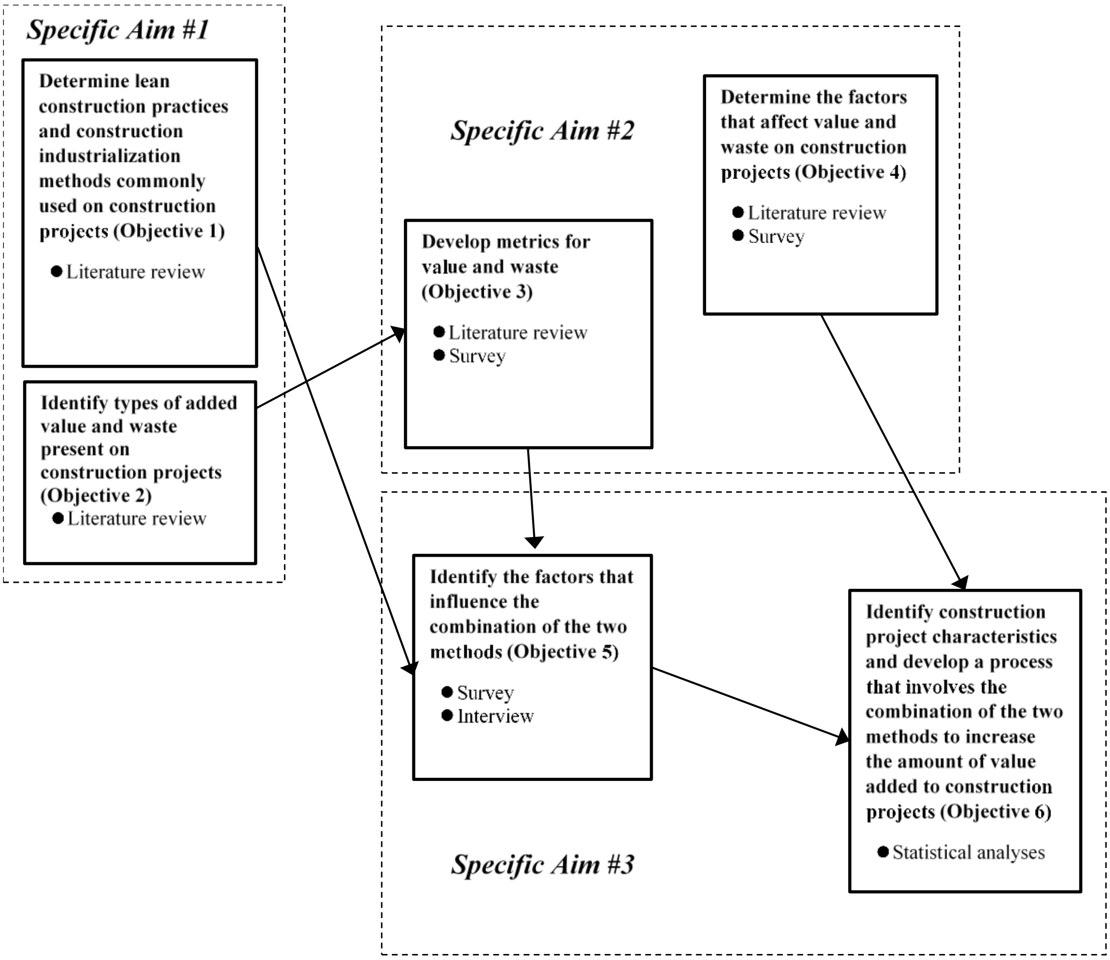


Figure 3.1 Research Aims

## 3.3 Research Design

A flowchart describing the research design and research methodology was developed and is shown in Figure 3.2. The flowchart is used to illustrate the procedures, goals and objectives of the research. As shown in the figure, the first stage involved setting the goals and define relevant terms and concepts to provide a theoretical basis for the research methods to be used. The second stage consisted of developing corresponding data collection tools. The impact of the two approaches (lean construction and construction industrialization) on each other is verified through surveys and interviews. After collecting the data, the researchers analyzed the data to obtain conclusions and results. A literature review, online survey, and construction site interviews were used for data collection in the research.


Figure 3.2 Research Process

## 3.4 Research Approach

Qualitative and quantitative research methods were used to conduct the research. Qualitative research (Fellows, 2021) is an unstructured exploratory technique and used to develop the criteria and scales contained in the survey questionnaires and interview questions. This type of research method was used to gain experiential and anecdotal insights into the topic. Quantitative research (Fellows, 2021) relies on mathematically related methods such as statistical methods. The reason for using this method was to clarify facts and values and further develop their in-depth connections. Different statistical methods were used to establish a causal relationship between two variables. Therefore, this method was used for data analysis and processing in the research.

## 3.5 Data Collection

The research design divides the data collection into three parts: literature review, online survey, and interviews. The researchers set different goals based on the target questions, and literature review, survey, and interviews were established as methods for achieving these specific goals. Figure 3.3 shows the methodology flow in detail. As shown in the figure, the research methods are roughly divided into four parts, namely literature review, survey, interviews, and statistical analysis. The literature review supported completing Specific Aims #1 and #2. The survey was used to fulfill, in part, Specific Aim #2 and Objective 5. Interviews were used as a method to complete Objective 5. Statistical analysis was used as a method for Objective 6. Through the application of several research methods, processes that combine the benefits of the combination of lean construction and construction industrialization were identified.

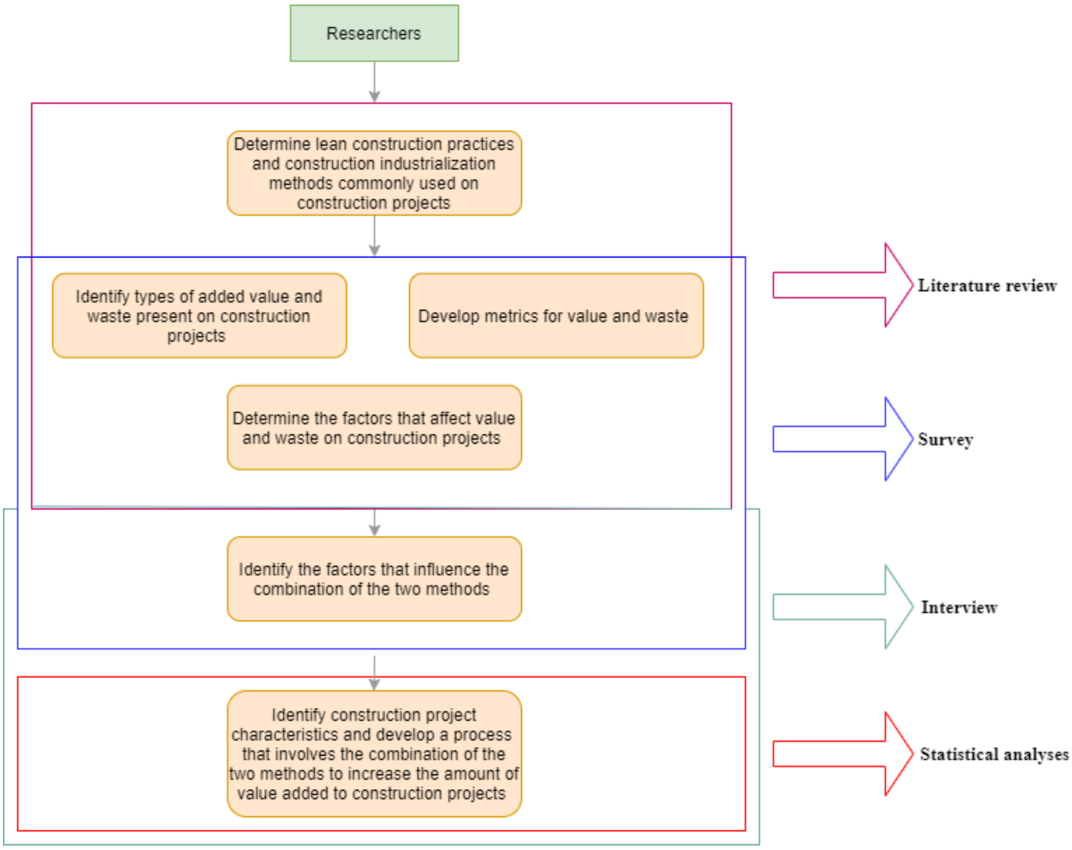


Figure 3.3 Research Methods

## 3.6 Bias Controls

One of the more subtle errors in research is the hard-to-identify biases that are present in the research process, tools, and data. Therefore, several control measures were used to reduce bias in the research. The control measures are described below.

### 3.6.1 List of Participants

A list of potentially eligible individuals was provided by the School of Civil and Construction Engineering at Oregon State University. The list includes construction industry-related professionals with personal academic connections to OSU. Those on the list were sent a questionnaire in which the respondents were asked to provide information such as company type, company size, job title, work experience, etc. to determine their eligibility. Rather than seeking participants from the entire industry (including workers, engineers, and managers), the list used limits the target participant population to those with some experience and with connections to OSU, which may introduce bias in the current research.

The selection of the interview participants was divided into two parts. First, the researchers obtained a list of potential respondents through channels such as the Internet, industry websites, contact lists, and paper authors. The second step confirmed that the interviewed participants have at least one or more areas of expertise or experience such as lean construction or construction industrialization. The research team reached out to everyone on the list via email and asked if they would like to participate in the study. Since the current study focuses on lean construction and construction industrialization, the knowledge background of the participants is important in the performance of the study, and bias can be reduced by screening researchers with relevant knowledge background.

## 3.7 Survey Design

### 3.7.1 Questionnaire Design

Two of the purposes of the survey were to determine how well lean construction aligns with the industrialization of construction and to identify improvement processes accordingly. The survey questionnaire had to be approved by the OSU Institutional Review Board (IRB). After approval, the researchers emailed the survey invitation, explanation, and link to the questionnaire to the targeted participants.

The survey questions were designed to utilize the Likert scale for responses (Joshi 2015). As shown in Figure 3.4, the questionnaire was organized into several sections related to the topic.

The following is a description of each stage of the process shown in Figure 3.4. The questionnaire is important for the survey, and the results of the survey are presented in a subsequent section. A copy of the survey questionnaire is provided in the Appendix.

i. Personal Demographic Information

This section focuses on the background and experience of the participant. Questions ask about the type and size of company that the participant works for, and the participant's job title and work experience. Finally, they were asked to provide their knowledge of lean construction and construction industrialization. Separate work trades for subcontractors were listed to determine the nature of their work and to explore the relationship between work types and construction methods.

ii. Lean Construction Section

In this section, participants were asked to answer questions related to the lean construction based on their understanding of lean construction and their involvement in lean construction practices on projects. To ensure participants better understand the relevant concepts, each practice was followed by a brief explanation of the practice. Participants were then asked whether their project implements the practices and to provide reasons why the project chose these practices. A Likert scale (where 0 = no impact, and 5 = extreme impact) was used to measure the value and waste reduction that lean construction practices brought to the project. The value brought by lean construction practices is divided into internal and external value because of the expectation of finding the relationship between the source of value and the type of project.

iii. Construction Industrialization Section

Similar to lean construction, participants were asked to answer questions related to construction industrialization based on their understanding of the topic associated with the methods of construction industrialization on their project. To ensure participants clearly understand the relevant concepts, a brief explanation of each method was provided. For each method implemented, participants were then asked to provide reasons why the project chose the methods. Likert scales (from 0 to 5 where 0 = no impact and 5 = extreme impact) were used to record the value and waste reduction brought to the project by different construction industrialization methods. Each factor on the scale used in this section was the same as in the lean construction section to make the two sections comparable.

iv. Combination of two methods

This section of the questionnaire aimed to explore the impact of two or more implementations of the same method on the project. Similar Likert scales from 0 to 5 were used, including the impact of lean construction and construction industrialization on each other. The influencing factors were also listed, using a Likert scale from -3 to 3 where -3 = high negative impact and +3 = high positive impact, to capture the degree of impact of different aspects such as budget, efficiency, quality, and safety.

v. Linked-out survey questionnaire

At the end of the questionnaire, a question was asked whether the participant was available for a follow-up interview to collect additional information about a specific project. A linked-out survey questionnaire was designed to capture their interest in participating in an interview and identify a project on which to collect more information. If the participant was interested in providing a construction site for the researchers to investigate, a new questionnaire link was provided, and the participant used the link to provide personal contact information, project location, and other information. This information was used by the researchers as part of a follow-up interview.

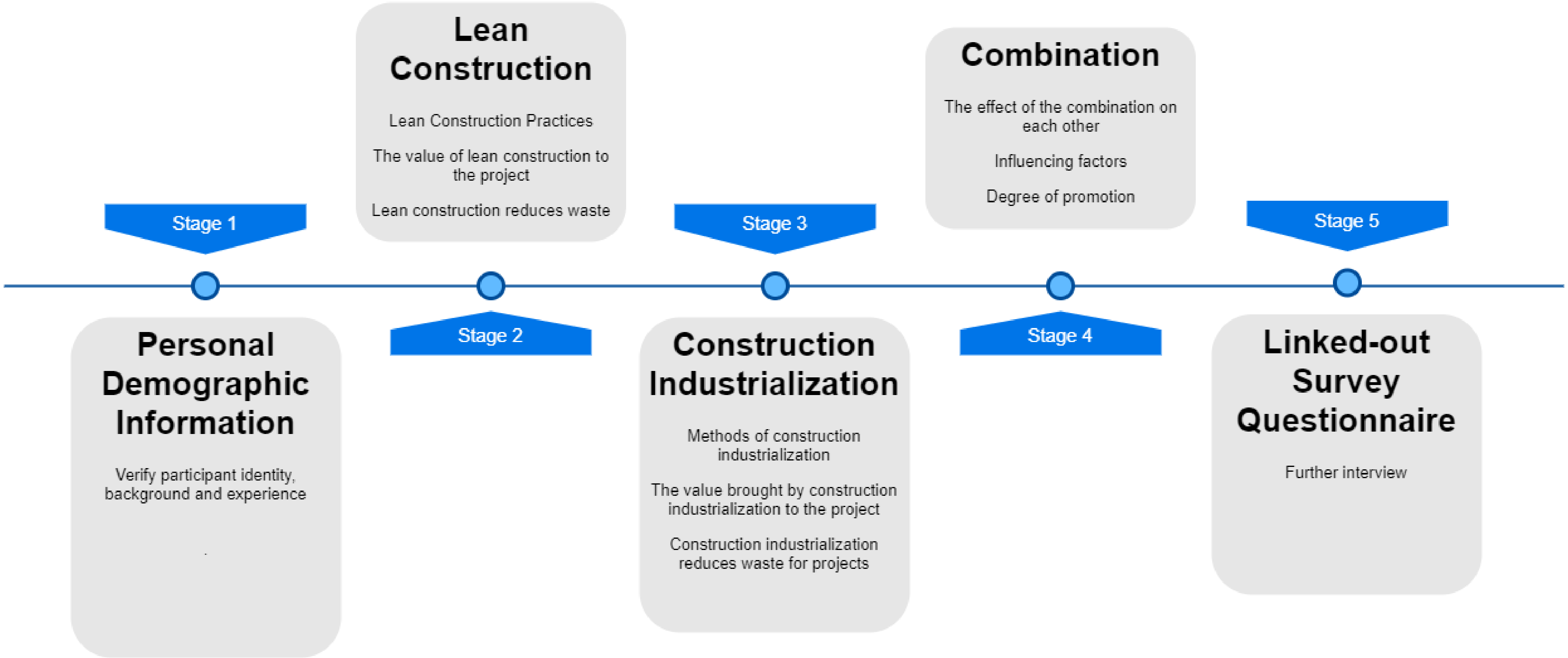


Figure 3.4 Survey Process

### 3.7.2 Questionnaire Distribution

The survey questions approved by the IRB were entered into Qualtrics, where different representations were used depending on the type of question. The questionnaire was distributed with Qualtrics via Google Mail. The research team distributed the survey to 725 contacts in four eligible contractor categories (Secondary, General, Heavy Civil, and Vertical) and finally 690 people successfully received the mail. The contacts were those included in the list of industry contacts for the School of Civil and Construction Engineering.

## 3.8 Interview Design

Interviews were conducted through the survey's Linked-out questionnaire. The main subjects of the interviews were site-specific participants, such as managers, workers, and engineers. Similarly, the interview process involved human subjects, approval for conducting the interviews was gained from the IRB office. After approval, the researchers brought hard copies of the interview questionnaire to the sites to use as guidance when conducting the interviews. As shown in Figure 3.5, interviews were designed into several sections related to the topic.

1) Individual Basic Information

Since this interview questionnaire is a paper document that needs to be filled out in person by a construction site employee (not just the participants), it was necessary to ask the questions included in the questionnaire again during the interviews.

2) Lean Construction

Lean construction practices implemented in the project were presented again, and respondents answered based on their own experience and project situation. Responses regarding the performance of each practice (if implemented) included in the project were recorded using a Likert scale (0 to 5, from no impact to high impact).

3) Construction Industrialization

Similar to that for lean construction, the construction industrialization method was proposed again, and respondents answered based on their own experience and project situation. The participant’s perspective of the performance of each method (if implemented) on the project was recorded using a Likert scale (0 to 5, from no impact to high impact).

4) Project Information

This section required respondents to answer several project-related questions, involving project duration, safety, and construction efficiency, etc. In order to prevent interviews from involving project-related secrets, the researchers avoided asking about direct project information when designing the questions.

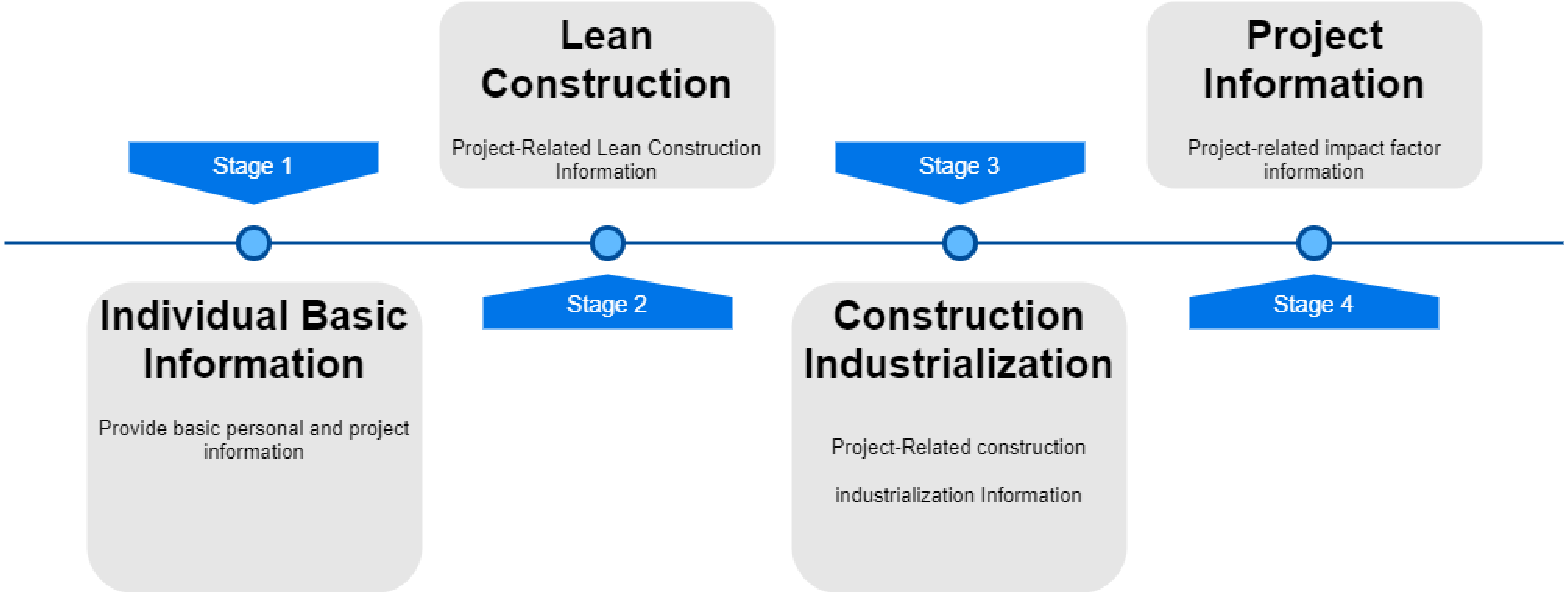


Figure 3.5 Interview Process

# 4 RESULTS

## 4.1 Introduction

This section describes the survey and interview results. Participant demographics are presented to document if they were sufficiently eligible to be part of the data set. Then, the participant responses related to lean construction and construction industrialization are introduced. Finally, the specific impact of lean construction and construction industrialization on the project while the participants are working is explained. This section provides a detailed description of the lean construction, construction industrialization, and combination sections in the survey, including lean construction practices, construction industrialization methods, value and waste identification, and impact factors. The weighted mean is used in the presentation of the results, and it is calculated as shown in Equation 1:

$$\text{Weighted Mean} = \frac{\sum_{i}^{n} (Scale\ degree)_i * (Quantity\ on\ the\ scale)_i}{Total\ number\ of\ responses} \qquad \text{Eq. 1}$$

In addition, unless otherwise specified, the horizontal axis in the figures (Sections 4.4 and 4.5) represents the number of responses, and the vertical axis represents the categories of the corresponding subtitle.

## 4.2 Participant Suitability Verification

The first part of the questionnaire focused on questions about the participant's background, experience, and personal demographics. Panelists were asked to provide the following information: company type, project type, education level, current position, years of professional experience, company size, and their knowledge of lean construction and construction industrialization.

Out of a total of 690 contacts from the industry who matched the contractor category (secondary, general, heavy civil, vertical), 41 responses were received (5.94%). Participants are involved in different aspects of construction, such as construction and consulting firms, and general or subcontracting firms. They are also involved in different types of projects, focusing on commercial and institutional buildings, residential buildings, bridges, roads, tunnels, and utilities. Appendix I provides the demographic information for each participant.

As shown in Appendix I, a total of 36 responses were used in this research. A total of five surveys were excluded from the dataset because the participants did not complete the questionnaire completely, such as providing incomplete personal information, or were unfamiliar with both lean construction and construction industrialization.

## 4.3 Personal Demographic Information

As shown in Figure 4.1, in a total of 36 questionnaires, 32 (89%) of the participants work in construction companies, and a small number (11%) of the participants work in consulting companies and design companies.

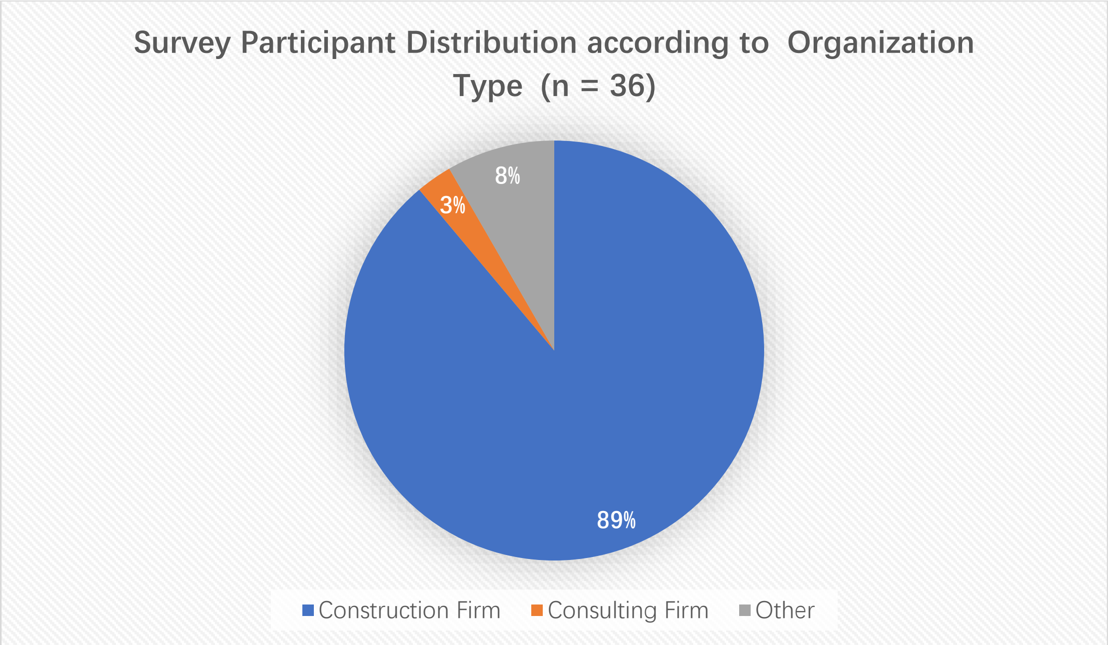


Figure 4.1 Survey Participant Distribution according to Organization Type (n = 36)

As shown in Figure 4.2, most of the participants (29 out of 36, 80%) have more than 10 years of experience in the industry.

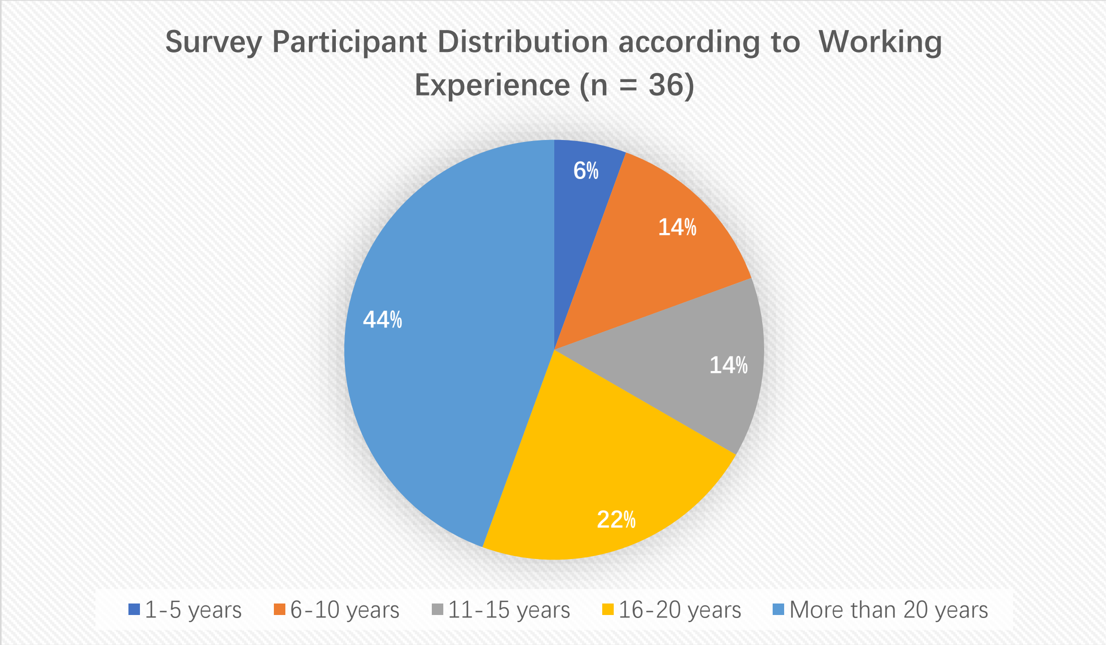


Figure 4.2 Survey Participant Distribution according to Work Experience (n = 36)

As shown in Figure 4.3, about half (18 out of 36, 50%) of the participants work for large institutions or businesses with more than 500 employees, and the other half work for companies with a company size ranging from less than ten to 500 employees.

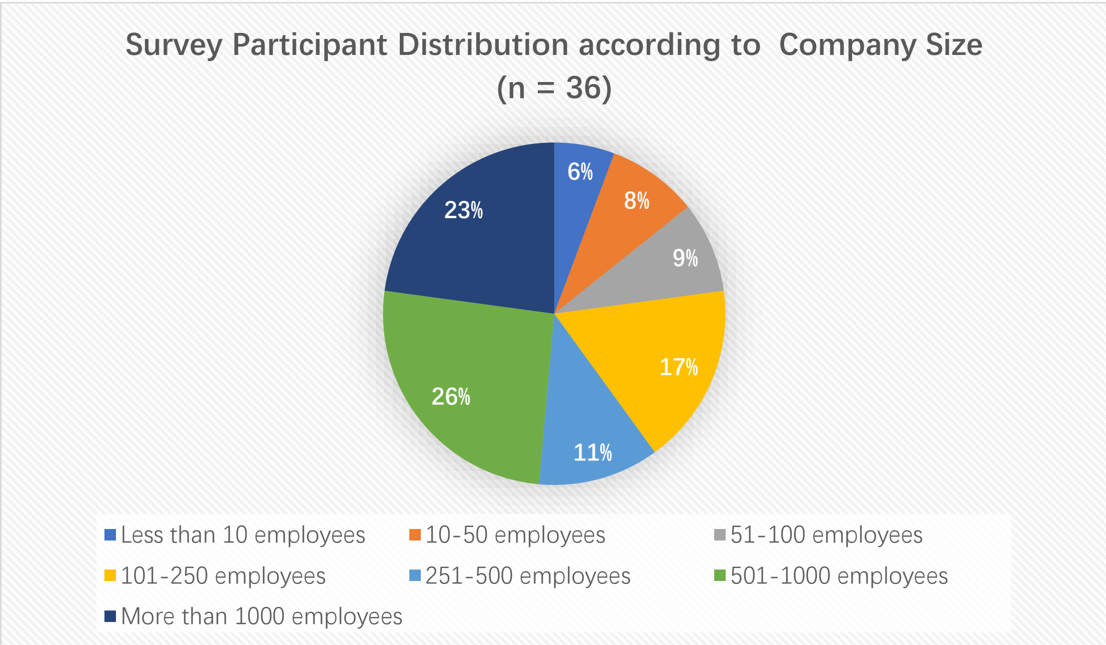


Figure 4.3 Survey Participant Distribution according to Company Size (n = 36)

As shown in Figure 4.4, more than a quarter (13 out of 36, 36%) of the participants work as project managers or project engineers in their company, and the vast majority (23 of 36, 64%) of the participants have other project-related positions/title, such as president, VP or owner.

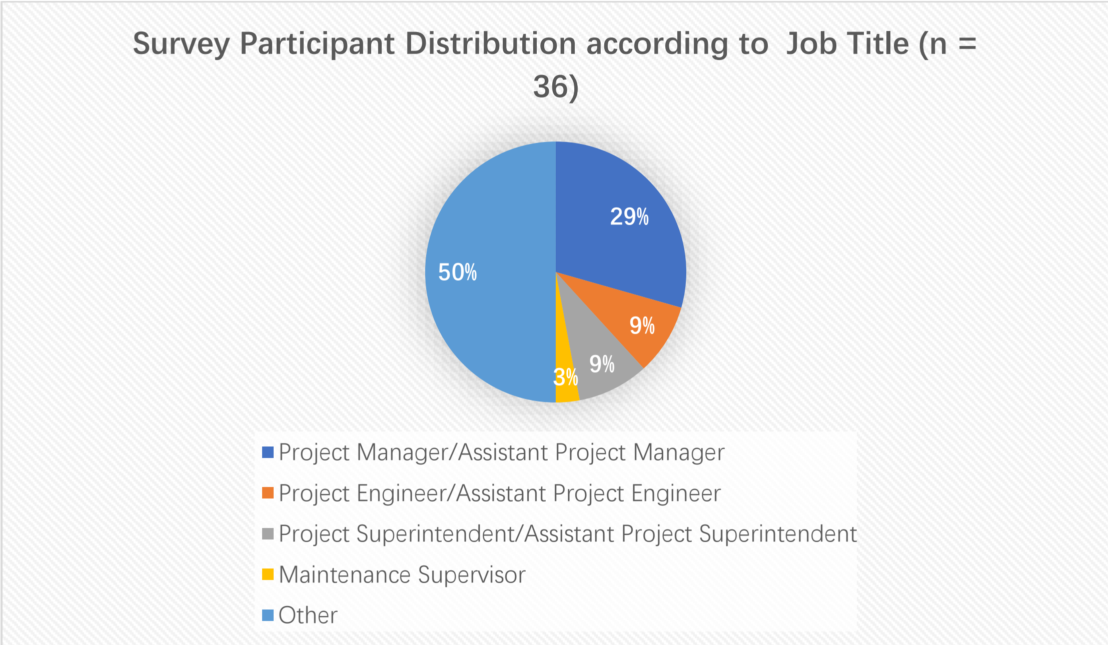


Figure 4.4 Survey Participant Distribution according to Job Title (n = 36)

As shown in Figure 4.5, more than half (21 out of 36, 58%) of participants are involved in major projects involving commercial and institutional buildings, and a quarter (9 out of 36, 25%) are involved in major projects involving roads and bridge.

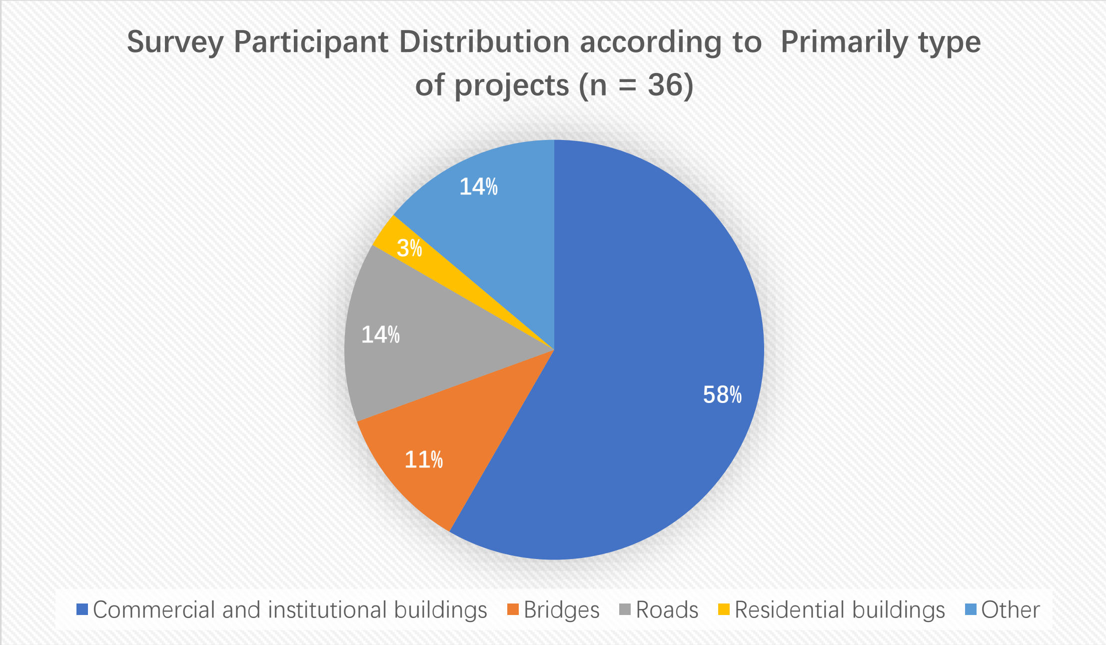


Figure 4.5 Survey Participant Distribution according to Primarily Type of Projects (n = 36)

## 4.4 Lean Construction

### 4.4.1 Lean Construction Practices

Figure 4.6 shows a summary of the responses to the question "What lean construction techniques/practices are applied to the projects you are involved in?" The different colors in the figure correspond to the different lean construction practice categories shown in Figure 2.1 in Section 2.3 (blue for Planning and Control Practices, and green for Construction and Site Management Practices). Other includes Gemba walks, under Construction and Site Management Practices. According to Demirkesen (2021), Gemba means "actual place." To create value in an organization, performing work in the actual place helps to reduce waste and land overproduction for manufacturing. Gemba walks make problems visible and suggest improvement ideas with proper consideration of the root cause. The lean construction practices within the Planning and Control Practices category have a higher combined average selection rate.

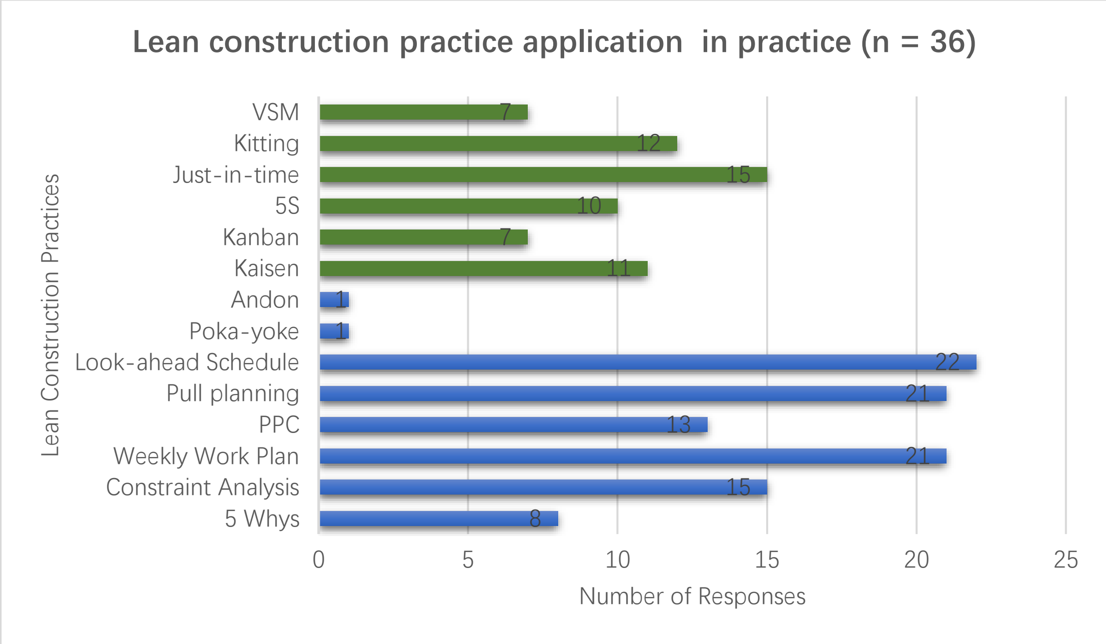


Figure 4.6 Lean Construction Practice Application in Practice (n = 36)

#### 4.4.1.1 Lean Construction Practices and Types of Construction Firms

Figure 4.7 shows the choice of lean construction practices by different construction companies. This result is obtained by applying lean construction practices as a data source to different types of construction companies. Nearly half (15 of 32, 47%) of the respondents chose Pull planning, Look-ahead schedule, and Weekly work plan as lean practices that are implemented in their construction company.

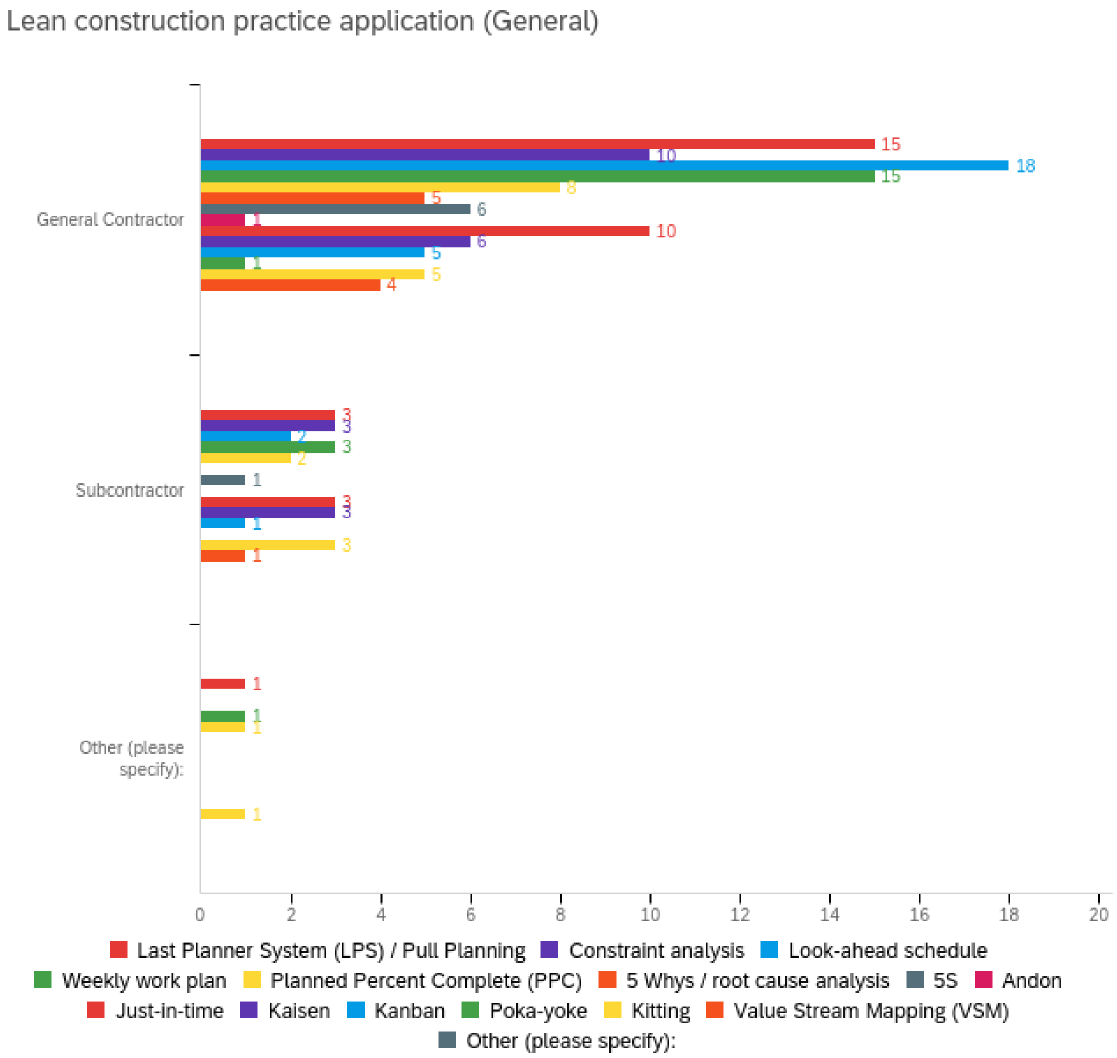


Figure 4.7 Lean Construction Practice Application (General)

#### 4.4.1.2 Lean Construction Practices and Work Trade

Figure 4.8 shows the choice of subcontractor work trade for lean construction practices. This result is obtained by applying lean construction practices as a data source to different types of work trades. Unselected work trade options are hidden. Mechanical contractors expressed little preference for lean construction practices. Pull planning, Constraint Analysis, Weekly work plan, JIT, Kaizen and Kitting were chosen by more Electrical subcontractors.

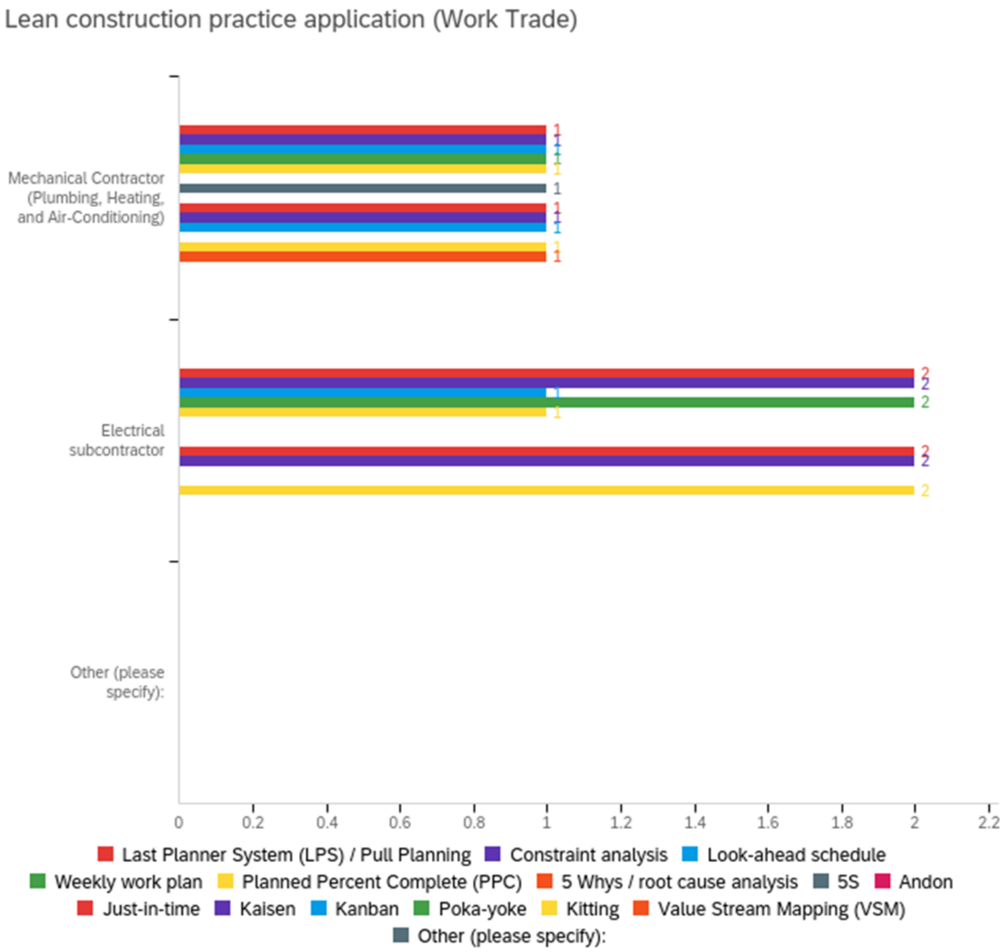


Figure 4.8 Lean Construction Practice Application (Work Trade)

### 4.4.2 Reasons for Lean Construction Applications

Below are the results of the participants' responses to the question "What was the reason for choosing the lean construction techniques/practices used in the project you were involved in?"

- *"Efficiency and constant improvement."*
- *"Such techniques help with efficiency and accountability for all team members at all levels within the company."*
- *"Our Mission is to Engage, Grow, and Empower People to lead the industry and one way we accomplish this is by living out the foundations of lean*

*construction through continuous improvement and respect for people. And we will continuously improve our industry through ongoing lean principles and practices."*

- *"Maintain competitiveness."*

### 4.4.3 Lean Construction Value Identification

Figure 4.9 and Table 4.1 show summaries of the responses the question "To what extent, using a scale of 0-5, do you think the application of lean construction techniques/practices on a project can provide the following added value?" All weighted means are above 3.0. "Improve efficiency" received the highest weighted mean rating at approximately 4.0 (high impact), while "Reduce costs" was rated the lowest overall (weighted mean rating = 3.45; moderate to high impact).

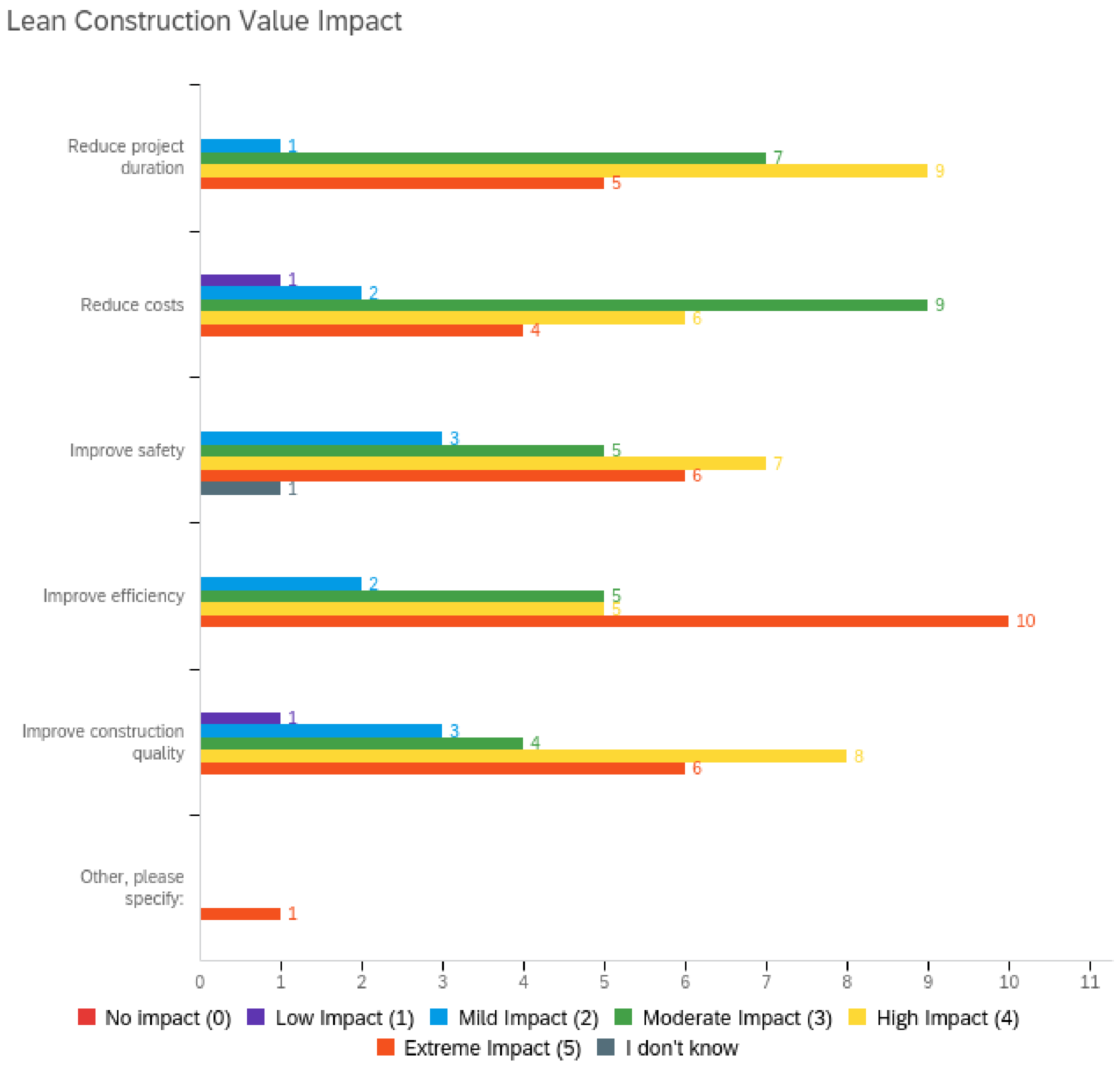


Figure 4.9 Lean Construction Value Impact

Table 4.1 Lean Construction Value Impact

| # | Value | No Impact (0) | | Low Impact (1) | | Mild Impact (2) | | Moderate Impact (3) | | High Impact (4) | | Extreme Impact (5) | | I don't know | | Total | Weighted Mean Rating |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | % | N | % | N | % | N | % | N | % | N | % | N | % | N | N | |
| 1 | Reduce project duration | 0.00% | 0 | 0.00% | 0 | 4.55% | 1 | 31.82% | 7 | 40.91% | 9 | 22.73% | 5 | 0.00% | 0 | 22 | 3.82 |
| 2 | Reduce costs | 0.00% | 0 | 4.55% | 1 | 9.09% | 2 | 40.91% | 9 | 27.27% | 6 | 18.18% | 4 | 0.00% | 0 | 22 | 3.45 |
| 3 | Improve safety | 0.00% | 0 | 0.00% | 0 | 13.64% | 3 | 22.73% | 5 | 31.82% | 7 | 27.27% | 6 | 4.55% | 1 | 22 | 3.76 |
| 4 | Improve efficiency | 0.00% | 0 | 0.00% | 0 | 9.09% | 2 | 22.73% | 5 | 22.73% | 5 | 45.45% | 10 | 0.00% | 0 | 22 | 4.05 |
| 5 | Improve construction quality | 0.00% | 0 | 4.55% | 1 | 13.64% | 3 | 18.18% | 4 | 36.36% | 8 | 27.27% | 6 | 0.00% | 0 | 22 | 3.68 |
| 6 | Other, please specify: | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 100.00% | 1 | 0.00% | 0 | 1 | 5.00 |

### 4.4.4 Lean Construction External Impact Factors

Figure 4.10 and Table 4.2 provide the results from the question "To what extent, using a scale of 0-5, do the External factors listed below affect the amount of added value?" All values except Weather Conditions and Finance of, and Payment for, Completed Work have a weighted mean rating above 3.0 (excluding others). Impact on Labor and Technical Personnel received weighted mean ratings greater than 4.0, indicating high to extreme impact.

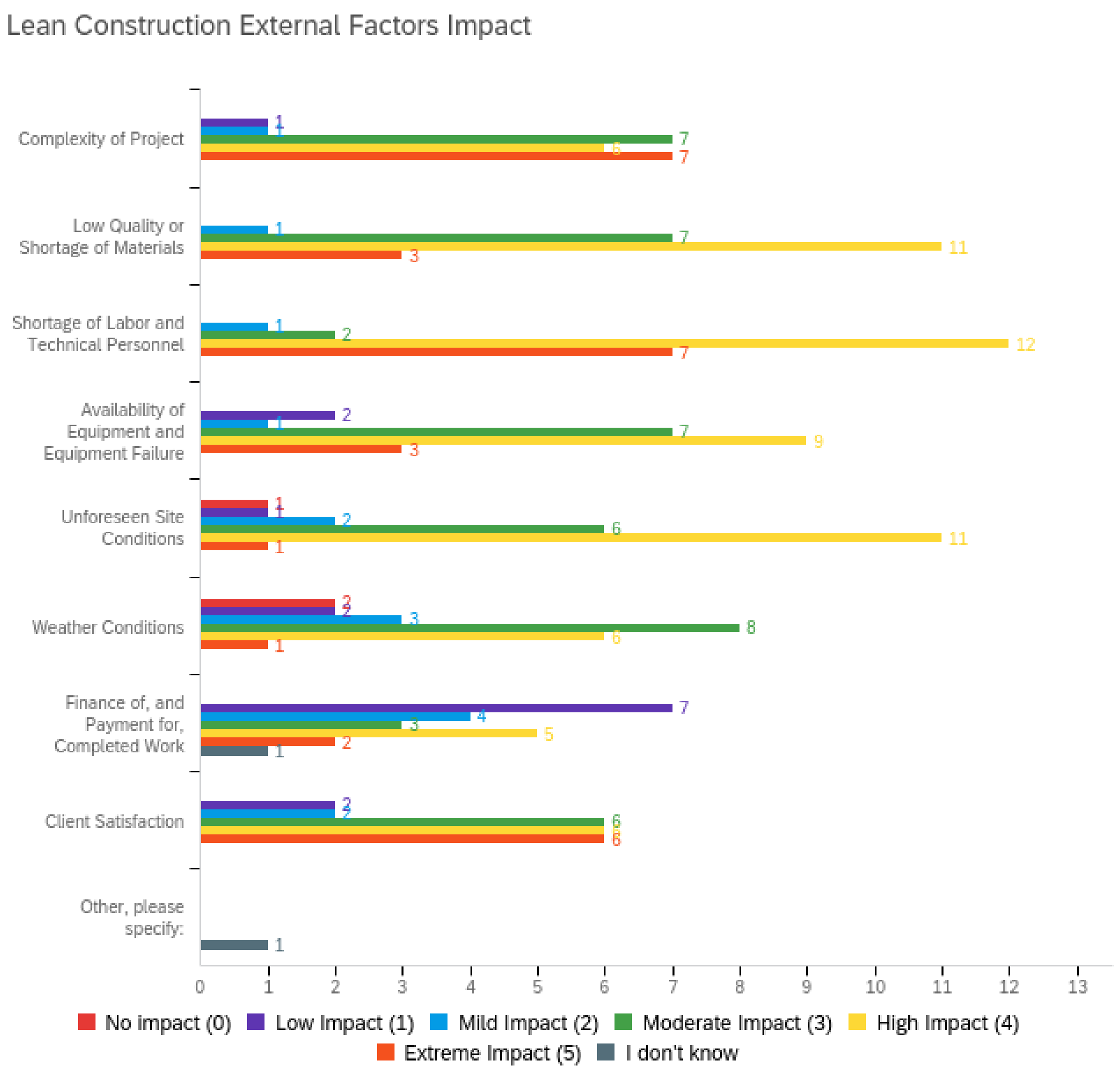


Figure 4.10 Lean Construction External Factors Impact

Table. 4.2 Lean Construction External Factors Impact

| # | External Factor | No Impact (0) | | Low Impact (1) | | Mild Impact (2) | | Moderate Impact (3) | | High Impact (4) | | Extreme Impact (5) | | I don't know | | Total | Weighted Mean Rating |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | % | N | % | N | % | N | % | N | % | N | % | N | % | N | N | |
| 1 | Complexity of Project | 0.00% | 0 | 4.55% | 1 | 4.55% | 1 | 31.82% | 7 | 27.27% | 6 | 31.82% | 7 | 0.00% | 0 | 22 | 3.77 |
| 2 | Low Quality or Shortage of Materials | 0.00% | 0 | 0.00% | 0 | 4.55% | 1 | 31.82% | 7 | 50.00% | 11 | 13.64% | 3 | 0.00% | 0 | 22 | 3.73 |
| 3 | Shortage of Labor and Technical Personnel | 0.00% | 0 | 0.00% | 0 | 4.55% | 1 | 9.09% | 2 | 54.55% | 12 | 31.82% | 7 | 0.00% | 0 | 22 | 4.14 |
| 4 | Availability of Equipment and Equipment Failure | 0.00% | 0 | 9.09% | 2 | 4.55% | 1 | 31.82% | 7 | 40.91% | 9 | 13.64% | 3 | 0.00% | 0 | 22 | 3.45 |
| 5 | Unforeseen Site Conditions | 4.55% | 1 | 4.55% | 1 | 9.09% | 2 | 27.27% | 6 | 50.00% | 11 | 4.55% | 1 | 0.00% | 0 | 22 | 3.27 |
| 6 | Weather Conditions | 9.09% | 2 | 9.09% | 2 | 13.64% | 3 | 36.36% | 8 | 27.27% | 6 | 4.55% | 1 | 0.00% | 0 | 22 | 2.77 |
| 7 | Finance of, and Payment for Completed Work | 0.00% | 0 | 31.82% | 7 | 18.18% | 4 | 13.64% | 3 | 22.73% | 5 | 9.09% | 2 | 4.55% | 1 | 22 | 2.57 |
| 8 | Client Satisfaction | 0.00% | 0 | 9.09% | 2 | 9.09% | 2 | 27.27% | 6 | 27.27% | 6 | 27.27% | 6 | 0.00% | 0 | 22 | 3.55 |
| 9 | Other, please specify: | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 100.00 % | 1 | 1 | 0.00 |

### 4.4.5 Lean Construction Internal Impact Factors

Figure 4.9 and Table 4.3 show summaries of the responses to the question "To what extent, using a scale of 0-5, do the Internal factors listed below affect the amount of added value?" All values have a weighted mean rating above 3.0 (excluding others). Weighted mean ratings greater than 4.0 (high impact) were given for poor planning, poor communication, and attitudes of site personnel towards work.

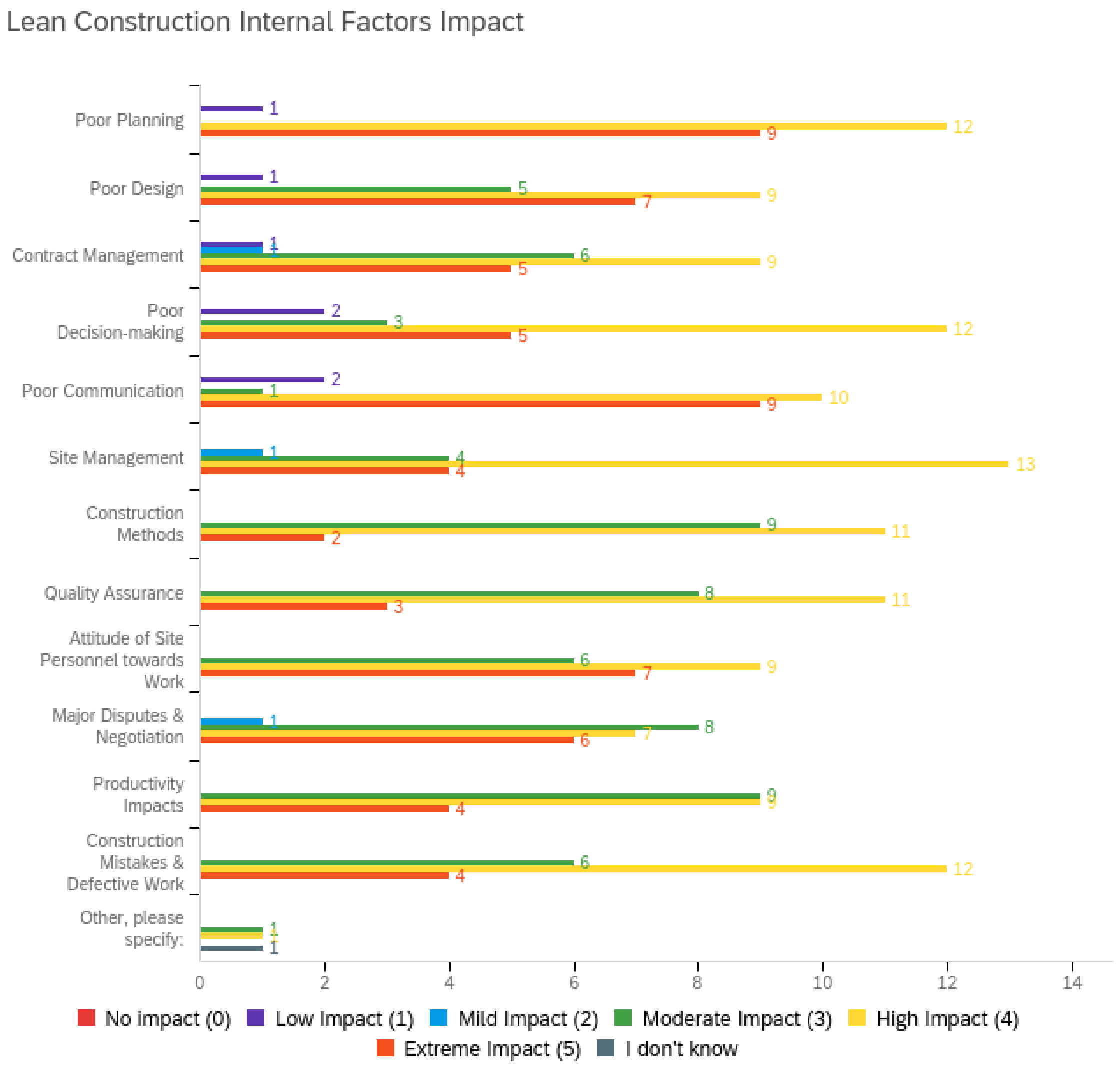


Figure 4.11 Lean Construction Internal Factors Impact

Table 4.3 Lean Construction Internal Factors Impact

| # | Internal Factor | No Impact (0) | | Low Impact (1) | | Mild Impact (2) | | Moderate Impact (3) | | High Impact (4) | | Extreme Impact (5) | | I don't know | | Total | Weighted Mean Rating |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | % | N | % | N | % | N | % | N | % | N | % | N | % | N | N | |
| 1 | Poor Planning | 0.00% | 0 | 4.55% | 1 | 0.00% | 0 | 0.00% | 0 | 54.55% | 12 | 40.91% | 9 | 0.00% | 0 | 22 | 4.27 |
| 2 | Poor Design | 0.00% | 0 | 4.55% | 1 | 0.00% | 0 | 22.73% | 5 | 40.91% | 9 | 31.82% | 7 | 0.00% | 0 | 22 | 3.95 |
| 3 | Contract Management | 0.00% | 0 | 4.55% | 1 | 4.55% | 1 | 27.27% | 6 | 40.91% | 9 | 22.73% | 5 | 0.00% | 0 | 22 | 3.73 |
| 4 | Poor Decision-making | 0.00% | 0 | 9.09% | 2 | 0.00% | 0 | 13.64% | 3 | 54.55% | 12 | 22.73% | 5 | 0.00% | 0 | 22 | 3.82 |
| 5 | Poor Communication | 0.00% | 0 | 9.09% | 2 | 0.00% | 0 | 4.55% | 1 | 45.45% | 10 | 40.91% | 9 | 0.00% | 0 | 22 | 4.09 |
| 6 | Site Management | 0.00% | 0 | 0.00% | 0 | 4.55% | 1 | 18.18% | 4 | 59.09% | 13 | 18.18% | 4 | 0.00% | 0 | 22 | 3.91 |
| 7 | Construction Methods | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 40.91% | 9 | 50.00% | 11 | 9.09% | 2 | 0.00% | 0 | 22 | 3.68 |
| 8 | Quality Assurance | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 36.36% | 8 | 50.00% | 11 | 13.64% | 3 | 0.00% | 0 | 22 | 3.77 |
| 9 | Attitude of Site Personnel towards Work | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 27.27% | 6 | 40.91% | 9 | 31.82% | 7 | 0.00% | 0 | 22 | 4.05 |
| 10 | Major Disputes & Negotiation | 0.00% | 0 | 0.00% | 0 | 4.55% | 1 | 36.36% | 8 | 31.82% | 7 | 27.27% | 6 | 0.00% | 0 | 22 | 3.82 |
| 11 | Productivity Impacts | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 40.91% | 9 | 40.91% | 9 | 18.18% | 4 | 0.00% | 0 | 22 | 3.77 |
| 12 | Construction Mistakes & Defective Work | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 27.27% | 6 | 54.55% | 12 | 18.18% | 4 | 0.00% | 0 | 22 | 3.91 |
| 13 | Other, please specify: | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 33.33% | 1 | 33.33% | 1 | 0.00% | 0 | 33.33% | 1 | 3 | 2.33 |

### 4.4.6 Lean Construction Waste Identification

Figure 4.10 and Table 4.4 show the results from the question “To what extent, using a scale of 0-5, do you think the application of lean construction techniques/practices on a project can provide reductions in the following types of waste?” All weighted mean ratings are above 3.0 (excluding others). Inventory and waiting have the highest weighted mean rating, while over-production has the lowest.

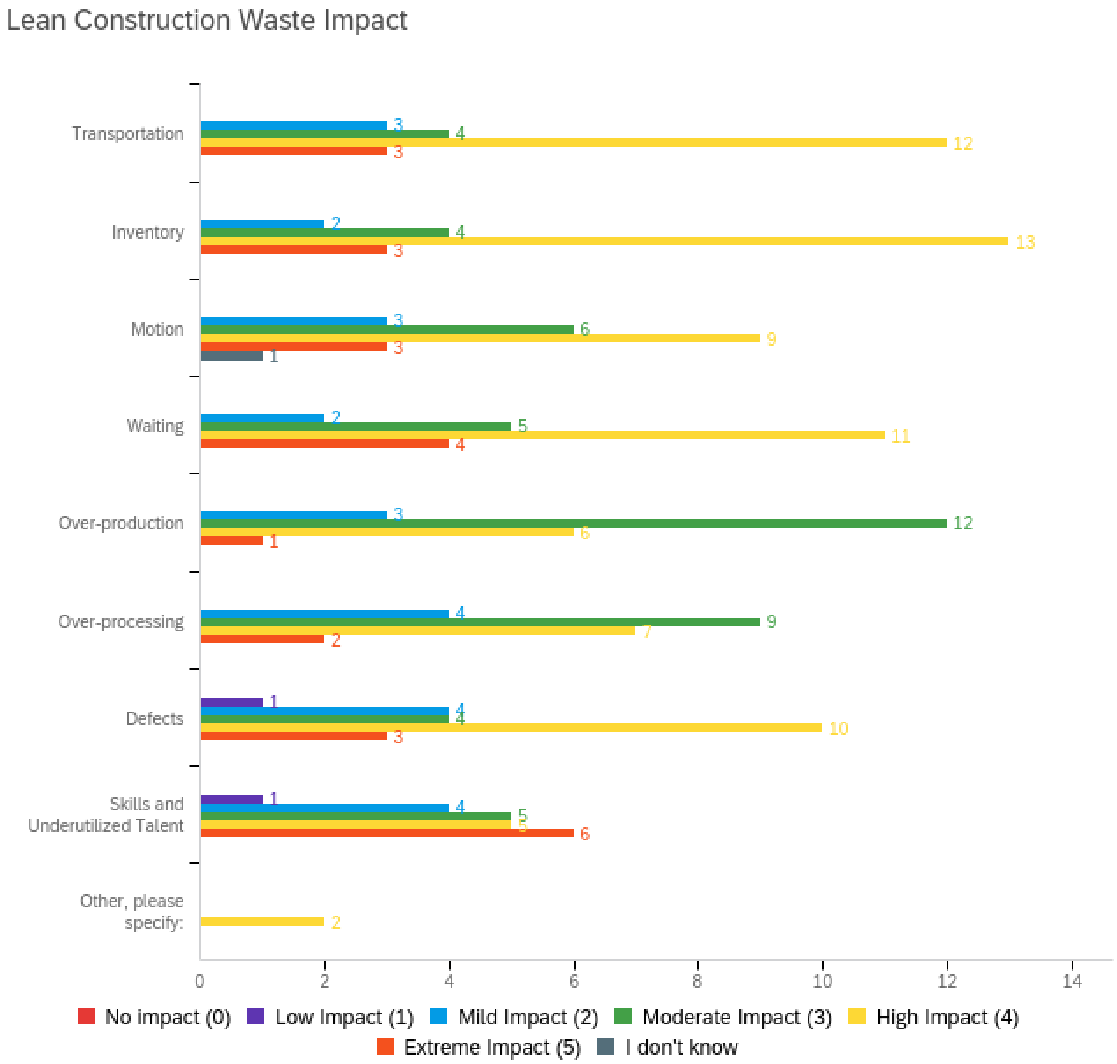


Figure 4.12 Lean Construction Waste Impact

Table. 4.4 Lean Construction Waste Impact

| # | Type of Waste | No Impact (0) | | Low Impact (1) | | Mild Impact (2) | | Moderate Impact (3) | | High Impact (4) | | Extreme Impact (5) | | I don't know | | Total | Weighted Mean Rating |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | % | N | % | N | % | N | % | N | % | N | % | N | % | N | N | |
| 1 | Unneeded Transportation | 0.00% | 0 | 0.00% | 0 | 13.64% | 3 | 18.18% | 4 | 54.55% | 12 | 13.64% | 3 | 0.00% | 0 | 22 | 3.68 |
| 2 | Extra Inventory | 0.00% | 0 | 0.00% | 0 | 9.09% | 2 | 18.18% | 4 | 59.09% | 13 | 13.64% | 3 | 0.00% | 0 | 22 | 3.77 |
| 3 | Unneeded Motion | 0.00% | 0 | 0.00% | 0 | 13.64% | 3 | 27.27% | 6 | 40.91% | 9 | 13.64% | 3 | 4.55% | 1 | 22 | 3.57 |
| 4 | Waiting | 0.00% | 0 | 0.00% | 0 | 9.09% | 2 | 22.73% | 5 | 50.00% | 11 | 18.18% | 4 | 0.00% | 0 | 22 | 3.77 |
| 5 | Over-production | 0.00% | 0 | 0.00% | 0 | 13.64% | 3 | 54.55% | 12 | 27.27% | 6 | 4.55% | 1 | 0.00% | 0 | 22 | 3.23 |
| 6 | Over-processing | 0.00% | 0 | 0.00% | 0 | 18.18% | 4 | 40.91% | 9 | 31.82% | 7 | 9.09% | 2 | 0.00% | 0 | 22 | 3.32 |
| 7 | Defects | 0.00% | 0 | 4.55% | 1 | 18.18% | 4 | 18.18% | 4 | 45.45% | 10 | 13.64% | 3 | 0.00% | 0 | 22 | 3.45 |
| 8 | Underutilized Skills and Talent | 0.00% | 0 | 4.76% | 1 | 19.05% | 4 | 23.81% | 5 | 23.81% | 5 | 28.57% | 6 | 0.00% | 0 | 21 | 3.36 |
| 9 | Other, please specify: | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 100.00% | 1 | 0.00% | 0 | 0.00% | 0 | 2 | 2.50 |

## 4.5 Construction Industrialization

### 4.5.1 Construction Industrialization Methods

Figure 4.11 shows a summary of the responses to the question "Please indicate the types of construction industrialization applications implemented on your projects. Select all that apply." The selectivity for Mass production is relatively low, while Preassembly and Prefabrication are implemented by more companies.

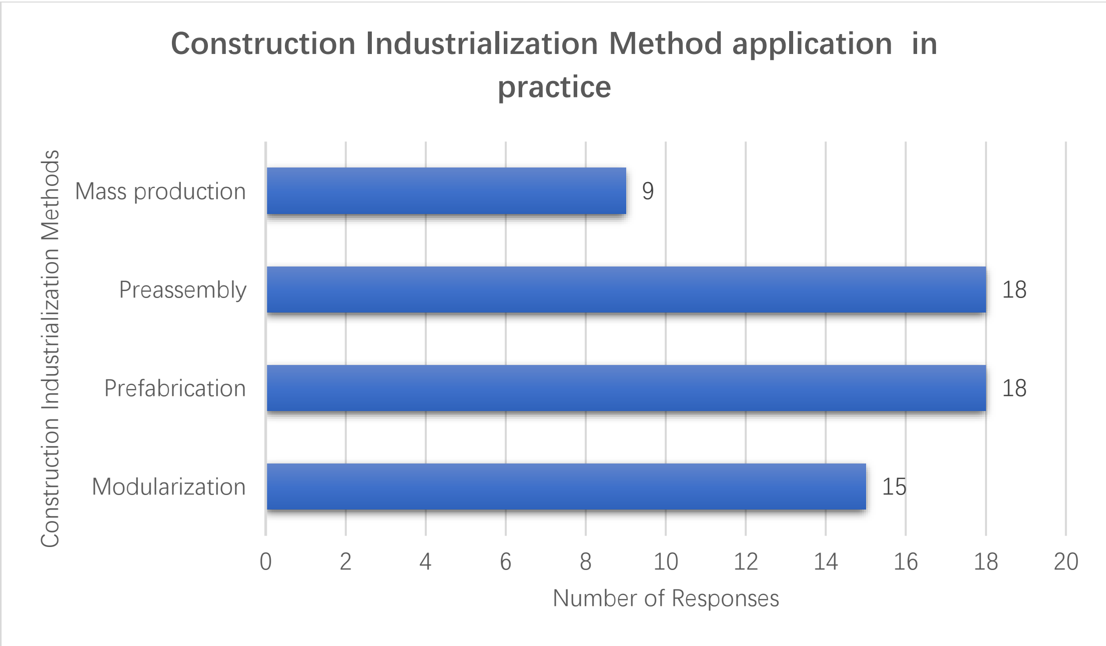


Figure 4.13 Construction Industrialization Method Application in Practice

#### 4.5.1.1 Construction Industrialization Methods and Types of Construction Firms

Figure 4.14 shows the construction company's choice of construction industrialization methods according to the type of construction company (general contractor or subcontractor). This result is obtained by applying construction industrialization methods as a data source to different types of construction companies. The work trade options that were not selected are not shown in the figure. More than 31% (10 out of 32) of the construction companies use Modularization, Prefabrication, or Preassembly.

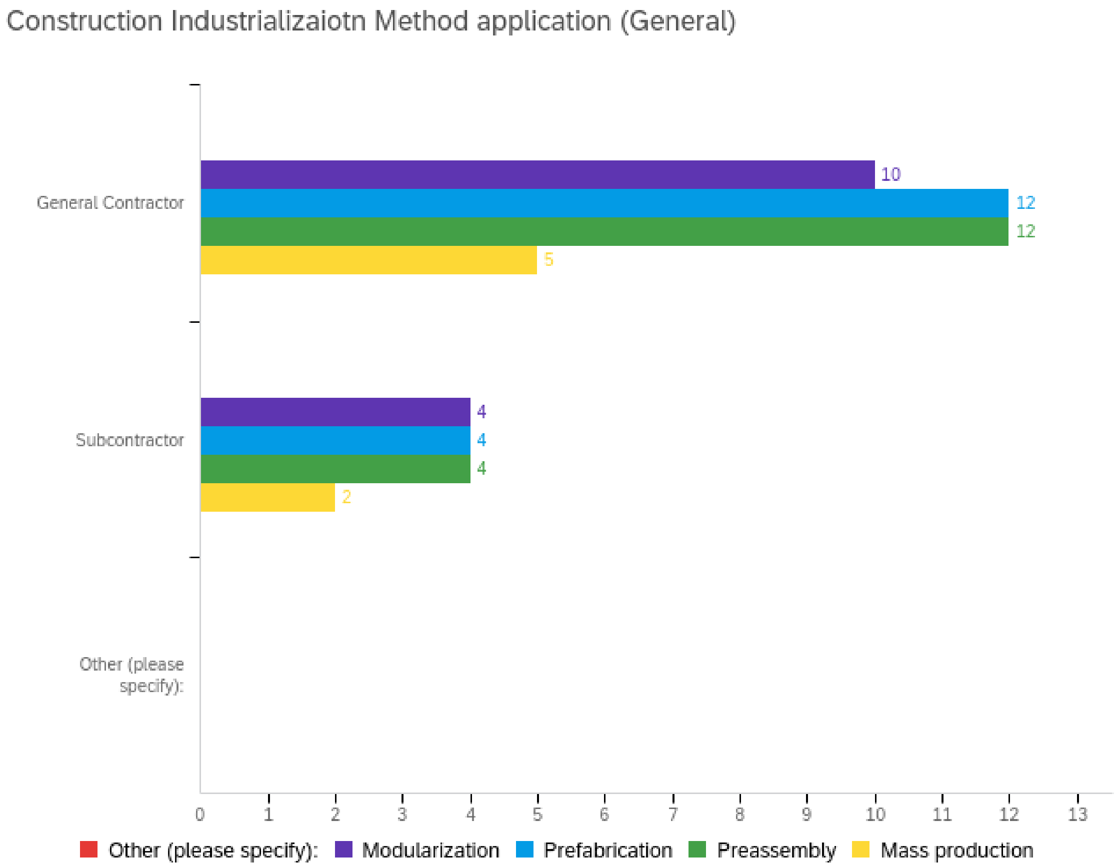


Figure 4.14 Construction Industrialization Method Application (General)

#### 4.5.1.2 Construction Industrialization Methods and Work Trade

Figure 4.15 illustrates the responses regarding construction industrialization method according to the subcontractor's work trade. This result is obtained by applying construction industrialization methods as a data source to different types of work trades. Unselected work trades are not shown. While the number of responses is low, mechanical contractors and electrical subcontractors choose to have little preference for construction industrialization methods, and almost all of the methods have been used.

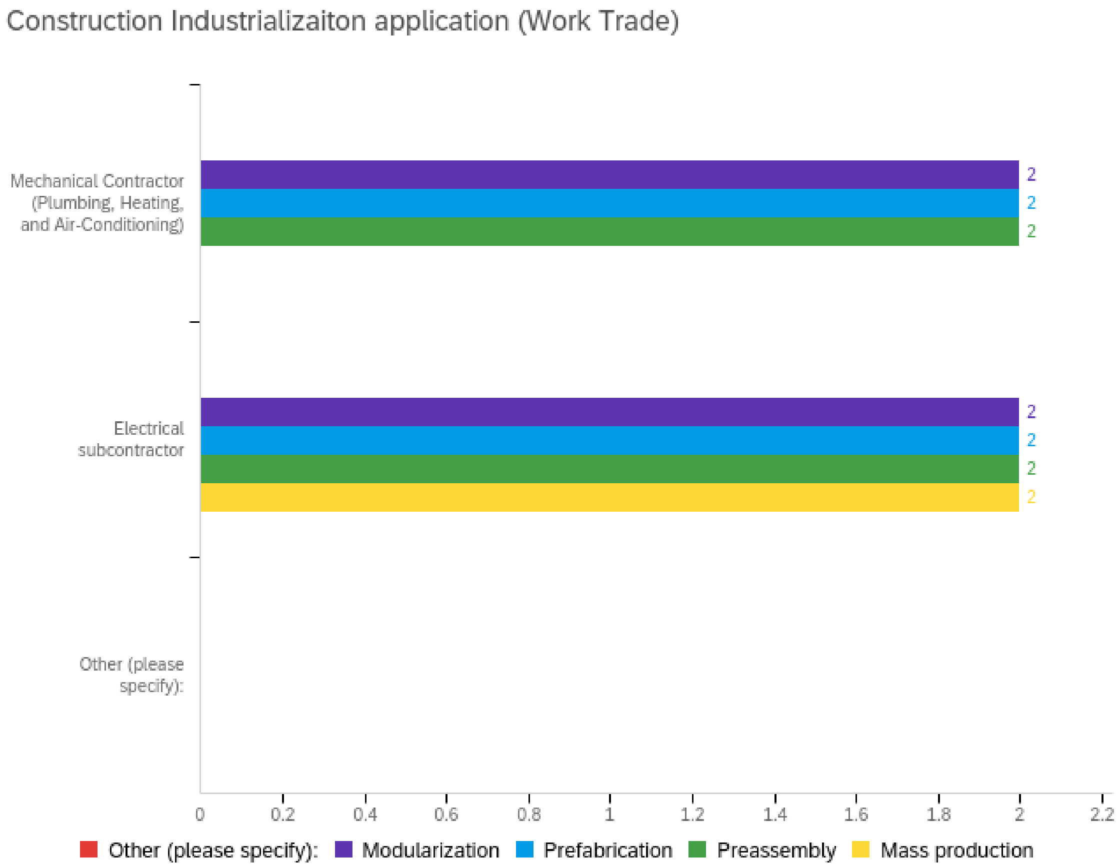


Figure 4.15 Construction Industrialization Application (Work Trade)

### 4.5.2 Reasons For Construction Industrialization Applications

Below are the results of the participants' responses to the question "What are the reasons for choosing the construction industrialization applications that are implemented on your projects?"

- *"One reason is to bring value to the project by solving problems early with innovative solutions provided by the team in a big room team meeting"*
- *"Schedule savings."*
- *"CPI is a core value at our company."*
- *"Safer work, more quality product, less waste, more efficient, lower cost."*

- *"Standardization, efficiencies, JIT deliveries, minimize project site storage, decrease project site labor."*
- *"Performing as much work in a controlled environment, as our fabrication shops allow for increased productivity and reduced travel and non-productive time."*

### 4.5.3 Construction Industrialization Value Identification

Figure 4.16 and Table 4.5 present a summary of the responses to the question "To what extent, using a scale of 0-5, do you think the application of construction industrialization on a project can provide the following added value?" All weighted mean ratings are above 3.0, where Reduce project duration, Improve safety, and Improve efficiency received the highest weighted mean ratings (all above 4.0).

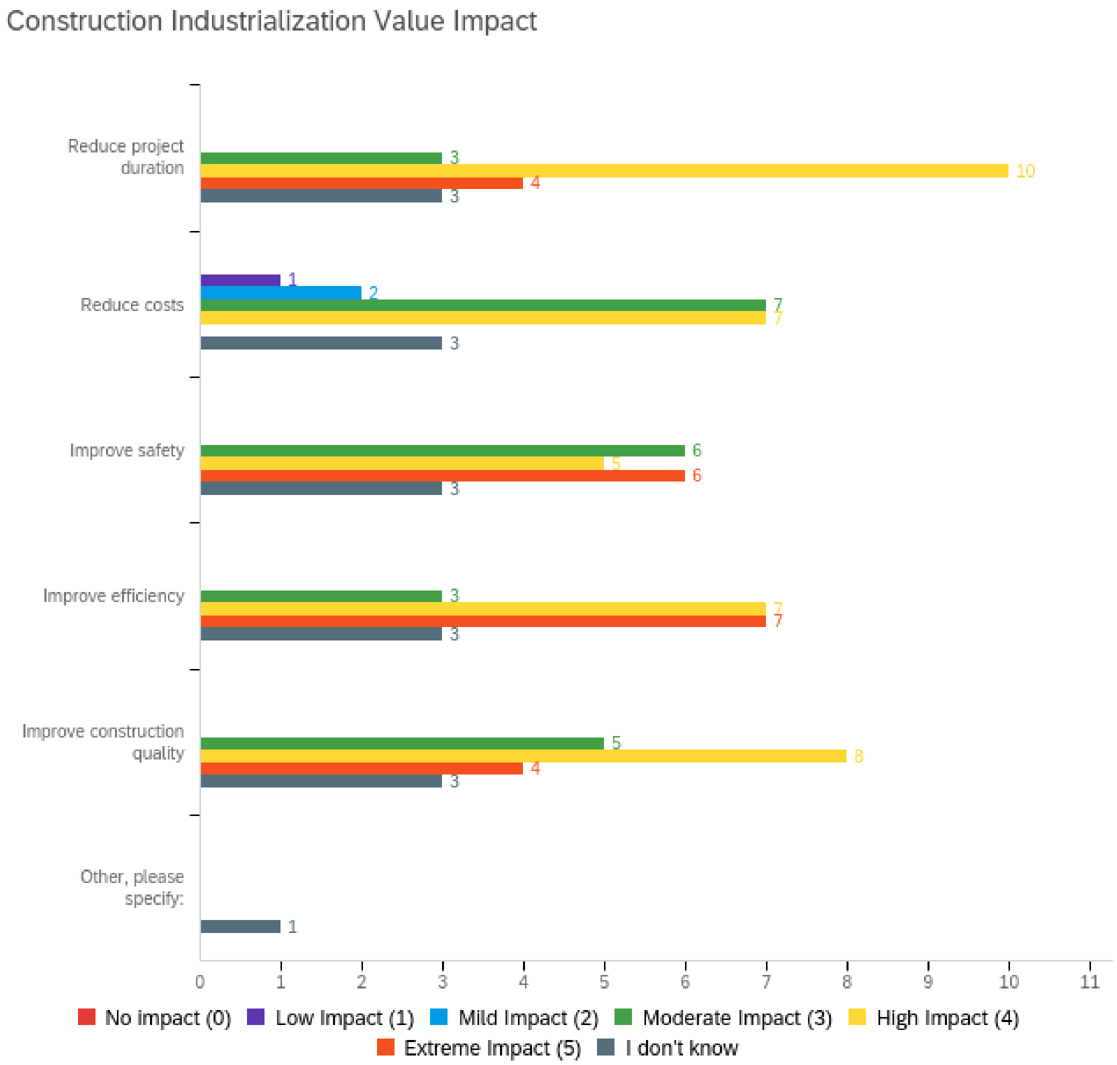


Figure 4.16 Construction Industrialization Value Impact

Table 4.5 Construction Industrialization Value Impact

| # | Value | No Impact (0) | | Low Impact (1) | | Mild Impact (2) | | Moderate Impact (3) | | High Impact (4) | | Extreme Impact (5) | | I don't know | | Total | Weighted Mean Rating |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | % | N | % | N | % | N | % | N | % | N | % | N | % | N | N | |
| 1 | Reduce project duration | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 15.00% | 3 | 50.00% | 10 | 20.00% | 4 | 15.00% | 3 | 20 | 4.06 |
| 2 | Reduce costs | 0.00% | 0 | 5.00% | 1 | 10.00% | 2 | 35.00% | 7 | 35.00% | 7 | 0.00% | 0 | 15.00% | 3 | 20 | 3.18 |
| 3 | Improve safety | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 30.00% | 6 | 25.00% | 5 | 30.00% | 6 | 15.00% | 3 | 20 | 4.00 |
| 4 | Improve efficiency | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 15.00% | 3 | 35.00% | 7 | 35.00% | 7 | 15.00% | 3 | 20 | 4.24 |
| 5 | Improve construction quality | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 25.00% | 5 | 40.00% | 8 | 20.00% | 4 | 15.00% | 3 | 20 | 3.94 |
| 6 | Other, please specify: | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 100.00% | 1 | 1 | 0.00 |

### 4.5.4 Construction Industrialization External Impact Factors

Figure 4.17 and Table 4.6 illustrate the responses to the question "To what extent, using a scale of 0-5, do the External factors listed below affect the amount of added value?" As can be seen in the figure and table, all weighted mean ratings are higher than 3.0 (excluding others). The lowest weighted mean rating was given for Finance of, and Payment for, Completed Work (weighted mean rating = 2.78). Complexity of the project received the highest weighted mean rating (4.0, high impact).

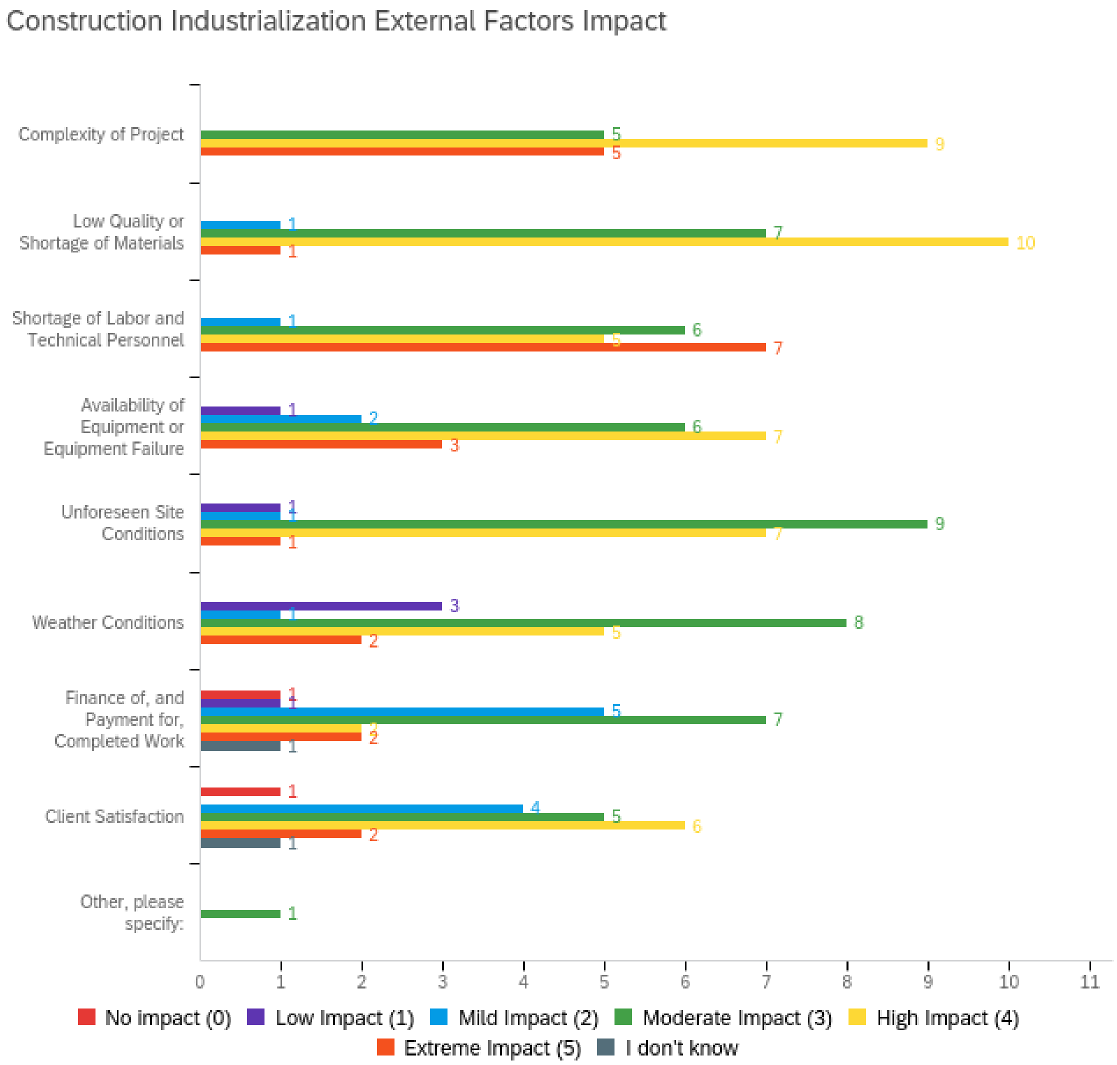


Figure 4.17 Construction Industrialization External Factors Impact

Table 4.6 Construction Industrialization External Factors Impact

| # | External Factor | No Impact (0) | | Low Impact (1) | | Mild Impact (2) | | Moderate Impact (3) | | High Impact (4) | | Extreme Impact (5) | | I don't know | | Total | Weighted Mean Rating |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | % | N | % | N | % | N | % | N | % | N | % | N | % | N | N | |
| 1 | Complexity of Project | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 26.32% | 5 | 47.37% | 9 | 26.32% | 5 | 0.00% | 0 | 19 | 4.00 |
| 2 | Low Quality or Shortage of Materials | 0.00% | 0 | 0.00% | 0 | 5.26% | 1 | 36.84% | 7 | 52.63% | 10 | 5.26% | 1 | 0.00% | 0 | 19 | 3.58 |
| 3 | Shortage of Labor and Technical Personnel | 0.00% | 0 | 0.00% | 0 | 5.26% | 1 | 31.58% | 6 | 26.32% | 5 | 36.84% | 7 | 0.00% | 0 | 19 | 3.95 |
| 4 | Availability of Equipment or Equipment Failure | 0.00% | 0 | 5.26% | 1 | 10.53% | 2 | 31.58% | 6 | 36.84% | 7 | 15.79% | 3 | 0.00% | 0 | 19 | 3.47 |
| 5 | Unforeseen Site Conditions | 0.00% | 0 | 5.26% | 1 | 5.26% | 1 | 47.37% | 9 | 36.84% | 7 | 5.26% | 1 | 0.00% | 0 | 19 | 3.32 |
| 6 | Weather Conditions | 0.00% | 0 | 15.79% | 3 | 5.26% | 1 | 42.11% | 8 | 26.32% | 5 | 10.53% | 2 | 0.00% | 0 | 19 | 3.11 |
| 7 | Finance of, and Payment for, Completed Work | 5.26% | 1 | 5.26% | 1 | 26.32% | 5 | 36.84% | 7 | 10.53% | 2 | 10.53% | 2 | 5.26% | 1 | 19 | 2.78 |
| 8 | Client Satisfaction | 5.26% | 1 | 0.00% | 0 | 21.05% | 4 | 26.32% | 5 | 31.58% | 6 | 10.53% | 2 | 5.26% | 1 | 19 | 3.17 |
| 9 | Other, please specify: | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 100.00% | 1 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 1 | 3.00 |

### 4.5.5 Construction Industrialization Internal Impact Factors

Figure 4.18 and Table 4.7 show summaries of the responses to the question "To what extent, using a scale of 0-5, do the Internal factors listed below affect the amount of added value?" All of the internal factors received weighted mean ratings above 3.0 (excluding others), with Attitude of Site Personnel Towards Work and Productivity rated highest (weighted mean rating = 4.05 and 4.11, respectively).

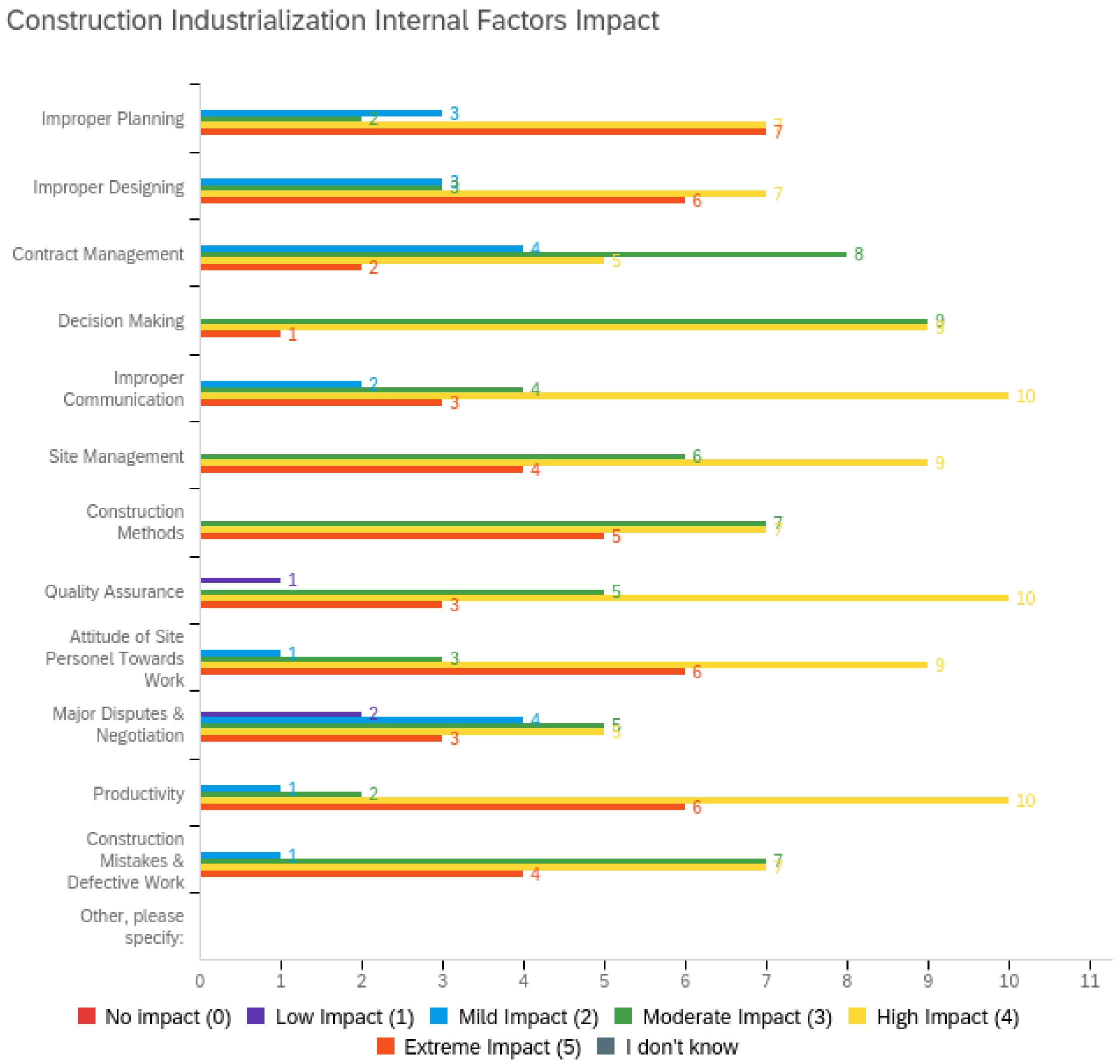


Figure 4.18 Construction Industrialization Internal Factors Impact

Table 4.7 Construction Industrialization Internal Factors Impact

| # | Internal Factor | No Impact (0) | | Low Impact (1) | | Mild Impact (2) | | Moderate Impact (3) | | High Impact (4) | | Extreme Impact (5) | | I don't know | | Total | Weighted Mean Rating |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | % | N | % | N | % | N | % | N | % | N | % | N | % | N | N | |
| 1 | Improper Planning | 0.00% | 0 | 0.00% | 0 | 15.79% | 3 | 10.53% | 2 | 36.84% | 7 | 36.84% | 7 | 0.00% | 0 | 19 | 3.95 |
| 2 | Improper Designing | 0.00% | 0 | 0.00% | 0 | 15.79% | 3 | 15.79% | 3 | 36.84% | 7 | 31.58% | 6 | 0.00% | 0 | 19 | 3.84 |
| 3 | Contract Management | 0.00% | 0 | 0.00% | 0 | 21.05% | 4 | 42.11% | 8 | 26.32% | 5 | 10.53% | 2 | 0.00% | 0 | 19 | 3.26 |
| 4 | Decision Making | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 47.37% | 9 | 47.37% | 9 | 5.26% | 1 | 0.00% | 0 | 19 | 3.58 |
| 5 | Improper Communication | 0.00% | 0 | 0.00% | 0 | 10.53% | 2 | 21.05% | 4 | 52.63% | 10 | 15.79% | 3 | 0.00% | 0 | 19 | 3.74 |
| 6 | Site Management | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 31.58% | 6 | 47.37% | 9 | 21.05% | 4 | 0.00% | 0 | 19 | 3.89 |
| 7 | Construction Methods | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 36.84% | 7 | 36.84% | 7 | 26.32% | 5 | 0.00% | 0 | 19 | 3.89 |
| 8 | Quality Assurance | 0.00% | 0 | 5.26% | 1 | 0.00% | 0 | 26.32% | 5 | 52.63% | 10 | 15.79% | 3 | 0.00% | 0 | 19 | 3.74 |
| 9 | Attitude of Site Personnel Towards Work | 0.00% | 0 | 0.00% | 0 | 5.26% | 1 | 15.79% | 3 | 47.37% | 9 | 31.58% | 6 | 0.00% | 0 | 19 | 4.05 |
| 10 | Major Disputes & Negotiation | 0.00% | 0 | 10.53% | 2 | 21.05% | 4 | 26.32% | 5 | 26.32% | 5 | 15.79% | 3 | 0.00% | 0 | 19 | 3.16 |
| 11 | Productivity | 0.00% | 0 | 0.00% | 0 | 5.26% | 1 | 10.53% | 2 | 52.63% | 10 | 31.58% | 6 | 0.00% | 0 | 19 | 4.11 |
| 12 | Construction Mistakes & Defective Work | 0.00% | 0 | 0.00% | 0 | 5.26% | 1 | 36.84% | 7 | 36.84% | 7 | 21.05% | 4 | 0.00% | 0 | 19 | 3.74 |
| 13 | Other, please specify: | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0 | None |

### 4.5.6 Construction Industrialization Waste Identification

Figure 4.19 and Table 4.8 illustrate the responses received to the question "To what extent, using a scale of 0-5, do you think the application of construction industrialization on a project can provide reductions in the following types of waste?" All types of waste received weighted mean ratings above 3.0 (excluding others). Inventory, motion and waiting have the highest weighted mean rating, and over-processing has the lowest weighted mean rating.

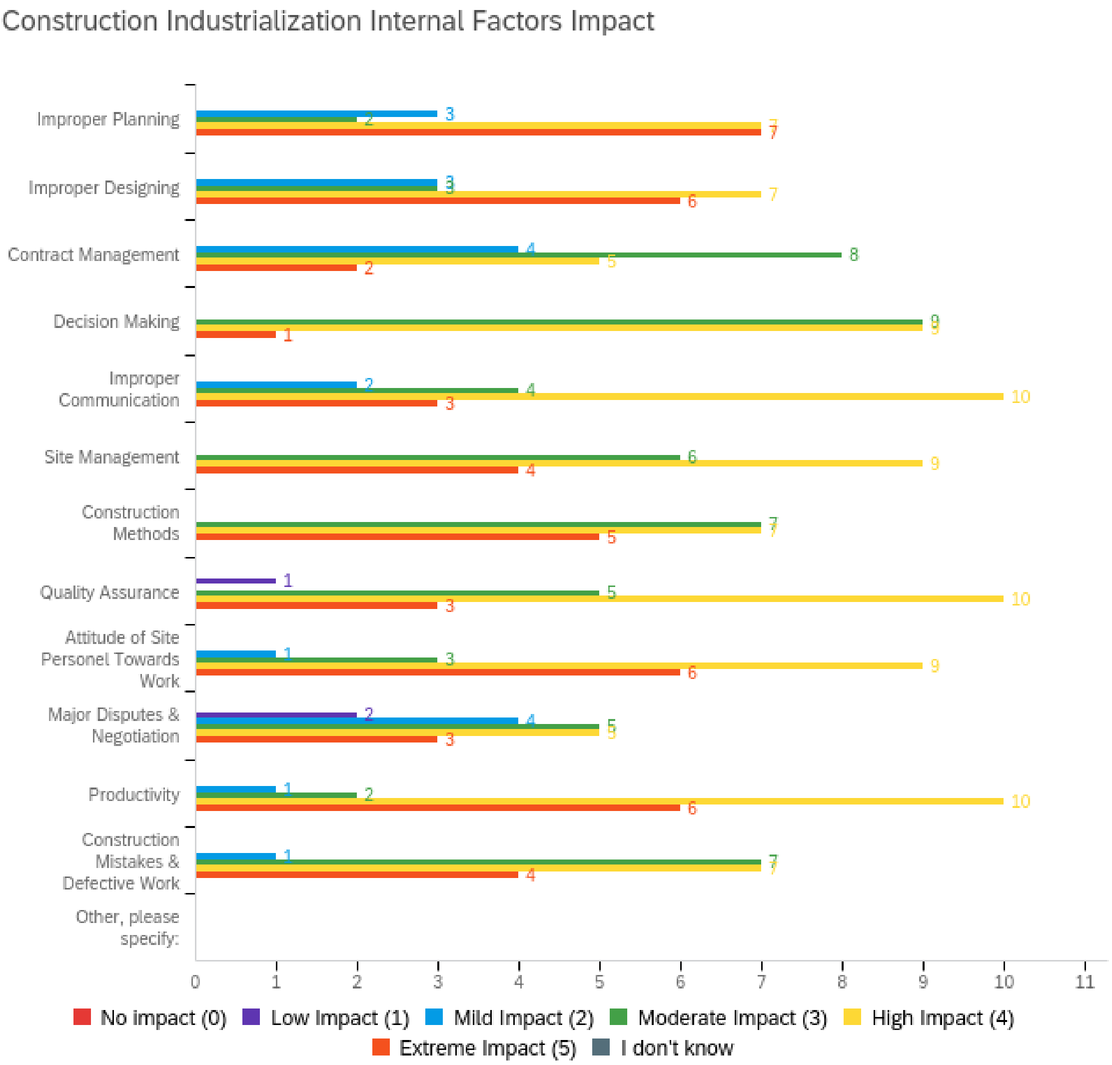


Figure 4.19 Construction Industrialization Waste Impact

Table 4.8 Construction Industrialization Waste Impact

| # | Type of Waste | No Impact (0) | | Low Impact (1) | | Mild Impact (2) | | Moderate Impact (3) | | High Impact (4) | | Extreme Impact (5) | | I don't know | | Total | Weighted Mean Rating |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | % | N | % | N | % | N | % | N | % | N | % | N | % | N | N | |
| 1 | Unneeded Transportation | 0.00% | 0 | 0.00% | 0 | 15.79% | 3 | 31.58% | 6 | 42.11% | 8 | 10.53% | 2 | 0.00% | 0 | 19 | 3.47 |
| 2 | Extra Inventory | 0.00% | 0 | 0.00% | 0 | 5.26% | 1 | 31.58% | 6 | 52.63% | 10 | 10.53% | 2 | 0.00% | 0 | 19 | 3.68 |
| 3 | Unneeded Motion | 0.00% | 0 | 0.00% | 0 | 5.26% | 1 | 36.84% | 7 | 42.11% | 8 | 15.79% | 3 | 0.00% | 0 | 19 | 3.68 |
| 4 | Waiting | 0.00% | 0 | 0.00% | 0 | 10.53% | 2 | 26.32% | 5 | 47.37% | 9 | 15.79% | 3 | 0.00% | 0 | 19 | 3.68 |
| 5 | Over-production | 0.00% | 0 | 0.00% | 0 | 21.05% | 4 | 31.58% | 6 | 36.84% | 7 | 10.53% | 2 | 0.00% | 0 | 19 | 3.37 |
| 6 | Over-processing | 0.00% | 0 | 10.53% | 2 | 10.53% | 2 | 21.05% | 4 | 42.11% | 8 | 15.79% | 3 | 0.00% | 0 | 19 | 3.42 |
| 7 | Defects | 0.00% | 0 | 10.53% | 2 | 5.26% | 1 | 21.05% | 4 | 42.11% | 8 | 21.05% | 4 | 0.00% | 0 | 19 | 3.58 |
| 8 | Underutilized Skills and Talent | 0.00% | 0 | 10.53% | 2 | 5.26% | 1 | 42.11% | 8 | 21.05% | 4 | 21.05% | 4 | 0.00% | 0 | 19 | 3.37 |
| 9 | Other (please specify): | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0 | None |

## 4.6 Combination of Lean Construction and Construction Industrialization

### 4.6.1 Lean Construction Affect on Construction Industrialization

Figure 4.20 and Table 4.9 summarize the responses to the question “To what extent, using a scale of 0-5, does lean construction influence construction industrialization?” Ninety percent of the respondents (26 out of 29) chose a rating of 3.0 or greater. The weighted mean rating for all responses was 3.29, indicating moderate to high impact.

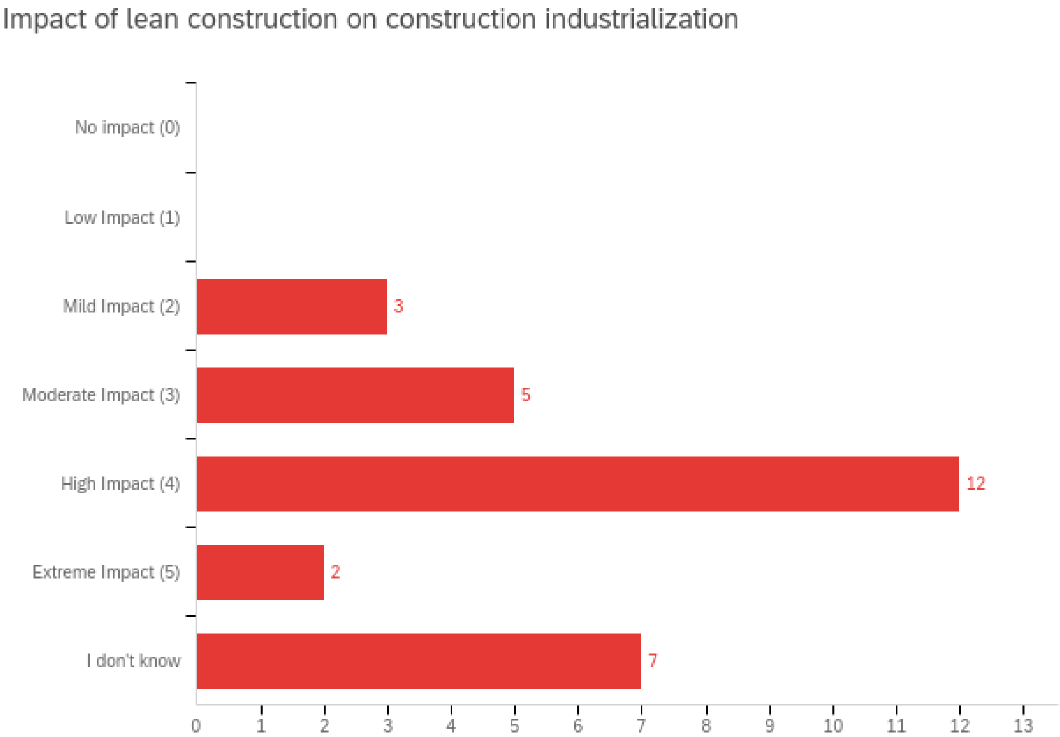


Figure 4.20 Impact of Lean Construction on Construction Industrialization

Table 4.9 Impact of Lean Construction on Construction Industrialization

| # | Rating | % | N |
|---|---|---|---|
| 1 | No Impact (0) | 0.00% | 0 |
| 2 | Low Impact (1) | 0.00% | 0 |
| 3 | Mild Impact (2) | 10.34% | 3 |
| 4 | Moderate Impact (3) | 17.24% | 5 |
| 5 | High Impact (4) | 41.38% | 12 |
| 6 | Extreme Impact (5) | 6.90% | 2 |
| 7 | I don't know | 24.14% | 7 |
| | Total | 100% | 29 |
| | Weighted Mean Rating | 3.59 | |

### 4.6.2 Construction Industrialization Affect on Lean Construction

Similarly, Figure 4.21 and Table 4.10 show summaries of the response to the question "To what extent, using a scale of 0-5, does construction industrialization influence lean construction?" Ninety percent of the respondents (27 out of 29) chose a rating of 3.0 or greater. The weighted mean rating for all responses was 3.41, indicating moderate to high impact.

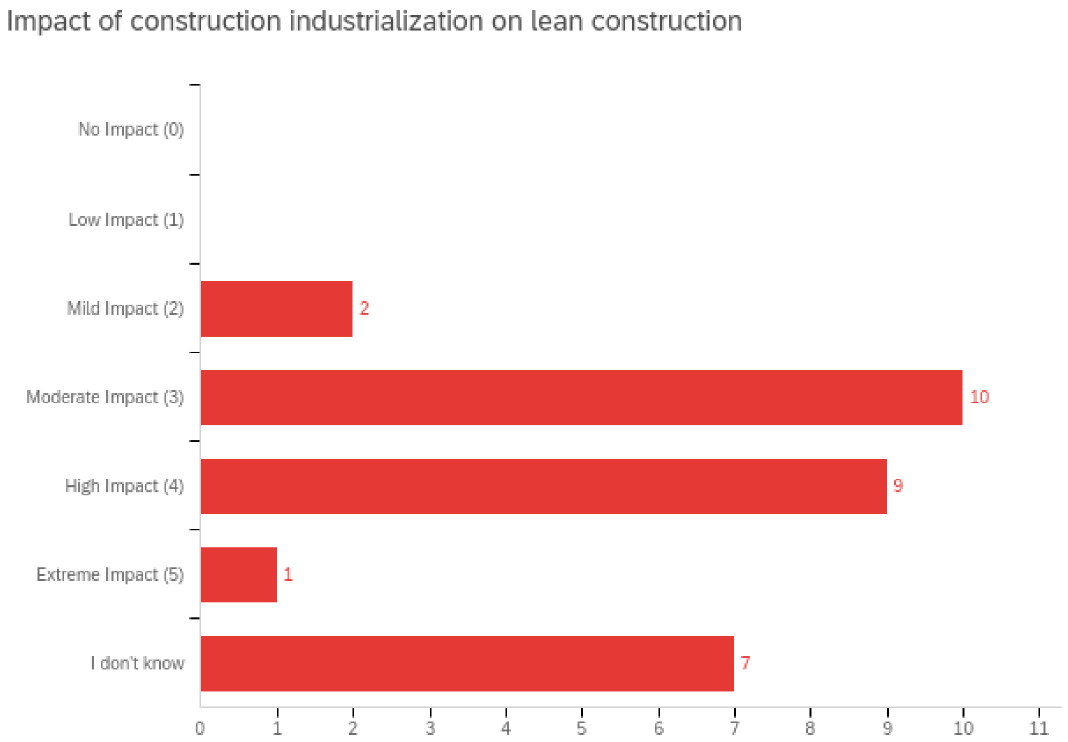


Figure 4.21 Impact of Construction Industrialization on Lean Construction

Table 4.10 Impact of Construction Industrialization on Lean Construction

| # | Rating | % | N |
|---|---|---|---|
| 1 | No Impact (0) | 0.00% | 0 |
| 2 | Low Impact (1) | 0.00% | 0 |
| 3 | Mild Impact (2) | 6.90% | 2 |
| 4 | Moderate Impact (3) | 34.48% | 10 |
| 5 | High Impact (4) | 31.03% | 9 |
| 6 | Extreme Impact (5) | 3.45% | 1 |
| 7 | I don't know | 24.14% | 7 |
| | Total | 100% | 29 |
| | Weighted Mean Rating | 3.41 | |

### 4.6.3 Budget Factors Affecting the Combination of Lean Construction and Construction Industrialization

Figure 4.22 and Table 4.11 summarize the responses to the question “When applying lean construction and construction industrialization together, to what extent are the following Budget factors impacted? Use a rating scale from -3 (high negative impact) to +3 (high positive impact).” All weighted mean ratings are above 1.00, except for Life-cycle costs. ‘Labor and soft costs’ has the highest weighted mean rating and ‘Life-cycle costs’ has the lowest weighted mean rating.

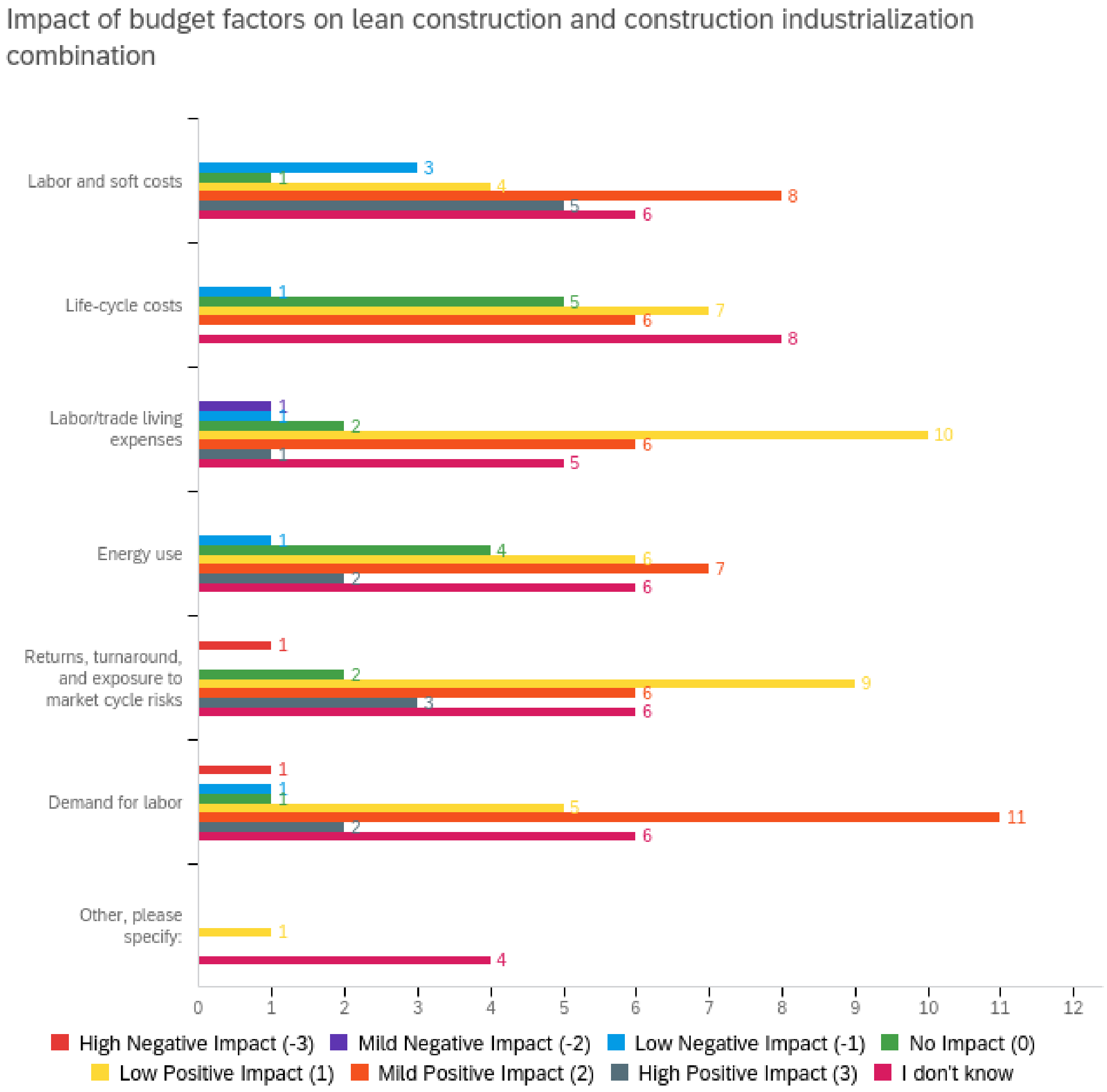


Figure 4.22 Impact of budget factors on lean construction and construction industrialization combination

Table 4.11 Impact of Budget Factors on Lean Construction and Construction Industrialization Combination

| # | Budget | High Negative Impact (-3) | | Mild Negative Impact (-2) | | Low Negative Impact (-1) | | No Impact (0) | | Low Positive Impact (1) | | Mild Positive Impact (2) | | High Positive Impact (3) | | I don't know | | Total | Weighted Mean Rating |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | % | N | % | N | % | N | % | N | % | N | % | N | % | N | % | N | N | |
| 1 | Labor and soft costs | 0.00% | 0 | 0.00% | 0 | 11.11% | 3 | 3.70% | 1 | 14.81% | 4 | 29.63% | 8 | 18.52% | 5 | 22.22% | 6 | 27 | 1.52 |
| 2 | Life-cycle costs | 0.00% | 0 | 0.00% | 0 | 3.70% | 1 | 18.52% | 5 | 25.93% | 7 | 22.22% | 6 | 0.00% | 0 | 29.63% | 8 | 27 | 0.95 |
| 3 | Labor/trade living expenses | 0.00% | 0 | 3.85% | 1 | 3.85% | 1 | 7.69% | 2 | 38.46% | 10 | 23.08% | 6 | 3.85% | 1 | 19.23% | 5 | 26 | 1.05 |
| 4 | Energy use | 0.00% | 0 | 0.00% | 0 | 3.85% | 1 | 15.38% | 4 | 23.08% | 6 | 26.92% | 7 | 7.69% | 2 | 23.08% | 6 | 26 | 1.25 |
| 5 | Returns, turnaround, and exposure to market cycle risks | 3.70% | 1 | 0.00% | 0 | 0.00% | 0 | 7.41% | 2 | 33.33% | 9 | 22.22% | 6 | 11.11% | 3 | 22.22% | 6 | 27 | 1.29 |
| 6 | Demand for labor | 3.70% | 1 | 0.00% | 0 | 3.70% | 1 | 3.70% | 1 | 18.52% | 5 | 40.74% | 11 | 7.41% | 2 | 22.22% | 6 | 27 | 1.38 |
| 7 | Other, please specify: | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 20.00% | 1 | 0.00% | 0 | 0.00% | 0 | 80.00% | 4 | 5 | 1.00 |

### 4.6.4 Efficiency Factors Affecting the Combination of Lean Construction and Construction Industrialization

Figure 4.23 and Table 4.12 provide summaries of the responses to the question "When applying lean construction and construction industrialization together, to what extent are the following Budget factors impacted? Use a rating scale from -3 (high negative impact) to +3 (high positive impact)." The weighted mean ratings of 'Ability to work in parallel' and 'Construction efficiency' are higher than 2.0 (excluding other). The weighted mean ratings for 'Requirements needed to enter a construction site' and 'Worker turnover and labor retention' are lower than 1.0.

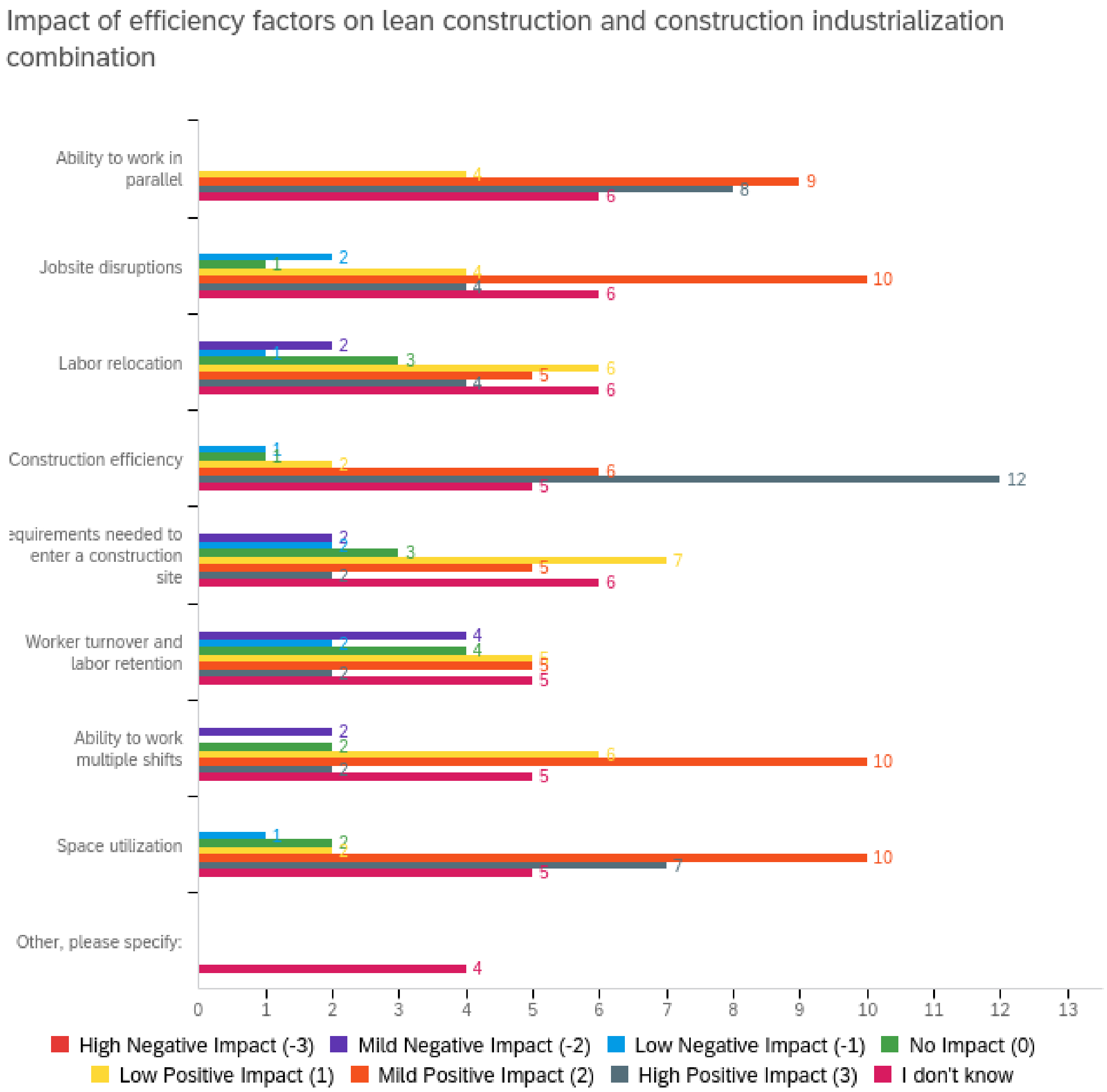


Figure 4.23 Impact of Efficiency Factors on Lean Construction and Construction Industrialization Combination

Table. 4.12 Impact of Efficiency Factors on Lean Construction and Construction Industrialization Combination

| # | Efficiency | High Negative Impact (-3) | | Mild Negative Impact (-2) | | Low Negative Impact (-1) | | No Impact (0) | | Low Positive Impact (1) | | Mild Positive Impact (2) | | High Positive Impact (3) | | I don't know | | Total | Weighted Mean Rating |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | % | N | % | N | % | N | % | N | % | N | % | N | % | N | % | N | N | |
| 1 | Ability to work in parallel | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 14.81% | 4 | 33.33% | 9 | 29.63% | 8 | 22.22% | 6 | 27 | 2.19 |
| 2 | Jobsite disruptions | 0.00% | 0 | 0.00% | 0 | 7.41% | 2 | 3.70% | 1 | 14.81% | 4 | 37.04% | 10 | 14.81% | 4 | 22.22% | 6 | 27 | 1.62 |
| 3 | Labor relocation | 0.00% | 0 | 7.41% | 2 | 3.70% | 1 | 11.11% | 3 | 22.22% | 6 | 18.52% | 5 | 14.81% | 4 | 22.22% | 6 | 27 | 1.10 |
| 4 | Construction efficiency | 0.00% | 0 | 0.00% | 0 | 3.70% | 1 | 3.70% | 1 | 7.41% | 2 | 22.22% | 6 | 44.44% | 12 | 18.52% | 5 | 27 | 2.23 |
| 5 | Requirements needed to enter a construction site (e.g., background check) | 0.00% | 0 | 7.41% | 2 | 7.41% | 2 | 11.11% | 3 | 25.93% | 7 | 18.52% | 5 | 7.41% | 2 | 22.22% | 6 | 27 | 0.81 |
| 6 | Worker turnover and labor retention | 0.00% | 0 | 14.81 % | 4 | 7.41% | 2 | 14.81% | 4 | 18.52% | 5 | 18.52% | 5 | 7.41% | 2 | 18.52% | 5 | 27 | 0.59 |
| 7 | Ability to work multiple shifts | 0.00% | 0 | 7.41% | 2 | 0.00% | 0 | 7.41% | 2 | 22.22% | 6 | 37.04% | 10 | 7.41% | 2 | 18.52% | 5 | 27 | 1.27 |
| 8 | Space utilization | 0.00% | 0 | 0.00% | 0 | 3.70% | 1 | 7.41% | 2 | 7.41% | 2 | 37.04% | 10 | 25.93% | 7 | 18.52% | 5 | 27 | 1.91 |
| 9 | Other, please specify: | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 100.00 % | 4 | 4 | 0.00 |

### 4.6.5 Quality/Safety/Project Duration/Environment Factors Affecting the Combination of Lean Construction and Construction Industrialization

Figure 4.24 and Table 4.13 present the responses to the question "When applying lean construction and construction industrialization together, to what extent are the following Quality/Safety/Project Duration/Environment factors impacted? Use a rating scale from -3 (high negative impact) to +3 (high positive impact)." The weighted mean rating was above 2.00 for all factors except 'Environmental performance' and 'Generated construction waste and waste management'. 'Schedule/time certainty and construction cycles' has the highest weighted mean rating and 'Environmental performance' has the lowest weighted mean rating.

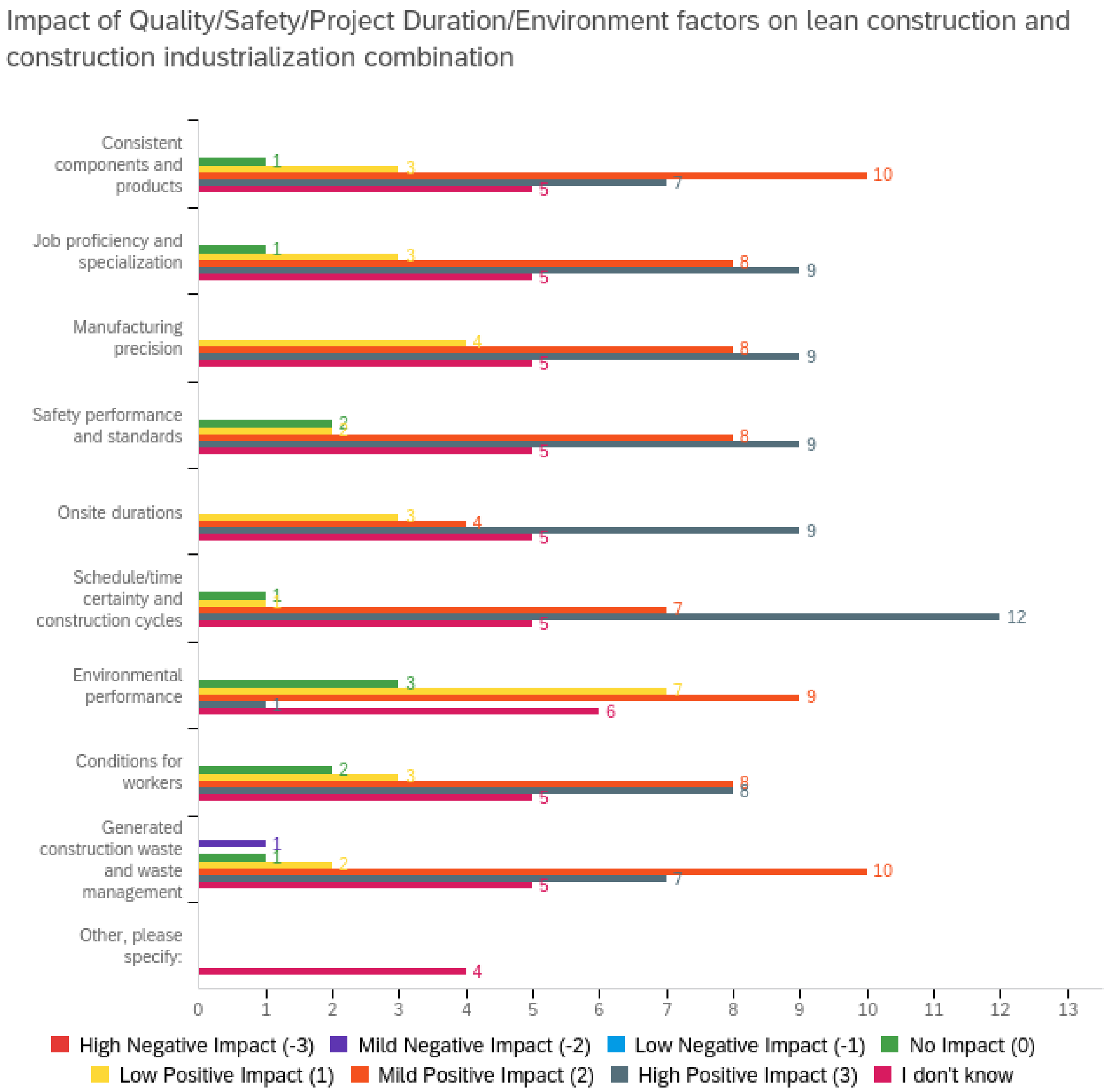


Figure 4.24 Impact of Quality/Safety/Project Duration/Environment Factors on Lean Construction and Construction Industrialization Combination

Table 4.13 Impact of Quality/Safety/Project Duration/Environment Factors on Lean Construction and Construction Industrialization Combination

| # | Quality/Safety/Project Duration/Environment | High Negative Impact (-3) | | Mild Negative Impact (-2) | | Low Negative Impact (-1) | | No Impact (0) | | Low Positive Impact (1) | | Mild Positive Impact (2) | | High Positive Impact (3) | | I don't know | | Total | Weighted Mean Rating |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | % | N | % | N | % | N | % | N | % | N | % | N | % | N | % | N | N | |
| 1 | Consistent components and products | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 3.85% | 1 | 11.54% | 3 | 38.46% | 10 | 26.92% | 7 | 19.23% | 5 | 26 | 2.10 |
| 2 | Job proficiency and specialization | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 3.85% | 1 | 11.54% | 3 | 30.77% | 8 | 34.62% | 9 | 19.23% | 5 | 26 | 2.19 |
| 3 | Manufacturing precision | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 15.38% | 4 | 30.77% | 8 | 34.62% | 9 | 19.23% | 5 | 26 | 2.24 |
| 4 | Safety performance and standards | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 7.69% | 2 | 7.69% | 2 | 30.77% | 8 | 34.62% | 9 | 19.23% | 5 | 26 | 2.14 |
| 5 | Onsite durations | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 14.29% | 3 | 19.05% | 4 | 42.86% | 9 | 23.81% | 5 | 21 | 2.38 |
| 6 | Schedule/time certainty and construction cycles | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 3.85% | 1 | 3.85% | 1 | 26.92% | 7 | 46.15% | 12 | 19.23% | 5 | 26 | 2.43 |
| 7 | Environmental performance | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 11.54% | 3 | 26.92% | 7 | 34.62% | 9 | 3.85% | 1 | 23.08% | 6 | 26 | 1.40 |
| 8 | Conditions for workers | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 7.69% | 2 | 11.54% | 3 | 30.77% | 8 | 30.77% | 8 | 19.23% | 5 | 26 | 2.05 |
| 9 | Generated construction waste and waste management | 0.00% | 0 | 3.85% | 1 | 0.00% | 0 | 3.85% | 1 | 7.69% | 2 | 38.46% | 10 | 26.92% | 7 | 19.23% | 5 | 26 | 1.95 |
| 10 | Other, please specify: | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 100.00% | 4 | 4 | 0.00 |

### 4.6.6 Other Factors Affecting the Combination of Lean Construction and Construction Industrialization

Figure 4.25 and Table 4.14 illustrate the responses to the question “When applying lean construction and construction industrialization together, to what extent are the following Other factors impacted? Use a rating scale from -3 (high negative impact) to +3 (high positive impact).” The weighted mean ratings of Predictability, Competitiveness in the market, and Desire to innovate are higher than 2.0 (excluding other). The factors Litigation performance and Traffic received weighted mean ratings lower than 1.0. The highest weighted mean ratings were given to ‘Desire to innovate’.

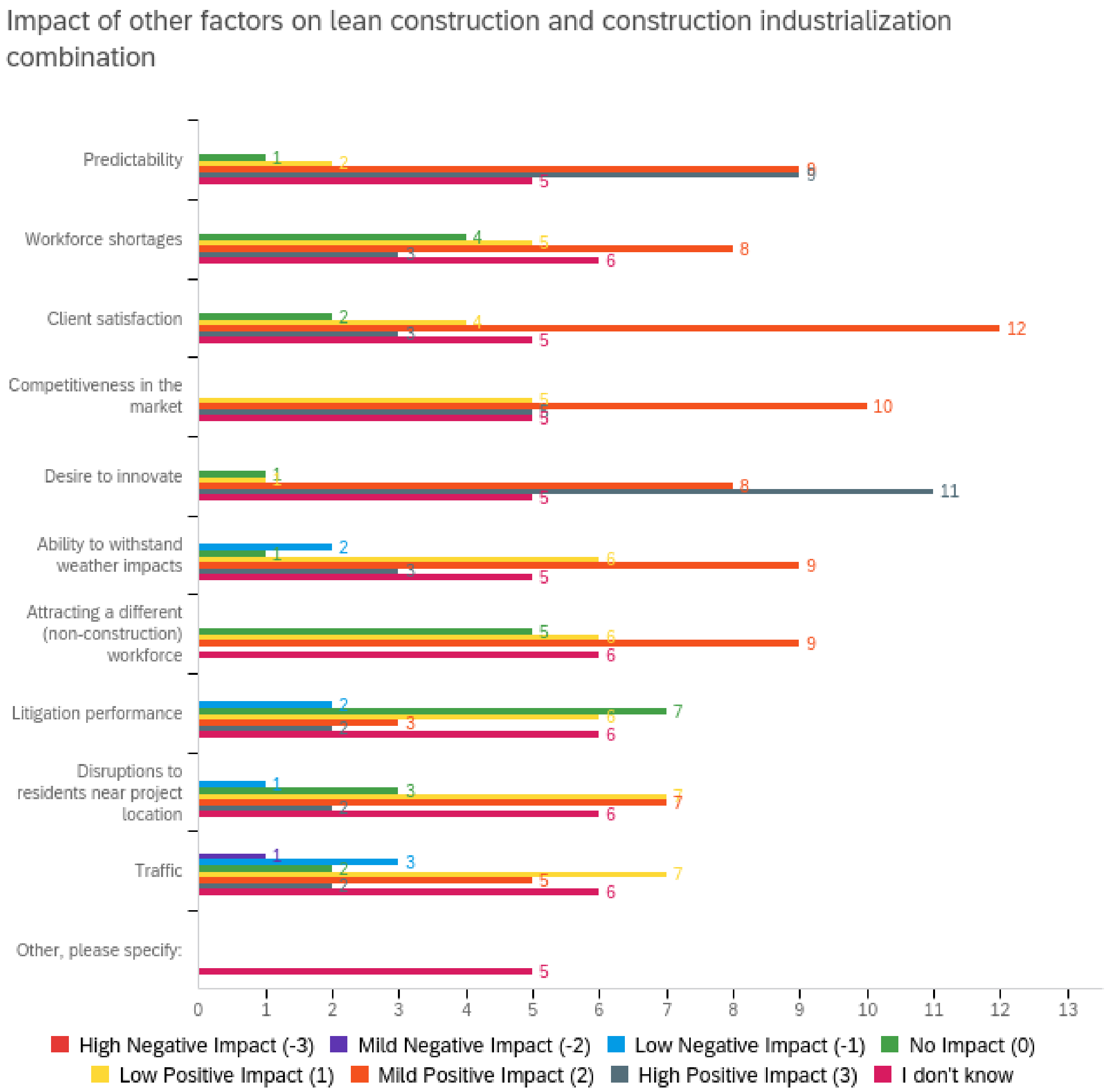


Figure 4.25 Impact of Other Factors on Lean Construction and Construction Industrialization Combination

Table 4.14 Impact of Other Factors on Lean Construction and Construction Industrialization Combination

| # | Other | High Negative Impact (-3) | | Mild Negative Impact (-2) | | Low Negative Impact (-1) | | No Impact (0) | | Low Positive Impact (1) | | Mild Positive Impact (2) | | High Positive Impact (3) | | I don't know | | Total | Weighted Mean Rating |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | % | N | % | N | % | N | % | N | % | N | % | N | % | N | % | N | N | |
| 1 | Predictability | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 3.85% | 1 | 7.69% | 2 | 34.62% | 9 | 34.62% | 9 | 19.23% | 5 | 26 | 2.24 |
| 2 | Workforce shortages | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 15.38% | 4 | 19.23% | 5 | 30.77% | 8 | 11.54% | 3 | 23.08% | 6 | 26 | 1.50 |
| 3 | Client satisfaction | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 7.69% | 2 | 15.38% | 4 | 46.15% | 12 | 11.54% | 3 | 19.23% | 5 | 26 | 1.76 |
| 4 | Competitiveness in the market | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 20.00% | 5 | 40.00% | 10 | 20.00% | 5 | 20.00% | 5 | 25 | 2.00 |
| 5 | Desire to innovate | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 3.85% | 1 | 3.85% | 1 | 30.77% | 8 | 42.31% | 11 | 19.23% | 5 | 26 | 2.38 |
| 6 | Ability to withstand weather impacts | 0.00% | 0 | 0.00% | 0 | 7.69% | 2 | 3.85% | 1 | 23.08% | 6 | 34.62% | 9 | 11.54% | 3 | 19.23% | 5 | 26 | 1.48 |
| 7 | Attracting a different (non-construction) workforce | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 19.23% | 5 | 23.08% | 6 | 34.62% | 9 | 0.00% | 0 | 23.08% | 6 | 26 | 1.20 |
| 8 | Litigation performance | 0.00% | 0 | 0.00% | 0 | 7.69% | 2 | 26.92% | 7 | 23.08% | 6 | 11.54% | 3 | 7.69% | 2 | 23.08% | 6 | 26 | 0.80 |
| 9 | Disruptions to residents near project location | 0.00% | 0 | 0.00% | 0 | 3.85% | 1 | 11.54% | 3 | 26.92% | 7 | 26.92% | 7 | 7.69% | 2 | 23.08% | 6 | 26 | 1.30 |
| 10 | Traffic | 0.00% | 0 | 3.85% | 1 | 11.54% | 3 | 7.69% | 2 | 26.92% | 7 | 19.23% | 5 | 7.69% | 2 | 23.08% | 6 | 26 | 0.90 |
| 11 | Other, please specify: | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 0.00% | 0 | 100.00 % | 5 | 5 | 0.00 |

### 4.6.7 Degree of Mutual Improvement Between Lean Construction and Construction Industrialization

The survey questionnaire also explored how lean construction and construction industrialization can work together to provide mutual benefit to a project. Figure 4.26 and Table 4.15 show summaries of the responses to the question "To what extent, using a scale of 0-5, do lean construction and construction industrialization promote each other?" Twenty-five out the 27 respondents who answered this question (93%) chose a rating of 3.0 or greater, indicating moderate or greater impact. The weighted mean rating for all respondents was 3.64.

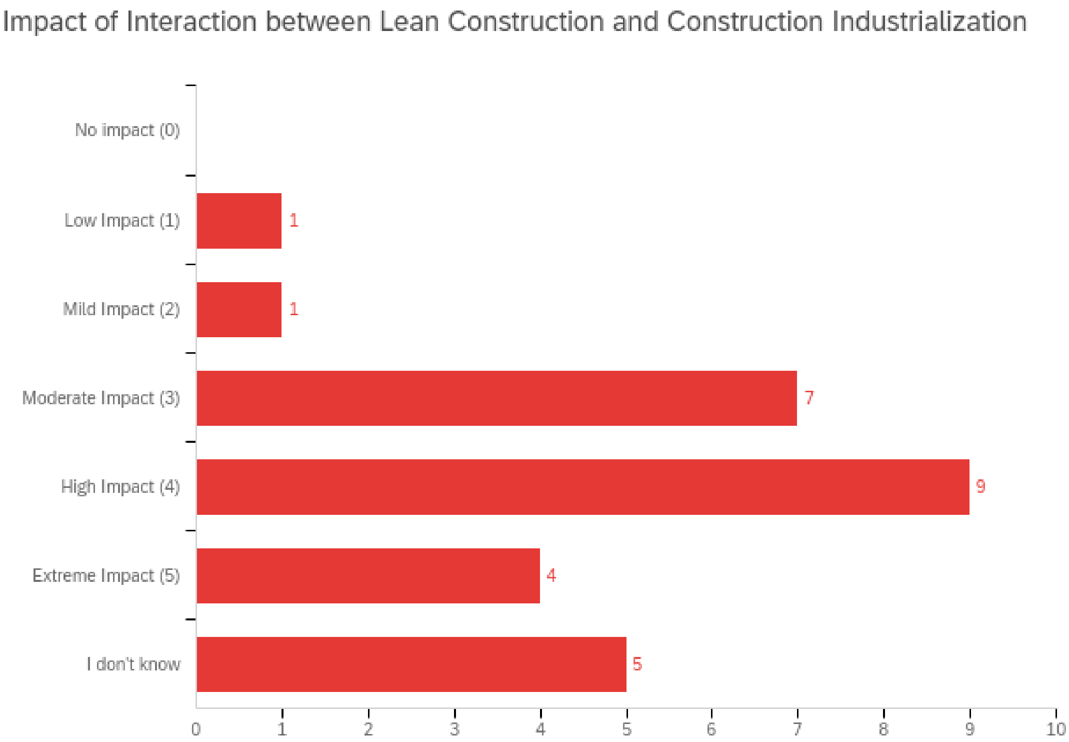


Figure 4.26 Impact of Interaction between Lean Construction and Construction Industrialization

Table 4.15 Impact of Interaction between Lean Construction and Construction Industrialization

| # | Rating | % | N |
|---|---|---|---|
| 1 | No Impact (0) | 0.00% | 0 |
| 2 | Low Impact (1) | 3.70% | 1 |
| 3 | Mild Impact (2) | 3.70% | 1 |
| 4 | Moderate Impact (3) | 25.93% | 7 |
| 5 | High Impact (4) | 33.33% | 9 |
| 6 | Extreme Impact (5) | 14.81% | 4 |
| 7 | I don't know | 18.52% | 5 |
| | Total | 100% | 27 |
| | Weighted Mean Rating | 3.64 | |

## 4.7 Interviews

Six construction personnel located on four different construction sites were interviewed. The interviews requested information regarding the interviewee's job title, work experience, application of lean construction and construction industrialization practices related to the project, and information about the project. The interview participants' job titles included project engineer, foreman, equipment operator, and project superintendent. Information about each of the four project sites is as follows:

1) Arts and Education Construction Project

The Oregon State University Arts and Education Complex, located on the corner of 15th Street and Washington Road, is a 49,000-square-foot building. The arts and education complex will become the center for performing arts programs and performances, integrating music, theater, and visual arts programs. Construction of the building has an estimated duration of two years and a project budget of $70 million.

2) Completing Reser Stadium

This $153 million project will fully renovate the west side of the stadium and is expected to take two years to complete. The project involves the complete demolition and reconstruction of the west side of Reser Stadium and the construction of year-round university facilities, including a new state-of-the-art Interactive Welcome Center for incoming freshmen considering OSU; a new health center facility for students on the Corvallis campus; a healthcare facility for OSU faculty and staff; and added meeting space for college students, faculty, and staff.

3) Fairbanks Hall Renovation

Fairbanks Hall is one of the oldest and most enduring buildings on the Corvallis campus. This 3-story, a 26,000-square-foot timber structure was built in 1892. OSU intends to update the structure, and a comprehensive renovation will create much-needed space on the currently unfinished fourth floor; reduce building energy costs through planned energy efficiency measures; support faculty and student recruitment and retention; and, for the first time, all students, faculty, staff, and OSU guests will have full access.

4) Community Hall Slope

The goal of this project is to improve the accessibility of Community Hall. The project includes complete renovation of relevant grounds and pathways near the Valley Library and Community Hall, and will provide a better experience for students, faculty, and staff through a planned construction process.

### 4.7.1 Personal Demographic Information

Figure 4.27 illustrates a summary of the responses to the interview question "Which of the following best describes your current job title?" Project engineers constituted the largest proportion, with a ratio of 50% (3 out of 6).

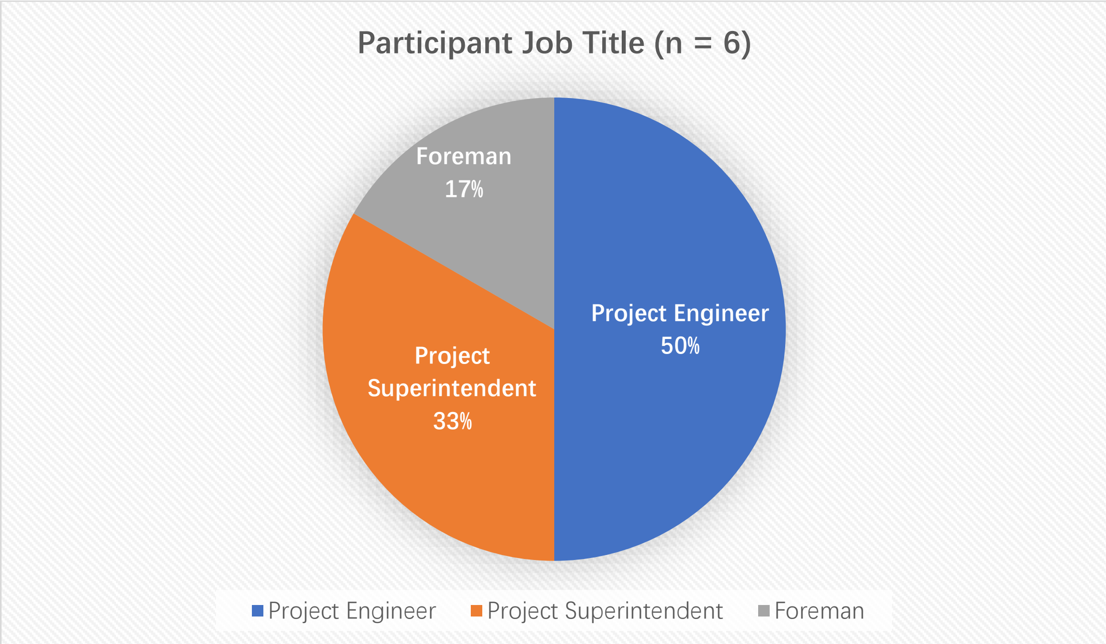


Figure 4.27 Participant Job Title (n = 6)

The responses to the question "How many years of construction industry experience do you have?" are shown in Figure 4.28. Those with less than 10 years of work experience accounted for the majority of participants (4 out of 6, 67%).

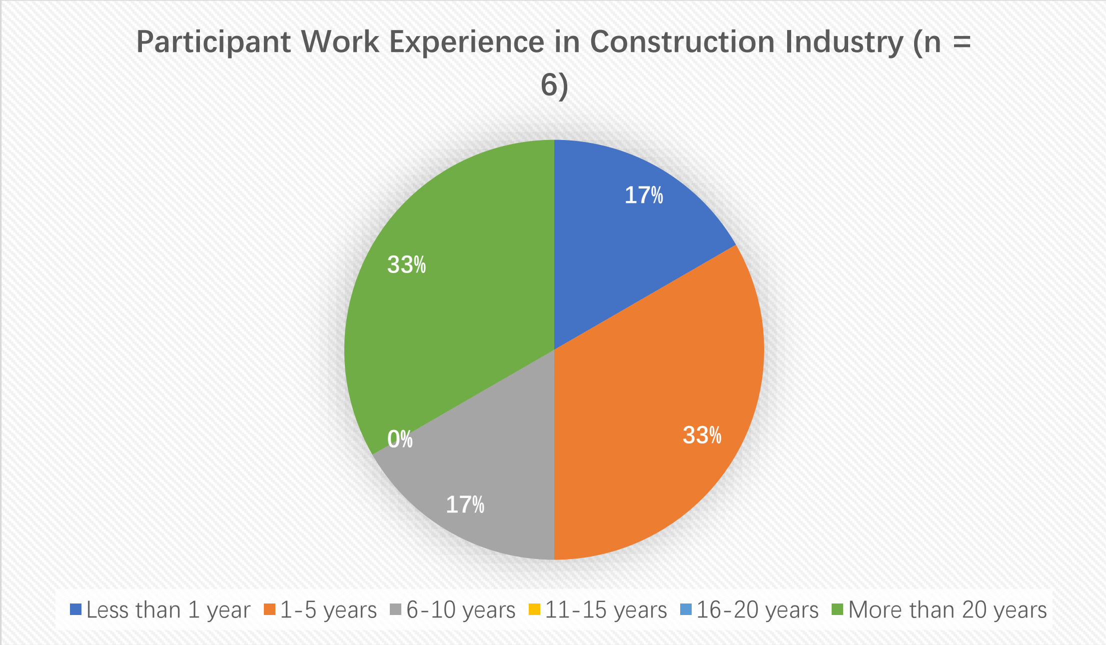


Figure 4.28 Participant Work Experience in Construction Industry (n = 6)

### 4.7.2 Lean Construction

Figure 4.29 and Table 4.16 summarize the responses to the interview question regarding the overall performance of lean construction on a specific project. Responses were given using a Likert-type scale from 0-5. Eighty-three percent of participants chose moderate or high impact.

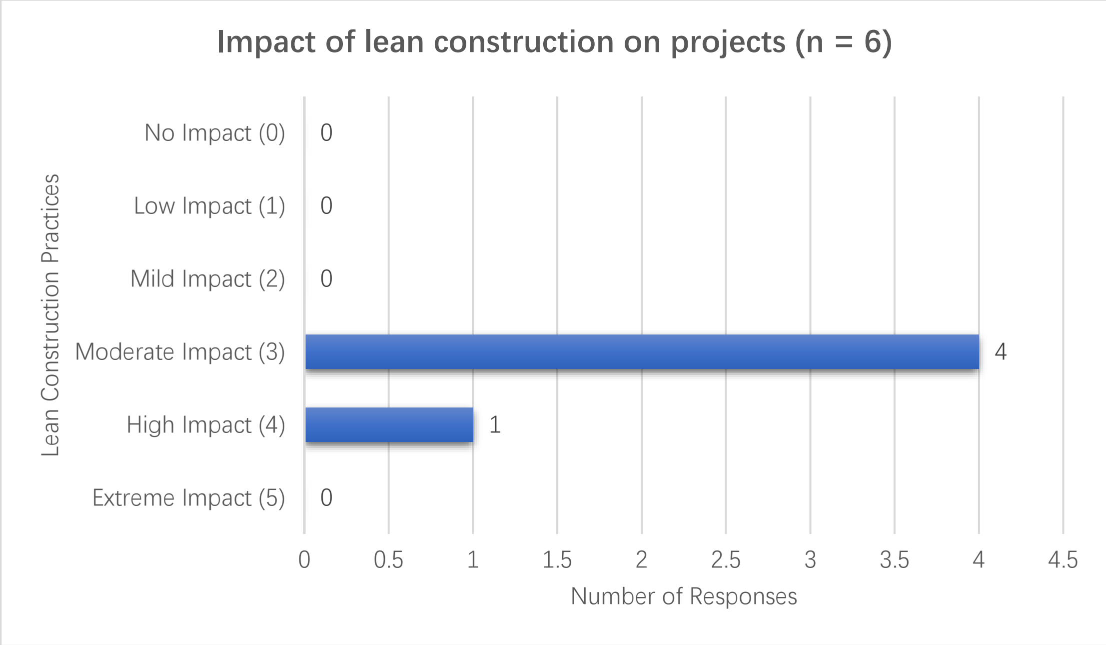


Figure 4.29 Impact of Lean Construction on Projects (n = 6)

Table 4.16 Impact of Lean Construction on Projects

| # | Rating | % | N |
|---|---|---|---|
| 1 | No Impact (0) | 0.00% | 0 |
| 2 | Low Impact (1) | 0.00% | 0 |
| 3 | Mild Impact (2) | 0.00% | 0 |
| 4 | Moderate Impact (3) | 66.67% | 4 |
| 5 | High Impact (4) | 16.67% | 1 |
| 6 | Extreme Impact (5) | 0.00% | 0 |
| 7 | I don't know | 16.67% | 1 |
| | Total | 100% | 6 |
| | Weighted Mean Rating | 3.20 | |

Table 4.17 shows the participants' perceptions of how well lean construction practices are performed on specific projects (using a scale of 0-5 where 0 = no impact and 5 = extreme impact). With the exception of PPC, the weighted mean rating of all

lean construction practices is above 4.0 (high impact). Andon has the highest weighted mean rating and PPC has the lowest weighted mean rating.

Table 4.17 Performance of Lean Construction Practices

| Lean Practice | Is it implemented? | | How well is it implemented? (*Use a scale of 0-5*) | | | | | | Weighted Mean Rating |
|---|---|---|---|---|---|---|---|---|---|
| | Yes | No | 0 | 1 | 2 | 3 | 4 | 5 | |
| Pull planning | 5 | 1 | 0 | 0 | 0 | 0 | 1 | 4 | 4.80 |
| Constraint Analysis | 4 | 2 | 0 | 0 | 0 | 0 | 2 | 2 | 4.50 |
| Look-ahead schedule | 6 | 0 | 0 | 0 | 0 | 0 | 1 | 5 | 4.83 |
| Weekly work plan | 6 | 0 | 0 | 0 | 0 | 0 | 2 | 4 | 4.67 |
| Planned Percent Complete (PPC) | 4 | 2 | 0 | 0 | 0 | 3 | 0 | 1 | 3.50 |
| 5 Whys / Root cause analysis | 4 | 2 | 0 | 0 | 0 | 1 | 2 | 1 | 4.00 |
| 5S | 5 | 1 | 0 | 0 | 0 | 1 | 1 | 3 | 4.40 |
| Andon | 2 | 4 | 0 | 0 | 0 | 0 | 0 | 2 | 5.00 |
| Just-in-time | 4 | 2 | 0 | 0 | 0 | 1 | 2 | 1 | 4.00 |
| Kaisen | 4 | 2 | 0 | 0 | 0 | 0 | 1 | 3 | 4.75 |
| Kanban | 3 | 3 | 0 | 0 | 0 | 1 | 1 | 1 | 4.00 |
| Poka-yoke | 4 | 2 | 0 | 0 | 0 | 4 | 0 | 1 | 4.25 |
| Kitting | 3 | 3 | 0 | 0 | 1 | 0 | 0 | 2 | 4.00 |
| Value Stream Mapping (VSM) | 3 | 3 | 0 | 0 | 0 | 1 | 0 | 2 | 4.33 |

### 4.7.3 Construction Industrialization

Figure 4.30 and Table 4.18 show how the interviewees responded regarding the overall performance of construction industrialization on a specific project (using a scale of 0-5). Approximately 66% of participants indicated that construction industrialization has a moderate or high impact on a project. The weighted mean rating for all responses was 3.50.

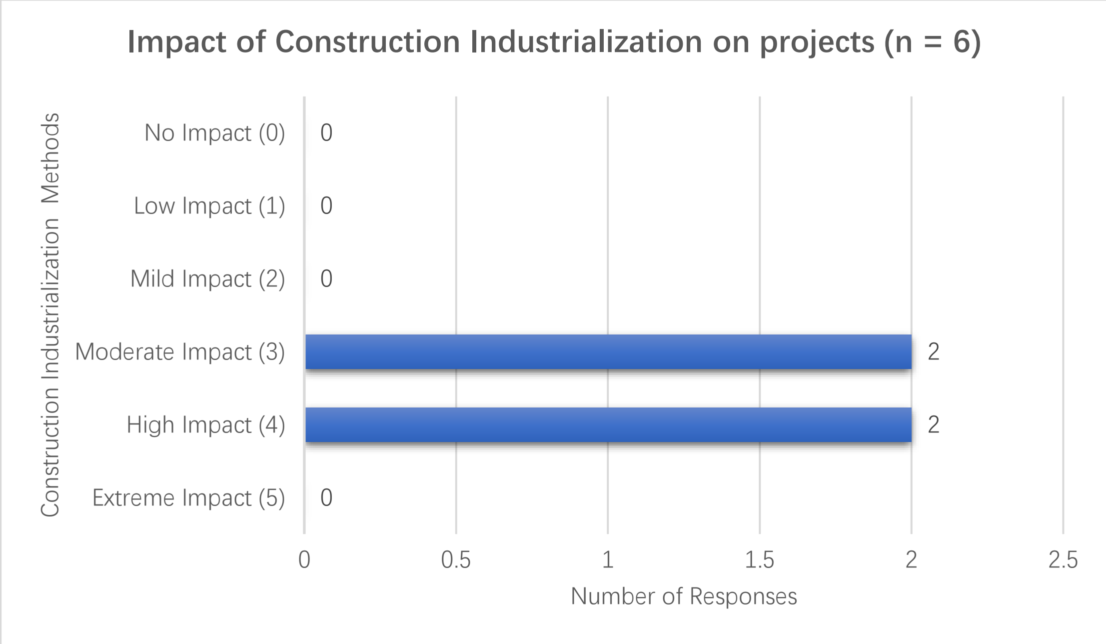


Figure 4.30 Impact of Construction Industrialization on Projects (n = 6)

Table. 4.18 Impact of Construction Industrialization on Projects

| # | Rating | % | N |
|---|---|---|---|
| 1 | No Impact (0) | 0.00% | 0 |
| 2 | Low Impact (1) | 0.00% | 0 |
| 3 | Mild Impact (2) | 0.00% | 0 |
| 4 | Moderate Impact (3) | 33.33% | 2 |
| 5 | High Impact (4) | 33.33% | 2 |
| 6 | Extreme Impact (5) | 0.00% | 0 |
| 7 | I don't know | 33.33% | 2 |
| | Total | 100% | 6 |
| | Weighted Mean Rating | 3.50 | |

Table 4.19 shows the interviewee's responses when asked how well construction industrialization methods are performed on specific projects (using a scale of 0-5). With the exception of Mass production, the weighted mean rating for all

construction industrialization methods is above 4.0 (high impact). The method receiving the highest implementation rating was Modularization.

Table. 4.19 Performance f Construction Industrialization Methods

| Industrialization Method | Is it implemented? | | How well is it implemented? (*Use a scale of 0-5*) | | | | | | Weighted Mean Rating |
|---|---|---|---|---|---|---|---|---|---|
| | Yes | No | 0 | 1 | 2 | 3 | 4 | 5 | |
| Modularization | 4 | 2 | 0 | 0 | 0 | 0 | 1 | 3 | 4.75 |
| Prefabrication | 3 | 3 | 0 | 0 | 0 | 1 | 0 | 2 | 4.33 |
| Preassembly | 3 | 3 | 0 | 0 | 0 | 1 | 0 | 2 | 4.33 |
| Mass production | 2 | 4 | 0 | 0 | 1 | 0 | 0 | 1 | 3.50 |

### 4.7.4 Project Information

Table 4.20 shows interviewee responses regarding information on specific projects with/without specific construction methods or practices. As can be seen in the table, Delayed activities is used to measure the efficiency of the project; Change orders and Non-conformance are used to measure the quality of the project; Injury accidents is used to measure safety performance on the project; Exceed budget is used to measure budget performance on the project; and the amount of prefabricated concrete and total concrete consumption are used to measure the industrialization rate of the project.

Table. 4.20 Project Performance Measures

| Project Performance Criteria | Has it occurred on project? | | How many times has it occurred on the project (Projects #1 - #4)? | | | |
|---|---|---|---|---|---|---|
| | Yes | No | #1 | #2 | #3 | #4 |
| Delayed activity | 4 | 0 | 1 | 1 | 1 | 1 |
| Change order | 4 | 0 | 25 | 3 | 3 | 25 |
| Injury accident | 3 | 1 | 0 | 0 | 1 | 0 |
| Non-conformance | 0 | 4 | None | | | |
| Exceed budget | 0 | 4 | None | | | |
| Prefabricated concrete (%) | None | | 2% | 0% | 0% | 70% |
| Total concrete consumption (cy) | None | | 3500 | None | Over 2000 | 2000 |

# 5 ANALYSIS AND DISCUSSION

## 5.1 Introduction

In previous chapters, the researchers presented the results of the literature review, online survey, and on-site interviews. This chapter presents the analysis of the extracted data and a discussion of the analysis. Answers to the following research questions are provided in this chapter:

1) Can values generated by lean construction and construction industrialization be measured?
2) Will the amount and type of value generated vary by work trade?
3) What are the factors that affect the value?
4) Can the degree and frequency of factors be measured?
5) Does lean construction fit in with construction industrialization on projects?

## 5.2 Analysis Tools and Methods

Microsoft Excel was used as a data analysis tool to analyze the data and answer the above research questions. Two Likert scales ranging from no impact (0) to extreme Impact (5), and from a strong negative impact (-3) to a strong positive impact (3), were used in the survey and interview questions to illustrate the effect of factors on specific construction methods. As described in the previous section, weighted means were used to quantify the aggregate opinion of the participant to each of the questions. Similar scales were used to measure the efficiency of the application of construction methods based on the interview responses.

## 5.3 Value Measurements

Through the previous chapters, the benefits of lean construction and construction industrialization are stated as adding value and reducing waste. The added value proposed by Saraf (2013) is summarized and used in this research, and includes aspects of the project duration, cost, safety, efficiency, and engineering quality. The types of reduced waste are described in the literature review, and can briefly be classified into the following eight categories: Overproduction; Waiting; Transportation; Over-Processing; Inventory; Motion; Defects; and Underutilized Skills and Talent. In order to make it easier to quantify and compare lean construction practices and construction industrialization, the research used the same added value and waste categories.

## 5.4 Work Trade and Value Amount

The construction methods chosen by the survey and interview participants within the different work trades are shown in the previous chapters. Lean construction practices in the PCP category are more widely used by general contractors, especially Look-ahead schedule, Pull planning, and Weekly work plan. No preference for subcontracting was found, and PCP and CSMP have similar selection rates between general contractors and subcontractors. For construction industrialization, general contractors prefer Prefabrication, Preassembly, and Modularization, while subcontractors have no obvious preference for construction industrialization methods. In general, except for Mass production, which is less of a choice for construction industrialization, the other three methods all have higher selection rates. Novotny (2018) divides subcontractors into eight types according to their work trade: 1) Plumbing, heating, and air-conditioning; 2) Painting and paper hanging; 3) Electrical work; 4) Masonry, stonework, tile setting, and plastering; 5) Carpentry and floor work; 6) Roofing, siding, and sheet metal work; 7) Concrete work; and 8) Special trade contractors. The work trades of the participants in this study were mainly mechanical contractors and electrical subcontractors. For lean construction practices, mechanical contractors had little practice preference, and electrical subcontractors had similar selection rates for PCP and CSMP (three each). For the choice of construction industrialization methods used on projects, mechanical contractors are more inclined to use Prefabrication, Preassembly, and Modularization, while no preference was exposed for electrical subcontractors.

## 5.5 Factors Affecting Value

Saraf (2013) also summarizes the factors that affect value. In the present research, the factors are divided into two categories: internal factors and external factors. External factors include Complexity of Project, Quality and Availability of Materials, Quality and Availability of Labor and Technical Personnel, Quality and Availability of Equipment, Site Conditions, Weather Conditions, Finance and Payment of Completed Work and Client Satisfaction. Internal factors include Amount and Quality of Planning, Design Process and Result, Contract Management, Decision-making, Communication, Site Management, Construction Methods, Quality Assurance, Attitude of Site

Personnel Towards Work, Major Disputes and Negotiation, Level of Productivity and Construction Mistakes and Defective Work.

### 5.5.1 Measurement of Factor Frequency and Degree

To measure the frequency of use and extent of impact of these factors such as work trade, target value or waste, Likert scales were used as in the survey and interviews. The Likert scale allowed for measuring the frequency of use. The weighted mean rating was used as a means to measure the degree of impact.

#### 5.5.1.1 Value Identification

All participants (Five of the five categories have a weighted mean rating above 3.0) who responded to the question about the value associated with lean construction and construction industrialization generally believed that lean construction has a positive effect (weighted mean rating higher than 3.0) on the value of construction, providing significant improvements (weighted mean rating $\geq$ 3.50) in construction efficiency (4.05), construction duration (3.82), construction quality (3.68), and construction safety (3.76). For construction industrialization, construction efficiency (weighted mean rating = 4.24) is significantly improved. It is worth noting that construction industrialization has a relatively low positive impact on cost reduction (weighted mean rating = 3.18). It can be seen that both lean construction and construction industrialization have a positive impact on construction projects. When these two methods are used separately, they both perform well in improving construction efficiency. However, cost reduction was not viewed as an added value provided by the two method.

#### 5.5.1.2 Value Impact Factors

##### 5.5.1.2.1 External Impact Factors

The results show that 75% (Six of the eight categories have a weighted mean rating above 3.0) participants generally believe that lean construction has a positive effect under the influence of external factors. The external factors ‘Labor and Technical Personnel’ (weighted mean rating = 4.14), ‘Complexity of project’ (3.77), ‘Low quality or shortage of materials’ (3.73), and ‘Payment for completed’ (3.55) have an obvious positive effect. There is limited positive effect of ‘Weather conditions’ (2.77), and ‘Finance of, and payment of, completed work’ (2.57). For construction industrialization, projects improved significantly under the influence of ‘Complexity of project’ (weighted mean rating = 4.00), ‘Labor and Technical personnel’ (3.95) and ‘Low quality or shortage of materials’ (3.69). Also, the positive impacts of ‘Finance of and payment of completed work’ (weighted mean rating = 2.78) is limited. It can be seen that lean construction and construction industrialization have a positive impact on construction projects. When using these two methods, projects are more likely to perform well in ‘Labor and Technical Personnel’, ‘Complexity of the project’, and ‘Low quality or shortage of materials’, and not perform well in ‘Finance and payment of completed work’.

##### 5.5.1.2.2 Internal Impact Factors

All participants (12 out of 12 categories) agreed that lean construction has a strong positive impact on internal factors. Similar conclusions can be drawn for construction industrialization. It can be seen that Internal factors have more positive effects on lean construction and construction industrialization projects.

#### 5.5.1.3 Waste Impact Factors

The results from the survey show that all participants (8 out of 8) who answered this question in the questionnaire believe that lean construction had a positive effect on reducing construction waste, which has a significant impact on Inventory (3.77), Waiting (3.77), and Transportation (3.68). For construction industrialization, Inventory (3.68), Motion (3.68), Waiting (3.69), and Defect (3.58) wastes receive significant improvements when construction industrialization is used. It can be seen that lean construction and construction industrialization have a positive impact on construction projects. When the two methods are used separately, both performed well under the influence of reducing inventory and waiting, while neither method improved under the influence of over-production and underutilized skills and talent.

## 5.6 Combination of Lean Construction and Construction Industrialization

### 5.6.1 Performance of Lean Construction and Construction Industrialization Combination

According to the survey results, the weighted mean rating of the impact of lean construction on construction industrialization was 3.59, and vice versa, 2.41. The hypothesis mentioned in Section 3.2.2 is that applying the combined methods can bring added value to the project and improve its performance in different situations (i.e., represented by impact factors). Compared to the results of the two methods applied separately, the results did not exceed expectations, and ranged from moderate impact to high impact.

### 5.6.2 Budget Factors

Participants who answered the question regarding budget factors generally believe that the combination of the two methods has a positive impact (weighted mean rating ≥ 1.00). Labor and soft costs (1.52), Demand for labor (1.38), Returns, turnaround, exposure to market cycle risks (1.29), Energy use (1.25), and Labor/trade living expenses (1.05) were clearly viewed as receiving positive impact. No particular limitations (weighted mean rating < 1.00) were found.

### 5.6.3 Efficiency Factors

For the 27 participants who answered the question related to efficiency factors, the participants generally rated the combination of the two methods as having a positive effect. The combination generally has positive influence on Construction efficiency (weighted mean rating = 2.23), Ability to work in parallel (2.19), Space utilization (1.91), Jobsite disruptions (1.62), and Ability to work multiple shifts (1.27). Limited impact was associated with 'Requirements needed to enter a construction site' (weighted mean rating = 0.81) and 'Worker turnover and labor retention' (0.59).

### 5.6.4 Quality/Safety/Project Duration/Environment Factors

Those participants who answered the question related to quality, safety, project duration, and environment factors generally had the perspective that the impact factors under this category performed better (weighted mean rating greater than 1.00 for all factors), and no special limitations were found (weighted mean < 1.00). The results show that the combination of the two methods has a positive impact on quality, safety, project duration, and environmental factors on projects. The weighted mean ratings of the seven factors exceed 2.00.

### 5.6.5 Other Factors

Twenty-six survey participants indicated that the impact factors under this category performed better (weighted mean $\geqslant 1.00$), except for Traffic (0.90), and Litigation performance (0.80). Typical other factors mentioned included environment, market, and client focus. No special restrictions were identified by the participants. It is worth noting that when lean construction and construction industrialization are combined on a project, it is difficult to conclude that these factors influence each other; that is, there is no obvious correlation between the factors in this category.

### 5.6.6 Mutual Improvement Between Lean Construction and Construction Industrialization

When asked about whether the combined application of lean construction and construction industrialization would provide better project performance, 27 participants generally agreed that the performance would get better (weighted mean rating = 3.64). The possible reason for the improved performance is that lean construction and construction industrialization eliminate each other's disadvantages at different levels, and then play a role in promoting each other. For example, the results in Section 6.4.3 show that the combined method performs better in terms of 'Labor and soft costs', which does not perform well when just applying construction industrialization. The results of the interviews reveal that projects that apply both lean construction and construction industrialization have fewer change orders, injury accidents, and non-conformance issues, and do not exceed budgets. Therefore, the combination provides better performance in terms of quality and safety.

# 6 IMPROVED PERFORMANCE UNDER COMBINED APPLICATION

## 6.1 Introduction

This chapter describes possible opportunities in which combined lean construction and construction industrialization methods enhance project performance. The researchers used findings from the literature review, online survey, and interviews to identify the combined methods that improve performance. Six categories identified from the literature review and survey were used to identify the combined methods. The combined methods were used to explore the following question:

1) Are there methods to increase the value of the project?

The results presented in this study are composed of target value, target waste, project objective factors, and employee factors.

## 6.2 Value Targets Resulting from the Combination of Lean Construction and Construction Industrialization

Table 6.1 shows the specific impact of the combined methods on project values. The table shows the additional positive impact that a combination of lean construction practices and construction industrialization methods can have. With the exception of some methods that do not provide value, the vast majority of lean construction practices and construction industrialization methods have a certain degree of value improvement. The combinations of methods that provide enhanced performance (marked as better) include Prefabrication and 5S, which improves safety. That is, when prefabrication techniques are applied with 5S on a project, improvements in safety will be realized to a greater extent than if either prefabrication or 5S is implemented on its own. In addition, Look-ahead schedule, Pull planning, Weekly work plan, and Constraint analysis have better performance in efficiency when combined with Prefabrication, respectively.

The combinations of methods that are not marked "better" can still be regarded as having a positive effect on a certain project aspect and are still beneficial, but the effect is not as obvious as those marked as “better”.

It is worth noting that some combinations of methods are not identified as adding enhanced value in Table 6.1, and are marked as "Not Applicable." However, this designation does not mean that the combination of methods cannot bring added value; it may require more investment to achieve expectations (time or budget).

The results reveal that the value increase brought by the combined approach is highly correlated with the value provided by lean construction practices, a phenomenon referred to in this research as "lean construction control". The possible reason for the correlation to lean construction is that lean construction provides greater diversity of value and is more widely used on projects. Second, lean construction practices are easier to implement than industrialized methods of construction because they do not require an off-site construction location (e.g., factory). When selecting and planning lean construction practices and construction industrialization methods for a project, Table 6.1 can be used to identify the value targets that the project expects to receive. Correspondingly, if a project places high priority on specific values, the target values shown in the table can be searched to find appropriate lean construction and construction industrialization methods to employ on a project that will enhance the value.

Table. 6.1 Value Targets Resulting from the Combination of Lean Construction and Construction Industrialization

| | | Construction Industrialization Methods | | | | |
|---|---|---|---|---|---|---|
| | | Modularization | Single-trade Prefabrication | Multi-trade prefabrication | Pre-assembly | Mass production |
| Lean Construction Practices | VSM | N/A | | | | |
| | Kitting | | | | | |
| | Just in time | Efficiency | Efficiency | Efficiency | Efficiency | Efficiency |
| | 5S | Safety | Safety (better) | Safety (better) | Safety | N/A |
| | Kanban | N/A | Efficiency | Efficiency | N/A | N/A |
| | Kaisen | Continuous improvement | Continuous improvement | Continuous improvement | Continuous improvement | Continuous improvement |
| | Andon | Communication | N/A | N/A | Communication | Communication |
| | Poka-yoke | N/A | Mistake proofing | Mistake proofing | Mistake proofing | N/A |
| | Look ahead schedule | Efficiency | Efficiency (better) | Efficiency (better) | N/A | N/A |
| | Pull planning | Efficiency | Efficiency (better) | Efficiency (better) | N/A | N/A |
| | PPC | Communication | N/A | N/A | Communication | Communication |
| | Weekly work plan | Efficiency | Efficiency (better) | Efficiency (better) | N/A | N/A |
| | Constraint analysis | Efficiency | Efficiency (better) | Efficiency (better) | N/A | N/A |
| | 5 Whys | N/A | Quality | Quality | N/A | N/A |

## 6.3 Waste Targets Resulting from the Combination of Lean Construction and Construction Industrialization

Table 6.2 shows instances in which the combination of lean construction and construction industrialization methods has an enhanced positive impact on types of waste. That is, table shows the impact of a combination of lean construction practices and construction industrialization methods in reducing waste. Lean construction practices which reduced waste combined with industrialized construction methods are both valuable to a certain extent. Communication is improved when VSM is combined with Prefabrication. Similarly, Space utilization is improved when Kitting is combined with Prefabrication and the performance of poka-yoke eliminates action waste (e.g., rework) when combined with all construction industrialization methods. For the combinations of VSM and Kitting with Modularization and Mass production, the role of lean construction practices and construction industrialization partially overlap, and the overlapping methods may not perform better in reducing waste; therefore, while they may be selected for inclusion on a project and provide value individually, the results are shown as not applicable in the table.

The table also shows how "lean construction controls," where the value increase from the combined approach is highly correlated with the reduction in waste from lean construction practices. However, the waste target may not meet expectations relative to the value target. The possible reason for not meeting expectations is that the combined approaches require more investment to meet expectations. When selecting and planning lean construction practices and construction industrialization methods for a project, Table 6.2 can be used to identify the waste targets that the project expects to receive. Correspondingly, if a project places high priority on reducing specific types of waste, the target wastes shown in the table can be searched to find appropriate lean construction and construction industrialization methods to employ on a project that will reduce waste.

Table. 6.2 Waste Targets Resulting from the Combination of Lean Construction and Construction Industrialization

| | | Construction Industrialization Methods | | | | |
|---|---|---|---|---|---|---|
| | | Modularization | Single-trade Prefabrication | Multi-trade prefabrication | Pre-assembly | Mass production |
| Lean Construction Methods | VSM | N/A | Communication | Communication | Communication | N/A |
| | Kitting | N/A | Space utilization | Space utilization | Space utilization | N/A |
| | Just in time | N/A | | | | |
| | 5S | | | | | |
| | Kanban | | | | | |
| | Kaisen | | | | | |
| | Andon | | | | | |
| | Poka-yoke | Action | Action | Action | Action | Action |
| | Look-ahead schedule | N/A | | | | |
| | Pull planning | | | | | |
| | PPC | | | | | |
| | Weekly work plan | | | | | |
| | Constraint analysis | | | | | |
| | 5 Whys | | | | | |

## 6.4 Combined Lean Construction and Construction Industrialization Methods based on Project Scale

Table 6.3 shows the different project scales for which the combined lean construction and construction industrialization methods are particularly applicable and provide enhanced benefit. Project scale is divided into three categories: small, medium, large, and super. Okere (2022) defines project scales as follows: Small as less than $10 million in project cost; Medium as $10 million - $100 million; Large as $100 million - $250 million; and Super is over $250 million. For the present research, the small and medium categories as defined by Okere were used, and Large and Super categories were combined such that Large consisted of projects more than $100 million.

It can be seen in the table that there is "construction industrialization control." That is, the project scale is highly correlated with the scale for which the construction industrialization method is suitable. One of the reasons for the correlation to construction industrialization is that construction industrialization methods typically have stricter site requirements than lean construction practices. Some lean construction practices can take place solely in an office, and the rest do not create significant requirements for the transformation of the construction site. Using Table 6.3, the appropriate project scale can be clarified through the combination of lean construction practices and construction industrialization methods. Correspondingly, the project scale can be searched in the table to find suitable lean construction and construction industrialization methods to implement.

Table. 6.3 Combined Lean Construction and Construction Industrialization Methods based on Project Scale

| | | Construction Industrialization Methods | | | | |
|---|---|---|---|---|---|---|
| | | Modularization | Single-trade Prefabrication | Multi-trade prefabrication | Pre-assembly | Mass production |
| Lean Construction Methods | VSM | Medium/Large-Scale (better) | Small/Medium-Scale | Medium/Large-Scale | Medium/Large-Scale | Large-Scale (better) |
| | Kitting | Medium/Large-Scale | Small/Medium-Scale (better) | Medium/Large-Scale | Medium/Large-Scale | Large-Scale |
| | Just in time | Large-Scale | Small/Medium-Scale | Medium/Large-Scale | Medium/Large-Scale | Large-Scale |
| | 5S | Large-Scale | Small/Medium-Scale (better) | Medium/Large-Scale | Medium/Large-Scale | Large-Scale |
| | Kanban | Large-Scale (better) | Small/Medium-Scale | Medium/Large-Scale | Medium/Large-Scale (better) | Large-Scale (better) |
| | Kaisen | Large-Scale | Small/Medium-Scale | Medium/Large-Scale | Medium/Large-Scale | Large-Scale |
| | Andon | Large-Scale (better) | Small/Medium-Scale | Medium/Large-Scale | Medium/Large-Scale | Large-Scale (better) |
| | Poka-yoke | Medium/Large-Scale | Small/Medium-Scale | Medium/Large-Scale | Medium/Large-Scale | Large-Scale |
| | Look-ahead schedule | Medium/Large-Scale | Small/Medium-Scale | Medium/Large-Scale | Medium/Large-Scale | Large-Scale |
| | Pull planning | Large-Scale | N/A | N/A | Large-Scale | Large-Scale |
| | PPC | Large-Scale | N/A | N/A | Large-Scale | Large-Scale |
| | Weekly work plan | Medium/Large-Scale | Small/Medium-Scale | Medium/Large-Scale | Medium/Large-Scale | Large-Scale |
| | Constraint analysis | Medium/Large-Scale | Small/Medium-Scale | Medium/Large-Scale | Medium/Large-Scale | Large-Scale |
| | 5 Whys | Medium/Large-Scale | Small/Medium-Scale | Medium/Large-Scale | Medium/Large-Scale | Large-Scale |

## 6.5 Combined Lean Construction and Construction Industrialization Methods based on Project Complexity

Table 6.4 reveals the different levels of project complexity for which the combined lean construction and construction industrialization methods are particularly applicable and provide enhanced benefit. Project complexity is divided into three categories, singular, normal, and complex following the categorization by Santana (1990). The level of complexity varies according to the degree of social, economic, and environmental impact, as well as the people and contractors employed.

As can be seen in the table, there is "joint control" between lean construction and construction industrialization. Joint control means project complexity is correlated with both lean construction and construction industrialization. It is worth noting that there are not many combined methods suitable for projects in the Singular category; the application of the two methods for low-complexity projects may cause unnecessary trouble to the project (i.e., “overkill”), so the combination is not recommended. Using the table, by selecting lean construction practices and construction industrialization methods, the target project complexity can be clarified. Correspondingly, the complexity of the project can be searched to find appropriate lean construction and construction industrialization methods to implement to achieve better project performance.

Table. 6.4 Combined Lean Construction and Construction Industrialization Methods based on Complexity of Project

| | | Construction Industrialization Methods | | | | |
|---|---|---|---|---|---|---|
| | | Modularization | Single-trade Prefabrication | Multi-trade prefabrication | Pre-assembly | Mass production |
| Lean Construction Methods | VSM | Normal/Complex | Complex | Normal/Complex | Normal/Complex | Normal/Complex |
| | Kitting | Complex | Complex | Normal/Complex | Normal/Complex | Complex |
| | Just in time | Normal/Complex | Complex | Normal/Complex | Normal/Complex | Normal/Complex |
| | 5S | Normal/Complex | Complex | Complex | Normal/Complex | Normal/Complex |
| | Kanban | Normal/Complex | Complex | Complex | Complex | Normal/Complex |
| | Kaisen | Normal/Complex | Complex | Complex | Complex | Normal/Complex |
| | Andon | Normal/Complex | Complex | Normal/Complex | Normal/Complex | Normal/Complex |
| | Poka-yoke | Complex | Normal/Complex | Normal/Complex | Normal/Complex | Complex |
| | Look-ahead schedule | Normal/Complex | Complex | Normal/Complex | Normal/Complex | Normal/Complex |
| | Pull planning | Normal/Complex | Complex | Complex | Normal/Complex | Normal/Complex |
| | PPC | Normal/Complex | Complex | Normal/Complex | Normal/Complex | Normal/Complex |
| | Weekly work plan | Complex | Singular/Normal | Normal/Complex | Complex | Complex |
| | Constraint analysis | Complex | Singular/Normal | Normal/Complex | Complex | Complex |
| | 5 Whys | Normal/Complex | Complex | Normal/Complex | Normal/Complex | Normal/Complex |

## 6.6 Combined Lean Construction and Construction Industrialization Methods based on Site Conditions

Table 6.5 shows the different site conditions for which the combined lean construction and construction industrialization methods are especially applicable and provide enhanced benefit. Khosravi (2014) classified project situations into five categories: hazardous operations, unsafe conditions, weather, welcome service, and construction stage and equipment. These categories include incorrect operating habits, uneven ground, construction in heavy fog, and lack of personal protective equipment, among others. For the present research, project situations are divided into three categories: low project situations, medium project situations, and high project situations A low project situation is one where four or more of the five situation categories listed above are present on the project; a medium project situation means that two or three of the five categories are present on the project; and a high project situation means that two or fewer categories are present on the project. A low project situation indicates that the project site conditions, operations, and culture are poor, while a high project situation indicates that the site conditions, operations, and culture are good.

"Construction industrialization control" can be seen from the data shown in the table. The applicability of combined methods is highly related to the construction industrialization methods employed. It is worth noting that the high site condition category is not very prevalent in the table. Projects with high site conditions applying both methods may not provide enhanced impact on project performance, but increase cost; therefore combined methods are not necessarily beneficial relative to the investment required. Starting with selected lean construction practices and construction industrialization methods, the table can be used to identify suitable project conditions for which the combination is particularly suitable. Correspondingly, when the likely site conditions are known, the project conditions can also be searched in the table to find suitable lean construction and construction industrialization methods to implemented.

Table. 6.5 Combined Lean Construction and Construction Industrialization Methods based on Site Condition

| | | Construction Industrialization Methods | | | | |
|---|---|---|---|---|---|---|
| | | Modularization | Single-trade Prefabrication | Multi-trade prefabrication | Pre-assembly | Mass production |
| Lean Construction Methods | VSM | Low | Low/Medium | Low/Medium | Low | Low |
| | Kitting | Low | Low/Medium | Low/Medium | Low | Low |
| | Just in time | Low | Low/Medium | Low/Medium | Low | Low |
| | 5S | Low | Low/Medium | Low/Medium | Medium | Low |
| | Kanban | Low | Low/Medium | Low/Medium | Medium | Low |
| | Kaisen | Low | Low/Medium | Low/Medium | Medium | Low |
| | Andon | Low | Low/Medium | Low/Medium | Medium | Low |
| | Poka-yoke | Low | Low/Medium | Low/Medium | Medium | Low |
| | Look-ahead schedule | Low | Low/Medium | Low/Medium | Low | Low |
| | Pull planning | Low | Low/Medium | Low/Medium | Low | Low |
| | PPC | Low | Low/Medium | Low/Medium | Low | Low |
| | Weekly work plan | Low | Low/Medium | Low/Medium | Low | Low |
| | Constraint analysis | Low | Low/Medium | Low/Medium | Low | Low |
| | 5 Whys | Low | Low/Medium | Low/Medium | Low | Low |

## 6.7 Combined Lean Construction and Construction Industrialization Methods based on Employee Skill Level

Table 6.6 reveals the different employee skill levels for which the combined lean construction and construction industrialization methods are particularly applicable and provide enhanced benefit. Khosravi (2014) divides project impact factors into eight categories, among which employee-related factors are: work group, contractor, supervision, and project management. Individual factors are divided into age and experience, drug abuse, unintended acts, intended acts, competitiveness and ability, attitude, and motivation. Employee skill levels are divided into three categories: high skill level, medium skill level, and low skill level.

In the present research, the individual factors described above are used to represent skill levels related to employees. Three skill level categories are used: low, medium, and high. Low skill level means that five or more of the individual factors mentioned above are disadvantaged; medium skill level means that three or four individual factors are disadvantaged; and high skill level means that two or fewer individual factors are disadvantaged. The disadvantage mentioned above means that the factor does not support effective project performance. Low represents a greater level of disadvantage than high. A typical disadvantage means that the worker cannot use the equipment properly and efficiently, and in a more serious cases, the worker may be injured.

It can be seen from the table that "lean construction control" exists. Whether the combined method can be implemented well given the employee skill level is highly related to lean construction, especially since management personnel are more familiar with the process of lean construction practice. Using Table 6.6, the appropriate employee skill level can be clarified through the combination of lean construction practice and construction industrialization methods. Correspondingly, the employee skill level on the project can be searched to find suitable lean construction and construction industrialization methods to implement.

Table. 6.6 Combined Lean Construction and Construction Industrialization Methods based on Employee Skill Level

| | | Construction Industrialization Methods | | | | |
|---|---|---|---|---|---|---|
| | | Modularization | Single-trade Prefabrication | Multi-trade prefabrication | Pre-assembly | Mass production |
| Lean Construction Methods | VSM | High | Low/Medium | Low/Medium | Medium/High | High |
| | Kitting | Medium | Low/Medium | Low/Medium | Medium | Medium |
| | Just in time | High | Medium | Medium | Medium/High | High |
| | 5S | Medium | Low/Medium | Low/Medium | Medium | Medium |
| | Kanban | Low | Medium | Medium | Medium | Medium |
| | Kaisen | High/Medium | Medium | Medium | Medium | High/Medium |
| | Andon | Medium | Low/Medium | Low/Medium | Medium | Medium |
| | Poka-yoke | Medium | Low/Medium | Low/Medium | Medium | Medium |
| | Look-ahead schedule | Medium | Low/Medium | Low/Medium | Medium | Medium |
| | Pull planning | High | Low/Medium | Low/Medium | Medium/High | High |
| | PPC | Medium | Low/Medium | Low/Medium | Medium | Medium |
| | Weekly work plan | Medium | Low/Medium | Low/Medium | Medium | Medium |
| | Constraint analysis | Medium | Low/Medium | Low/Medium | Medium | Medium |
| | 5 Whys | Medium | Low/Medium | Low/Medium | Medium | Medium |

# 7 CONCLUSIONS AND RECOMMENDATIONS

## 7.1 Introduction

This chapter summarizes the study process, presents the study's conclusions and limitations, and provides recommendations for further research. In addition, this chapter presents how the results of the research can be implemented in practice.

## 7.2 Summary

Lean construction and construction industrialization have been identified as providing benefit to projects. The main goal of this study is to explore lean construction and construction industrialization, and ultimately to expose how their relationship can be developed to enhance project value through the combination of the methods. Six objectives were developed to achieve the research goals: 1) Determine lean construction practices and construction industrialization methods commonly used on construction projects, 2) Identify types of added value and waste present on construction projects , 3) Develop metrics for value/waste and its influencing factors, 4) Determine the factors that affect value and waste on construction projects, 5) Identify the factors that influence the combination of the two methods, and 6) Develop an improved construction process to increase the amount of value added to construction projects.

The study used several methods to achieve these objectives. First, a literature review was used to define the concepts of lean construction and construction industrialization and to define the practices and methods to be used in the research. The literature review was also used to identify types of value and waste, and the factors that influence value and waste on projects. An online survey and interviews were selected to verify values, wastes, and factors, and the effectiveness and degree of impact of a combined approach to implementation of lean construction and construction industrialization. Finally, an evaluation method to strategically apply the combined approach on projects based on specific project criteria was developed.

The survey generated 36 responses from construction industry personnel. The survey questionnaire responses were used to: 1) obtain an assessment of lean construction practices and construction industrialization methods; 2) determine the specific impact of lean construction and construction industrialization on projects; and 3) obtain evaluations of lean construction methods, construction industrialization methods, and added value gained by the combination of the methods. Interviews are conducted through field investigations on four projects. The intent of the interviews was to: 1) clarify the nature of the project and its performance to date; 2) understand the application of lean construction and construction industrialization methods on the project; and 3) determine project performance after the combination approach is applied.

## 7.3 Limitations

This study has several limitations that affect the accuracy of the results and ability to generalize the results beyond the study samples. The identified limitations include the following:

a) Although the online survey was based on a web-distributed questionnaire, the participants were mostly industry workers with many years of work experience, and measures were developed to exclude non-compliant participants and reduce outliers, each participant provided subjective responses. There was no set standard for participants to follow to answer the questions. The subjective nature of the survey questions does not provide data as accurate as data obtained directly from a project or in an experiment. Therefore, the results of the research are subject to possible bias in the participant responses.

b) Due to strict participant vetting and no further survey responses and interviews available in a short period of time, the limitation of the small total sample size prevents the results of present research from accurately representing the industry.

c) The survey was designed to simplify the survey process and minimize the time needed to fill in the questionnaire with the goal of improving the survey response rate. To achieve these aims, the survey section that explores the influence of various factors on the degree of lean construction and construction industrialization was discarded. Therefore, these results cannot be added to the improved method. The specific rate of the improved value could not be determined and, as a result, the findings of the research may therefore lack some accuracy.

d) Although interviews were conducted on four different projects to verify the accuracy of the questionnaire results, the project sample size was low. Utilizing only a small sample of projects could lead to possible biases in the results due to the limited scopes of the projects compared to all types of projects constructed.

## 7.4 Conclusions and Contributions

### 7.4.1 Conclusions

Using different measurement dimensions, this study explores project performance associated with combining lean construction and construction industrialization methods. Target value, target waste, project objective factors, and employee factors are related to lean construction and construction industrialization methods. The value as defined in current literature and the value of the waste component are described in detail. Lean construction and industrialization of construction have been identified as delivering benefits to the project which are divided into added value and reduced waste. Five added values and eight wastes are identified in the present research. Several work trades are identified in the present research to determine the impact of value on them. External and internal factors are used as measures in the present research. Metrics for participants and factors are developed separately.

This research revealed that the combined application of lean construction and construction industrialization can promote each other. When each lean construction practice and construction industrialization method is identified, its positive impact and applicable scenarios can be organized by different criteria. The improved combined approach incorporates six aspects, each of which attempts to combine the application of lean construction practices and construction industrialization methods to realize better project performance.

### 7.4.2 Contributions

Höök (2008) mentioned that the transfer of traditional construction workers to factories and the establishment of construction industrial production requires careful implementation of lean principles. The present research becomes an important argument for this point of view. Nahmens (2009) argues that the presence of lean construction is associated with a significantly lower incidence of injuries compared to industrial builders who do not apply lean construction. The results of the present study also support this view. The contribution of this research to knowledge is the confirmation of the value and waste of lean construction and construction industrialization, and the identification of the contributing factors. Using the development of a Likert scale to measure their extent, the research also resulted in the creation of a method to utilize the findings associated with the combination of the methods to benefit project performance and clarify the applicable project types for each method. The research provides added value by exploring the combination of lean construction and construction industrialization to prove its development value under Industry 4.0. Therefore, the contribution of this research to practice is the development of integrated methods that can help project managers select appropriate lean construction practices and/or construction industrialization methods to improve project performance depending on the type and nature of the project.

### 7.4.3 Recommendations for Future Research

Given that the present study is research on lean construction and construction industrialization, after the study answers the desired research questions, subsequent research should focus on broader research areas. The following is a summary of recommendations for future research on the topic:

a) Lean construction and construction industrialization have been applied on many projects and are expected to be the subject of future research in the construction industry. However, there is currently little research on this topic, and there is not a large amount of data available to analyze the projects that successfully apply the combined methods. Future research needs to conduct data collection on more construction sites, especially those using a combination of lean construction and construction industrialization methods, to obtain more accurate data.

b) Further research is needed to explore a wider range of topics for different projects, such as how the combined methods should be implemented for different work trades to make the project perform better.

c) Additional research should include experimental methods in a laboratory setting. By establishing an experimental site, the conclusions stated above can be sampled and analyzed by laboratory data, and the performance of the corresponding lean construction practices and construction industrialization methods on actual projects can be further explored to identify the optimal combination method.

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# APPENDIX

Appendix A – Explanation of Research

**Interaction between Lean Construction and Construction Industrialization**

**Project Name:** Interaction between Lean Construction and Construction Industrialization

**Principal Investigator**: John Gambatese / Oregon State University

**Student Investigator**: Qichang Dai / Oregon State University

**Why am I being invited to take part in this study?**

We invite you to participate in this study because you are involved in the construction industry and may have an understanding of the application of lean construction or construction industrialization on projects.

**What is the purpose of this study?**

Researchers at Oregon State University are conducting academic research on the relationship between lean construction and construction industrialization. Lean construction and construction industrialization have been shown to bring value to a project. We hope to find the impact on the project when implementing the combination of the two practices, i.e., whether their combination adds added value. In addition, we aim to quantify the added value, if any, and measure its degree and frequency.

**What will happen during this study and how long will it take?**

During the survey, you will be asked to answer short answer questions, multiple choice questions, and evaluative questions related to the topic. You will also be asked to provide general demographic information related to your personal background. Lastly, we would like to know whether you know of any project sites on which additional interviews of site personnel could be conducted regarding project-specific outcomes related to the research topic.

The survey questionnaire is expected to take approximately 15-20 minutes to complete, and will be conducted online. Some of the questions are personal. You can choose not to answer any of the questions if you wish.

**How will my information be used?**

The information you provide is for research purposes only. Your responses to the survey questions will be summarized in a research thesis and one or more academic papers. No publications of the study results will include any information about your identity or affiliation.

All information provided will be kept strictly confidential and viewed only by the researchers. Your information and responses that are collected as part of the research, even if identifiers are removed, will not be used or distributed for future research studies.

**What are the risks of this study to participants?**

The survey has minimal risks, and all information that you provide will remain confidential, be used for research and educational purposes only, and accessed only by the researchers.

Accidental disclosure of the survey responses and personal information: Personal identities are not required to complete the survey, unless you choose to provide them for a follow-up interview and on-site interviews. Thus, interview responses cannot be traced to individual people or companies/organizations.

Internet: The security and confidentiality of information collected from you online cannot be guaranteed. Information collected online can be intercepted, corrupted, lost, destroyed, arrive late or incomplete, or contain viruses.

**What are the benefits of this study to the participants?**

There are no direct benefits to you as a participant or to the organization to which you belong. The study evaluates two practices used in the entire construction industry. The results of the study will help improve the efficiency and safety of construction projects and ultimately benefit the entire construction industry.

**Do I have a choice to be in the study?**

Participation in the study is voluntary. Participants may refuse to answer any questions and/or may withdraw from the study at any time. Participation or non-participation will not affect your relationship with your company/organization.

**What if I have questions?**

Participants are encouraged to ask any questions at any time about the study and its procedures, or about their rights as a participant. The investigators' names and contact information are included below so that you may ask questions and report any study-related problems.

- Qichang Dai, Graduate Student, Civil and Construction Engineering, Oregon State University, 211 Kearney Hall, Corvallis, OR 97331, E-mail: daiq@oregonstate.edu

- John Gambatese, School of Civil and Construction Engineering, Oregon State University, 101 Kearney Hall, Corvallis, OR 97331, Tel.: (541) 737-8913, E-mail: john.gambatese@oregonstate.edu

In addition, if you have any questions about your rights as a survey participant, please contact the Oregon State University Institutional Review Board (IRB) Office at (541) 737-8008, or by e-mail at: IRB@oregonstate.edu.

**Acknowledgment**

I have read the above description of the research. If I had questions or would have liked additional information, I contacted the study team and had all of my questions answered to my satisfaction. I agree to participate in the research, and am at least 18 years of age or older.

Appendix B – Survey questions

**Interaction between Lean Construction and Construction Industrialization**

***<u>Personal Demographic Information</u>***

Q1 What type of organization do you work for?

- ○ Design Firm
- ○ Construction Firm
- ○ Consulting Firm
- ○ Other, please specify: ________________________

If "Construction Firm" selected in Q1, display Q2: Please select the type of construction firm:

- ○ General Contractor
- ○ Subcontractor
- ○ Other, please specify: ________________________________

If "Subcontractor" selected in Q2, display Q3: Please select your work trade:

- ○ Mechanical (plumbing, heating, and air-conditioning)
- ○ Painting and Paper Hanging
- ○ Electrical
- ○ Masonry, Stonework, Tile Setting, and Plastering
- ○ Carpentry and Floor Work
- ○ Roofing, Siding, and Sheet Metal
- ○ Concrete
- ○ Steel Erection
- ○ Special Trade Contractors (Glass and glazing, excavation, and demolition)
- ○ Other, please specify: ________________________________

Q4 Please select the type(s) of projects which you typically work on:

- ○ Commercial and institutional buildings
- ○ Residential buildings
- ○ Bridges, roads, tunnels
- ○ Industrial facilities
- ○ Utilities
- ○ Other, please specify: ____________________________________

Q5 Which of the following best describes your current job title?

- ○ Project Manager / Assistant Project Manager
- ○ Project Engineer / Assistant Project Engineer
- ○ Project Superintendent / Assistant Project Superintendent
- ○ Safety Manager / Safety Engineer
- ○ Inspector
- ○ Foreman
- ○ Laborer
- ○ Equipment Operator
- ○ Other, please specify: ____________________________________

Q6 How many years of experience do you have working in the design/construction industry?

- ○ Less than 1 year
- ○ 1 - 5 years
- ○ 6 - 10 years
- ○ 11 - 15 years

- 16 - 20 years
- More than 20 years

Q7 What is the size of your company/organization? (Approximate number of employees)

- Less than 10 employees
- 10 and 50 employees
- 51 and 100 employees
- 101 and 250 employees
- 251 and 500 employees
- 501 and 1000 employees
- More than 1000 employees

Q8 *Lean construction* is a construction management technique based on production management theory, centering on the value stream in the project delivery process, using professional techniques and methods to maximize value and minimize waste. Do your company's projects apply lean construction techniques?

- Yes
- No
- I don’t know

If YES, complete the ***Lean Construction*** section. If NO, skip the ***Lean Construction*** section.)

Q9 C*onstruction industrialization* commonly refers to the fabrication of standardized components in an off-site or on-site facility and the use of large-scale equipment for production and construction. The construction methods can be divided into two types: off-site and on-site. Do your company’s projects involve construction industrialization?

- Yes
- No
- I don’t know

(If YES, complete the ***Construction Industrialization*** section. If NO, skip the ***Construction Industrialization*** section.)

***Lean Construction***

Q10 Which of the following lean practices are applied on the projects you are involved in? Select all that apply.

○ **Pull Planning: S**trategically planning segments of work in order to produce progressively elaborate Weekly Work Plans.

○ **Constraint Analysis:** An integral part of LPS that is applied as a proactive approach to problem-solving as a team.

○ **Look-ahead schedule:** Usually discussed in weekly team meetings where the team evaluates what it “can” do in the next 6 to 8 weeks. The goal is for the team to determine constraints, assign responsibilities, and commit to resolving the constraints before they affect the activity.

○ **Weekly work plan based on reliable commitments:** Tactical team collaboration to plan each day’s work, conditions for handoff and acceptance, sequencing, and synchronizing the next week’s work (the point of maximum progressive elaboration to create reliable work plans).

○ **Planned Percent Complete (PPC):** A basic measure of how well the planning system is working – calculated as the 'number of promises/activities completed on the day stated' divided by the 'total number of promises/activities made/planned for the week'.

○ **5 Whys / Root cause analysis:** Find the exact reason that led to a given problem by asking a sequence of "Why" questions.

○ **5S:** Housekeeping: Sort, Set in order, Shine, Standardize, Sustain.

○ **Andon:** A system designed to alert operators and managers of problems in real-time so that corrective measures can be taken immediately.

○ **Just-in-time:** An inventory management approach designed to eliminate waste by receiving goods only as they are needed for production processes.

○ **Kaisen:** Continuous improvement.

○ **Kanban:** A project management technique that uses tools such as billboards or signs to document and streamline the various steps in processes.

○ **Poka-yoke:** Designing a system to eliminate the possibility of mistakes and hence avoid defective products or services (i.e., mistake-proofing).

○ **Kitting:** A process in which individually separate, but related, items are grouped, packaged, and supplied together as one unit before delivering them to the particular place for installation, thus assembling a complete "kit" of parts required for the installation.

- ○ **Value Stream Mapping (VSM):** A process that helps individuals visually see and understand a given process rather than simply looking at results.
- ○ Other, please specify:

______________________________________________________________

Q11 What are the reasons for choosing which lean practices to implement on a project?

______________________________________________________________

______________________________________________________________

Q12 Using a scale of 0-5, to what extent do you think that the application of **lean construction** techniques on a project can provide the following added value?

| Value Added | No Impact (0) | Low Impact (1) | Mild Impact (2) | Moderate Impact (3) | High Impact (4) | Extreme Impact (5) | I don't know |
|---|---|---|---|---|---|---|---|
| Reduce project duration | | | | | | | |
| Reduce costs | | | | | | | |
| Improve safety | | | | | | | |
| Improve efficiency | | | | | | | |
| Improve construction quality | | | | | | | |
| Other, please specify: | | | | | | | |

Q13 Using a scale of 0-5, to what extent do you think the following **external** factors affect the amount of added value provided by **lean construction** techniques?

| External Factors | No Impact (0) | Low Impact (1) | Mild Impact (2) | Moderate Impact (3) | High Impact (4) | Extreme Impact (5) | I don’t know |
|---|---|---|---|---|---|---|---|
| Complexity of Project | | | | | | | |
| Quality and Availability of Materials | | | | | | | |
| Quality and Availability of Labor and Technical Personnel | | | | | | | |
| Quality and Availability of Equipment | | | | | | | |
| Site Conditions | | | | | | | |
| Weather Conditions | | | | | | | |
| Finance and Payment of Completed Work | | | | | | | |
| Client Satisfaction | | | | | | | |
| Other, please specify: | | | | | | | |

Q14 Using a scale of 0-5, to what extent do you think the following **internal** factors affect the amount of added value provided by **lean construction** techniques?

| Internal Factors | No Impact (0) | Low Impact (1) | Mild Impact (2) | Moderate Impact (3) | High Impact (4) | Extreme Impact (5) | I don't know |
|---|---|---|---|---|---|---|---|
| Amount and Quality of Planning | | | | | | | |
| Design Process and Result | | | | | | | |
| Contract Management | | | | | | | |
| Decision-making | | | | | | | |
| Communication | | | | | | | |
| Site Management | | | | | | | |
| Construction Methods | | | | | | | |
| Quality Assurance | | | | | | | |
| Attitude of Site Personnel Towards Work | | | | | | | |
| Major Disputes and Negotiation | | | | | | | |
| Level of Productivity | | | | | | | |
| Construction Mistakes and Defective Work | | | | | | | |
| Other, please specify: | | | | | | | |

Q15 Using a scale of 0-5, to what extent do you think that the application of **lean construction techniques** on a project can lead to reductions in the following types of **waste**?

| Types of Waste | No Impact (0) | Low Impact (1) | Mild Impact (2) | Moderate Impact (3) | High Impact (4) | Extreme Impact (5) | I don’t know |
|---|---|---|---|---|---|---|---|
| **Transportation** (*Unnecessary movement of materials or equipment, like moving from one area, floor, or material laydown space to another and then again to the work area where it will be put in place*) | | | | | | | |
| **Inventory** (*Some inventory on-hand may be required to keep the project progressing, but too much inventory can quickly add up and tie up cash and resources*) | | | | | | | |
| **Motion** *(To move and not add value)* | | | | | | | |
| **Waiting** *(Sometimes known as delay, waiting refers to periods of inactivity)* | | | | | | | |
| **Overproduction** (*Building something too soon, having too much of something already built, or building something quicker than what is needed*) | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Over-processing** (Refers to the redundant steps taken in a process such as altering or double-handling supplies or materials) | | | | | | | |
| **Defects** (*Materials that have been damaged or made incorrectly*) | | | | | | | |
| **Underutilized Skills and Talent** *(Failure to use people's skills, creativity, or knowledge on the project)* | | | | | | | |
| Other, please specify: | | | | | | | |

***<u>Construction Industrialization</u>***

Q16 Please indicate the type(s) of construction industrialization that is applied on the projects you are involved in. Select all that apply.

- ○ **Modularization:** S*ubstantial fabrication and assembly of components into modules at a location other than the construction site for transportation to and installation on the construction site*
- ○ **Prefabrication:** *Fabrication of buildings or building components at a location other than the construction site*
- ○ **Preassembly:** *Fabricate and assemble buildings or building components before traditional on-site construction*
- ○ **Mass production:** *Also known as flow production or repeated flow production, it refers to the production of a large number of standardized products on the production line*
- ○ Other, please specify: ______________________________

Q17 What are the reasons for choosing which construction industrialization method to use on a project?

______________________________

______________________________

Q18 Using a scale of 0-5, to what extent do you think that the application of **construction industrialization** techniques on a project can provide the following added value?

| Value Added | No Impact (0) | Low Impact (1) | Mild Impact (2) | Moderate Impact (3) | High Impact (4) | Extreme Impact (5) | I don't know |
|---|---|---|---|---|---|---|---|
| Reduce project duration | | | | | | | |
| Reduce costs | | | | | | | |
| Improve safety | | | | | | | |
| Improve efficiency | | | | | | | |
| Improve construction quality | | | | | | | |
| Other, please specify: | | | | | | | |

Q19 Using a scale of 0-5, to what extent do you think the following **external** factors affect the amount of added value provided by **construction industrialization** techniques?

| External Factors | No Impact (0) | Low Impact (1) | Mild Impact (2) | Moderate Impact (3) | High Impact (4) | Extreme Impact (5) | I don’t know |
|---|---|---|---|---|---|---|---|
| Complexity of Project | | | | | | | |
| Quality and Availability of Materials | | | | | | | |
| Quality and Availability of Labor and Technical Personnel | | | | | | | |
| Quality and Availability of Equipment | | | | | | | |
| Site Conditions | | | | | | | |
| Weather Conditions | | | | | | | |
| Finance and Payment of Completed Work | | | | | | | |
| Client Satisfaction | | | | | | | |
| Other, please specify: | | | | | | | |

Q20 Using a scale of 0-5, to what extent do you think the following **internal** factors affect the amount of added value provided by **construction industrialization** techniques?

| Internal Factors | No Impact (0) | Low Impact (1) | Mild Impact (2) | Moderate Impact (3) | High Impact (4) | Extreme Impact (5) | I don't know |
|---|---|---|---|---|---|---|---|
| Amount and Quality of Planning | | | | | | | |
| Design Process and Result | | | | | | | |
| Contract Management | | | | | | | |
| Decision-making | | | | | | | |
| Communication | | | | | | | |
| Site Management | | | | | | | |
| Construction Methods | | | | | | | |
| Quality Assurance | | | | | | | |
| Attitude of Site Personnel Towards Work | | | | | | | |
| Major Disputes and Negotiation | | | | | | | |
| Level of Productivity | | | | | | | |
| Construction Mistakes and Defective Work | | | | | | | |
| Other, please specify: | | | | | | | |

Q21 Using a scale of 0-5, to what extent do you think that the application of **construction industrialization techniques** on a project can lead to reductions in the following types of **waste**?

| Types of Waste | No Impact (0) | Low Impact (1) | Mild Impact (2) | Moderate Impact (3) | High Impact (4) | Extreme Impact (5) | I don't know |
|---|---|---|---|---|---|---|---|
| **Transportation** (*Unnecessary movement of materials or equipment, like moving from one area, floor, or material laydown space to another and then again to the work area where it will be put in place*) | | | | | | | |
| **Inventory** (*Some inventory on-hand may be required to keep the project progressing, but too much inventory can quickly add up and tie up cash and resources*) | | | | | | | |
| **Motion** *(To move and not add value)* | | | | | | | |
| **Waiting** *(Sometimes known as delay, waiting refers to periods of inactivity)* | | | | | | | |
| **Overproduction** (*Building something too soon, having too much of something already built, or building something quicker than what is needed*) | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Over-processing** (Refers to the redundant steps taken in a process such as altering or double-handling supplies or materials) | | | | | | | |
| **Defects** (*Materials that have been damaged or made incorrectly*) | | | | | | | |
| **Underutilized Skills and Talent** *(Failure to use people's skills, creativity, or knowledge on the project)* | | | | | | | |
| Other, please specify: | | | | | | | |

***Combination of Lean Construction and Construction Industrialization***

Q22 Using a scale of 0-5, to what extent does the implementation of **lean construction** techniques influence the benefits of **construction industrialization**?

| | No Impact (0) | Low Impact (1) | Mild Impact (2) | Moderate Impact (3) | High Impact (4) | Extreme Impact (5) | I don't know |
|---|---|---|---|---|---|---|---|
| Extent of Impact | | | | | | | |

Q23 Using a scale of 0-5, to what extent does the application of **construction industrialization** influence the benefits of **lean construction**?

| | No Impact (0) | Low Impact (1) | Mild Impact (2) | Moderate Impact (3) | High Impact (4) | Extreme Impact (5) | I don't know |
|---|---|---|---|---|---|---|---|
| Extent of Impact | | | | | | | |

Q24 When applying lean construction techniques and construction industrialization methods together, to what extent are the following **budget/economic** factors impacted? Please use a scale of from -3 to +3 where -3 = high negative impact, 0 = no impact, and +3 = high positive impact.

| Budget Factors | High Negative Impact (-3) | Mild Negative Impact (-2) | Low Negative Impact (-1) | No Impact (0) | Low Positive Impact (+1) | Mild Positive Impact (+2) | High Positive Impact (+3) | I don't know |
|---|---|---|---|---|---|---|---|---|
| Labor and soft costs | | | | | | | | |
| Life-cycle costs | | | | | | | | |
| Labor/trade living expenses | | | | | | | | |
| Energy use | | | | | | | | |
| Returns, turnaround, and exposure to market cycle risks | | | | | | | | |
| Demand for labor | | | | | | | | |
| Other, please specify: | | | | | | | | |

Q25 When applying lean construction techniques and construction industrialization methods together, to what extent are the following **efficiency/productivity** factors impacted? Please use a scale of from -3 to +3 where -3 = high negative impact, 0 = no impact, and +3 = high positive impact.

| Efficiency Factors | High Negative Impact (-3) | Mild Negative Impact (-2) | Low Negative Impact (-1) | No Impact (0) | Low Positive Impact (+1) | Mild Positive Impact (+2) | High Positive Impact (+3) | I don't know |
|---|---|---|---|---|---|---|---|---|
| Ability to work in parallel | | | | | | | | |
| Jobsite disruptions | | | | | | | | |
| Labor relocation | | | | | | | | |
| Constructability | | | | | | | | |
| Requirements needed to enter a construction site (background check) | | | | | | | | |
| Worker turnover and labor retention | | | | | | | | |
| Ability to work multiple shifts | | | | | | | | |
| Space utilization | | | | | | | | |
| Other, please specify: | | | | | | | | |

Q26 When applying lean construction techniques and construction industrialization methods together, to what extent are the following **quality, safety, project duration,**

**and environment** factors impacted? Please use a scale of from -3 to +3 where -3 = high negative impact, 0 = no impact, and +3 = high positive impact.

| Quality/Safety/Project Duration/Environment Factors | High Negative Impact (-3) | Mild Negative Impact (-2) | Low Negative Impact (-1) | No Impact (0) | Low Positive Impact (+1) | Mild Positive Impact (+2) | High Positive Impact (+3) | I don't know |
|---|---|---|---|---|---|---|---|---|
| Consistent components and products | | | | | | | | |
| Job proficiency and specialization | | | | | | | | |
| Manufacturing precision | | | | | | | | |
| Safety performance and standards | | | | | | | | |
| Onsite durations | | | | | | | | |
| Schedule/time certainty and construction cycles | | | | | | | | |
| Environmental performance | | | | | | | | |
| Conditions for workers | | | | | | | | |
| Generated construction waste and waste management | | | | | | | | |
| Other, please specify: | | | | | | | | |

Q27 When applying lean construction techniques and construction industrialization methods together, to what extent are the following **other project** factors impacted?

Please use a scale of from -3 to +3 where -3 = high negative impact, 0 = no impact, and +3 = high positive impact.

| Other Factors | High Negative Impact (-3) | Mild Negative Impact (-2) | Low Negative Impact (-1) | No Impact (0) | Low Positive Impact (+1) | Mild Positive Impact (+2) | High Positive Impact (+3) | I don't know |
|---|---|---|---|---|---|---|---|---|
| Predictability | | | | | | | | |
| Workforce shortages | | | | | | | | |
| Client satisfaction | | | | | | | | |
| Competitive in the market | | | | | | | | |
| Desire to innovate | | | | | | | | |
| Weather impacts | | | | | | | | |
| Attracting a different (non-construction) workforce | | | | | | | | |
| Litigation performance | | | | | | | | |
| Disruptions to residents near project location | | | | | | | | |
| Traffic | | | | | | | | |
| Other, please specify: | | | | | | | | |

Q28 Using a scale of 0-5, to what extent do l**ean construction** and **construction industrialization** promote each other?

| | None (0) | Low (1) | Mild (2) | Moderate (3) | High (4) | Extreme (5) | I don't know |
|---|---|---|---|---|---|---|---|
| Extent of promotion | | | | | | | |

***Linked-out Survey Questionnaire***

Q29 The research team would also like to interview construction workers/staff on project sites to ask them about lean construction and construction industrialization. Does your company have any project sites which the researchers could visit to conduct interviews with field personnel?

If one or more project sites are available, kindly select "Yes" and then provide your name and contact information in response to the additional survey questions. We will contact you to provide further information about the interviews and set up a time and date to visit the site(s). Your name and contact information, as well as your company and project site information, will not be associated with your responses to the present survey, and will be kept confidential.

- ○ Yes
- ○ No

***Thank you for participating in this survey!***

Appendix C – Linked-out survey questionnaire

Linked-out Survey Questions

(If respondent selected "Yes" to Q29 in survey questionnaire)

**Interaction between Lean Construction and Construction Industrialization**

***If Yes to Q29:***

Please provide your contact information, job title/position, and the location of the project site(s). The research team will contact you to gather additional information about potential interviews, obtain information about the project(s) where the interviews will take place, and schedule a day/time to visit the project site(s). Your contact and project information will not be associated with your survey response, and all information provided will be kept strictly confidential

Q1 Your name

________________________________________________________________

Q2 Email Address

________________________________________________________________

Q3 Phone number

______________________________________________________

Q4 Location of Project (City, State)

______________________________________________________

Q5 Your Job Title/Position

______________________________________________________

Appendix D – Follow-up interview explanation

**Interaction between Lean Construction and Construction Industrialization**

**Project Name:** Interaction between Lean Construction and Construction Industrialization

**Principal Investigator**: John Gambatese / Oregon State University

**Student Investigator**: Qichang Dai / Oregon State University

**Why am I being invited to take part in this study?**

We invite you to participate in this research study as you have been identified as a worker involved in the construction industry and may be available for an interview about lean construction and construction industrialization.

**What is the purpose of this study?**

According to previous studies, lean construction and construction industrialization have been shown to bring value to a project. The researchers aim to obtain evidence of whether the combination of lean construction and construction industrialization can promote each other and provide added value to a project. In addition, we aim to quantify the added value, if any, and measure its degree and frequency.

**What will happen during this study and how long will it take?**

We will ask you questions about your views on the research topic and ask you to share your experience/ideas related to the topic from previous projects. You will be asked to describe information related to the implementation of lean construction and construction industrialization on a project. Lastly, you will be asked whether additional information about the project (e.g., photos, documents, figure/tables, etc.) is available which we can use in our case study description about the project and study topic. You may print or take a screenshot of the consent page for your records.

It is expected that the interview will take approximately 30 minutes to complete. The information you provide is for research purposes only. Some of the questions are personal. You can choose not to answer any of the questions if you wish.

**How will my information be used?**

The information you provide is for research purposes only. Your responses to the interview questions will be summarized in a research thesis and one or more academic papers. No publications of the study results will include any information about your identity or affiliation.

All information provided will be kept strictly confidential and viewed only by the researchers. Your information and responses that are collected as part of the research, even if identifiers are removed, will not be used or distributed for future research studies.

**What are the risks of this study to participants?**

The interview has minimal risks, and all information that you provide will remain confidential, be used for research and educational purposes only, and accessed only by the researchers.

Accidental disclosure of the interview responses and personal information: There is a chance of accidental disclosure of interview responses and personal information; however this chance is very small. The information is stored in password-protected computer files located on secure servers. Your personal information will not be directly associated with your responses.

Internet: The security and confidentiality of information collected from you online cannot be guaranteed. Information collected online can be intercepted, corrupted, lost, destroyed, arrive late or incomplete, or contain viruses.

**What are the benefits of this study to the participants?**

There are no direct benefits to you as a participant or to the organization to which you belong. The study evaluates two practices used in the entire construction industry. The results of the study will help improve the efficiency and safety of construction projects and ultimately benefit the entire construction industry.

**Do I have a choice to be in the study?**

Participation in the study is voluntary. Participants may refuse to answer any questions and/or may withdraw from the study at any time. Participation or non-participation will not affect your relationship with your company/organization.

**What if I have questions?**

Participants are encouraged to ask any questions at any time about the study and its procedures, or about their rights as a participant. The investigators' names and contact information are included below so that you may ask questions and report any study-related problems.

- Qichang Dai, Graduate Student, Civil and Construction Engineering, Oregon State University, 211 Kearney Hall, Corvallis, OR 97331, E-mail: daiq@oregonstate.edu
- John Gambatese, School of Civil and Construction Engineering, Oregon State University, 101 Kearney Hall, Corvallis, OR 97331, Tel.: (541) 737-8913, E-mail: john.gambatese@oregonstate.edu

In addition, if you have any questions about your rights as a survey participant, please contact the Oregon State University Institutional Review Board (IRB) Office at (541) 737-8008, or by e-mail at: IRB@oregonstate.edu.

**Acknowledgment**

I have read the above description of the research. If I had questions or would have liked additional information, I contacted the study team and had all of my questions answered to my satisfaction. I agree to participate in the research, and am at least 18 years of age or older.

Appendix E – Jobsite interview question

**Jobsite Interview Questionnaire**

*Interaction between Lean Construction and Construction Industrialization*

***Personal Demographic Information***

Q1 Which of the following best describes your current job title?

- ○ Project Manager / Assistant Project Manager
- ○ Project Engineer / Assistant Project Engineer
- ○ Project Superintendent / Assistant Project Superintendent
- ○ Safety Manager / Safety Engineer
- ○ Inspector
- ○ Foreman
- ○ Laborer
- ○ Equipment Operator
- ○ Other, please specify: ________________________________

Q2 How many years of construction industry experience do you have?

- ○ Less than 1 year
- ○ 1 - 5 years
- ○ 6 - 10 years
- ○ 11 - 15 years
- ○ 16 - 20 years
- ○ More than 20 years

***Lean Construction***

Q3 Lean Construction features

| No Impact (0) | Low Impact (1) | Mild Impact (2) | Moderate Impact (3) | High Impact (4) | Extreme Impact (5) |
|---|---|---|---|---|---|

| Method/Process | Implemented? | | How well? (*Use a scale of 0-5*) |
|---|---|---|---|
| | Yes | No | |

| | | | |
|---|---|---|---|
| **Pull Planning: S**trategically planning segments of work in order to produce progressively elaborate Weekly Work Plans. | | | |
| **Constraint Analysis:** An integral part of LPS that is applied as a proactive approach to problem-solving as a team. | | | |
| **Look-ahead schedule:** Usually discussed in weekly team meetings where the team evaluates what it "can" do in the next 6 to 8 weeks. The goal is for the team to determine constraints, assign responsibilities, and commit to resolving the constraints before they affect the activity. | | | |
| **Weekly work plan based on reliable commitments:** Tactical team collaboration to plan each day's work, conditions for handoff and acceptance, sequencing, and synchronizing the next week's work (the point of maximum progressive elaboration to create reliable work plans). | | | |
| **Planned Percent Complete (PPC):** A basic measure of how well the planning system is working – calculated as the 'number of promises/activities completed on the day stated' divided by the 'total number of promises/activities made/planned for the week'. | | | |
| **5 Whys / Root cause analysis:** Find the exact reason that led to a given problem by asking a sequence of "Why" questions. | | | |
| **5S:** Housekeeping: Sort, Set in order, Shine, Standardize, Sustain | | | |
| **Andon:** A system designed to alert operators and managers of problems in real-time so that corrective measures can be taken immediately. | | | |
| **Just-in-time:** An inventory management approach designed to eliminate waste by receiving goods only as they are needed for production processes. | | | |
| **Kaisen:** Continuous improvement | | | |
| **Kanban:** A project management technique that uses tools such as billboards or signs to document and streamline the various steps in processes. | | | |
| **Poka-yoke:** Designing a system to eliminate the possibility of mistakes and hence avoid defective products or services (i.e., mistake-proofing). | | | |

| | | | |
|---|---|---|---|
| **Kitting:** A process in which individually separate, but related, items are grouped, packaged, and supplied together as one unit before delivering them to the particular place for installation, thus assembling a complete "kit" of parts required for the installation. | | | |
| **Value Stream Mapping (VSM):** A process that helps individuals visually see and understand a given process rather than simply looking at results. | | | |

***Construction Industrialization***

Q4 Construction Industrialization features

| No Impact (0) | Low Impact (1) | Mild Impact (2) | Moderate Impact (3) | High Impact (4) | Extreme Impact (5) |
|---|---|---|---|---|---|

| Method/Process | Implemented? Yes | Implemented? No | How well? (*Use a scale of 0-5*) |
|---|---|---|---|
| **Modularization:** *Substantial fabrication and assembly of components into modules at a location other than the construction site for transportation to and installation on the construction site* | | | |
| **Prefabrication:** *Fabrication of buildings or building components at a location other than the construction site* | | | |
| **Preassembly:** *Fabricate and assemble buildings or building components before traditional on-site construction* | | | |
| **Mass production:** *Also known as flow production or repeated flow production, it refers to the production of a large number of standardized products on the production line* | | | |

***Project Information***

Q5 Has any activity that you work on been delayed? If so, which activities and how many?

________________________________________________________________________

________________________________________________________________________

Q6 Has there been a change order for any part of your work? If so, how many?

________________________________________________________________________

________________________________________________________________________

Q7 Has there been an injury accident on the project? If so, how many?

____________________________________________________________________________

____________________________________________________________________________

Q8 Has any part of the work received a non-conformance notice? If so, how many?

____________________________________________________________________________

____________________________________________________________________________

Q9 Has any of the work exceeded the budget? If so, which work and by how much?

____________________________________________________________________________

____________________________________________________________________________

Q10 What is the approximate amount (%) of prefabricated concrete on the project?

____________________________________________________________________________

____________________________________________________________________________

Q11 What is the total amount of concrete consumption on the project (cubic yards)?

____________________________________________________________________________

____________________________________________________________________________

Appendix F – Recruitment email

Dear [insert first name of email recipient],

We are conducting a research study on lean construction and construction industrialization. The purpose of the study is to determine the impact of the combination of the two practices on a project, i.e., whether their combination adds added value to the project. In addition, we aim to quantify the added value, if any, and measure its degree and frequency.

Given your background and experience related to the construction industry, we would like to invite you to participate in this research study. Participation involves completing a survey questionnaire.

The survey is expected to take approximately 15-20 minutes to complete. If you are willing to participate in the study, please complete the survey questionnaire provided in the following link: (add survey link).

Participation in this study is voluntary. If you consent to participate, and understand the explanation of research provided with the survey, please complete the survey form. You may print or take a screenshot of the consent page for your records. Participation or non-participation will not affect your relationship with your company/organization. There is no direct benefit to you as a participant in the research; however, the research will be beneficial to the construction industry as a whole.

The survey has minimal risks, and all information that you provide will remain confidential, be used for research and educational purposes only, and accessed only by the researchers. Personal or company/organization names are not required or recorded, unless you choose to provide them. Names of participants will only be known to the researchers and not shared with the public. Publications of the study results will not include any information about your identity or affiliation.

For more information about this study, please contact the research team: Qichang Dai (Graduate Student) at daiq@oregonstate.edu , and Dr. John Gambatese (Professor) by phone at 541-737-8913 or email at john.gambatese@oregonstate.edu.

Thank you,

Qichang Dai

Graduate student researcher

Study Title: Interaction between Lean Construction and Construction Industrialization

Appendix G – Reminder recruitment email

Dear [insert first name of email recipient],

This email is a gentle reminder that you are invited to participate in an online survey regarding lean construction and construction industrialization. Provided below is our previous email inviting you to participate in the survey. Please consider participating in this important survey.

If you wish to opt-out of future emails about the study, please respond to this email indicating your preference to opt-out. We will remove you from our distribution list and not contact you again regarding this study.

INVITATION TO PARTICIPATE IN SURVEY:

We are conducting a research study on lean construction and construction industrialization. The purpose of the study is to determine the impact of the combination of the two practices on a project, i.e., whether their combination adds added value to the project. In addition, we aim to quantify the added value, if any, and measure its degree and frequency.

Given your background and experience related to the construction industry, we would like to invite you to participate in this research study. Participation involves completing a survey questionnaire.

The survey is expected to take approximately 15-20 minutes to complete. If you are willing to participate in the study, please complete the survey questionnaire provided in the following link: (add survey link).

Participation in this study is voluntary. If you consent to participate, and understand the explanation of research provided with the survey, please complete the survey form. You may print or take a screenshot of the consent page for your records. Participation or non-participation will not affect your relationship with your company/organization. There is no direct benefit to you as a participant in the research; however, the research will be beneficial to the construction industry as a whole.

The survey has minimal risks, and all information that you provide will remain confidential, be used for research and educational purposes only, and accessed only by the researchers. Personal or company/organization names are not required or recorded, unless you choose to provide them. Names of participants will only be known to the researchers and not shared with the public. Publications of the study results will not include any information about your identity or affiliation.

For more information about this study, please contact the research team: Qichang Dai (Graduate Student) at daiq@oregonstate.edu , and Dr. John Gambatese (Professor) by phone at 541-737-8913 or email at john.gambatese@oregonstate.edu.

Thank you,

Qichang Dai

Graduate student researcher

Study Title: Application of Lean Construction in Industrialized/Non-Industrialized Projects

Appendix H – IRB approval

HRPP and IRB Application and Protocol (Version 1.1)

## 1.0 General Information

***Please enter the full title of your study::**

Application of Lean Construction in Industrialized/Non-Industrialized Projects

***Short Title:**

Lean Construction and Construction Industrialization
* This field allows you to enter an abbreviated version of the Study Title to quickly identify this study.

**Anticipated study review level:**

Exempt

## 2.0 Add departments

**2.1 Add the PI's primary department if you do not see it listed below:**

| Is Primary? | Department Name |
|---|---|
| ◯ | **OSU** - ECC - Sch Civil & Construction Engr |

## 3.0 Study Team

**3.1 *Name of Principal Investigator (FAQ: Who can be a Principal Investigator (PI):**

Gambatese, John A

**3.2 Additional Study Team Members:**

**Additional investigators:**
(Do not list individuals who will receive IRB approval at their own external institution or whose institution has determined that they are not engaged.)

To remove a study team member prior to submitting the application, check the box next to their name and click the "remove" button.

Dai, Qichang
Student

**Non-Research Support Staff:**
(No access to participants, data, or specimens)

To remove a study team member prior to submitting the application, check the box next to their name and click the "remove" button.

**3.3 *Please add a Study Contact**

Dai, Qichang
Gambatese, John A

The Protocol Contact(s) will receive all important system notifications. The Principal Investigator cannot be removed as a study contact, however, additional study contact(s) can be added. All protocol contacts must be listed in 3.2 above.

To remove a study team member from the "protocol contact" section, check the box next to their name and click the "remove" button.

**3.4 If required by the PI's department, please select the Designated Department Approval(s):**

Add the name of the individual required to approve and sign off on this protocol from your department (e.g. the Department Chair or Dean). Skip if none.

## 4.0 Help Text

**4.1 Do you wish to see the application help text, examples, and links to additional information in this form?**

○ Yes ● No

## 5.0 Submission Type

**5.1 Select One:**

● New submission, not previously reviewed or approved by OSU
○ Re-submission of previously approved protocol (expired or migration into iRIS)
○ Request for .118 Determination
○ Convert .118 Determination to a new application

## 6.0 Study Summary

**6.1 Using lay language, briefly describe the study purpose or primary research question:**

50 words or fewer. You will be asked for aims, background justification, and specific methods and procedures in later sections.

The purpose of the study is to conduct academic research on the relationship between lean construction and construction industrialization. Lean construction and construction industrialization have been shown to bring value to a construction project independently. We hope to find the impact on the project when implementing the combination of the two practices, i.e., whether their combination adds additional value not present when implemented separately. In addition, we aim to quantify the added value, if any, and measure its degree and frequency.

## 7.0 Determination of Whether the Project Requires IRB Review

**7.1 "Research" is defined as a systematic investigation, including research development, testing and evaluation, designed to develop or contribute to generalizable knowledge. Does the project involve research at OSU or elsewhere?**

● Yes ○ No

**7.2 "Human subject" is defined as obtaining data about, or specimens from, one or more living individuals through intervention, OR interaction, OR the collection of identifiable private information. Does the project involve human subjects at OSU or elsewhere?**

◯ Yes ◉ No

**If you think the project does NOT involve human subjects, please explain why and provide the relevant project details:**

The research involves collecting and analyzing information about construction management techniques and practices, specifically those business practices related to lean construction and construction industrialization. The research is not about the individuals from whom the information is collected. The only involvement of individuals is to gather their opinions about the specific business practices.

**7.3 OSU Engagement:**

**Are any of the following true?**

- OSU is the only institution participating in this study
- OSU is the primary awardee on the funding
- OSU employees or students are obtaining consent from participants
- OSU employees or students will have access to individually identifiable data or samples

◉ Yes ◯ No

## 8.0 Sources of Funding and Support for this Project

**8.1 Is funding for the project pending/awarded?**

◯ Yes (Internal or External)

◉ No (Unfunded)

**8.6 Is an external (non-OSU) organization or company providing material, equipment, drugs, supplements, or devices for this study?**

◯ Yes ◉ No

## 9.0 Application Questions Complete

**9.1 Having completed the application questions, please return to section 1.0 to confirm that you have selected the appropriate review level, then return to this section to complete the application.**

**9.2 Click the box below to close all help text notes (required):**

If the application is complete and ready to be submitted, please click "Close Help Text, Examples, Links". If you are revising the application in response to submission corrections or review response, you can click "Re-open Help Notes" to make all help notes visible again.

◉ Close Help Text, Examples, Links

◯ Re-open Help Text, Examples, Links

**9.3 Please click Save & Continue to proceed to the Initial Review Submission Packet.**

The Initial Review Submission Packet is a short form filled out after this application has been completed. This is where you will attach documents.

Appendix I –Survey Participant Organization and Personal Demographic Information

| Participant | Organization | Working experience | Company size | Job title | Primarily type of projects |
|---|---|---|---|---|---|
| 1 | Construction Firm | More than 20 years | 101-250 employees | President | Commercial and institutional buildings |
| 2 | Construction Firm | 11-15 years | More than 1000 employees | Operations Manager | Commercial and institutional buildings |
| 3 | Construction Firm | More than 20 years | 251-500 employees | Project Manager/Assistant Project Manager | Commercial and institutional buildings |
| 4 | Construction Firm | 1-5 years | Less than 10 employees | Project Engineer/Assistant Project Engineer | Commercial and institutional buildings |
| 5 | Construction Firm | 6-10 years | 501-1000 employees | Project Engineer/Assistant Project Engineer | Commercial and institutional buildings |
| 6 | Construction Firm | 11-15 years | 101-250 employees | Division Manager | Commercial and institutional buildings |
| 7 | Construction Firm | More than 20 years | Less than 10 employees | Project Manager/Assistant Project Manager | Commercial and institutional buildings |
| 8 | Construction Firm | More than 20 years | 101-250 employees | President | Commercial and institutional buildings |
| 9 | Construction Firm | 6-10 years | 501-1000 employees | Lean Manager | Bridges |
| 10 | Construction Firm | More than 20 years | 101-250 employees | Chief Estimator | Marine and Underwater |
| 11 | Construction Firm | 16-20 years | 51-100 employees | Project Manager/Assistant Project Manager | Roads |
| 12 | Construction Firm | More than 20 years | 501-1000 employees | Project Manager/Assistant Project Manager | Commercial and institutional buildings |
| 13 | Construction Firm | More than 20 years | More than 1000 employees | Maintenance Supervisor | Roads |

| | | | | | |
|---|---|---|---|---|---|
| 14 | Construction Firm | More than 20 years | 501-1000 employees | VP | Roads |
| 15 | Construction Firm | 16-20 years | 501-1000 employees | Project Superintendent/Assistant Project Superintendent | Commercial and institutional buildings |
| 16 | Construction Technology Reseller | More than 20 years | 10-50 employees | Technology Sales Manager | Roads |
| 17 | Construction Firm | 11-15 years | More than 1000 employees | Project Superintendent/Assistant Project Superintendent | Commercial and institutional buildings |
| 18 | Supplier | 16-20 years | More than 1000 employees | Regional Sustainability Engineer | Bridges, Roads, Commercial buildings |
| 19 | Construction Firm | 6-10 years | 251-500 employees | Project Manager/Assistant Project Manager | Commercial and institutional buildings |
| 20 | Both Design and Construction | More than 20 years | More than 1000 employees | VP/General Manager | Commercial and institutional buildings |
| 21 | Construction Firm | 6-10 years | More than 1000 employees | Project Manager/Assistant Project Manager | Commercial and institutional buildings |
| 22 | Construction Firm | 16-20 years | 101-250 employees | Project Manager/Assistant Project Manager | Bridges |
| 23 | Construction Firm | More than 20 years | 501-1000 employees | Regional Manager | Bridges |
| 24 | Construction Firm | More than 20 years | 101-250 employees | Owner | Roads |
| 25 | Construction Firm | More than 20 years | 51 -100 employees | CEO | Commercial and institutional buildings |

| | | | | | |
|---|---|---|---|---|---|
| 26 | Construction Firm | More than 20 years | More than 1000 employees | Program Manager/Regional Manager | Bridges |
| 27 | Consulting Firm | 11-15 years | 501-1000 employees | Business Development Manager | Commercial and institutional buildings |
| 28 | Construction Firm | 16-20 years | 51-100 employees | Estimator | Industrial/Manufacturing/Power Generation |
| 29 | Construction Firm | 11-15 years | More than 1000 employees | Operations Manager | Commercial and institutional buildings |
| 30 | Construction Firm | 16-20 years | More than 1000 employees | Project Superintendent/Assistant Project Superintendent | Commercial and institutional buildings |
| 31 | Construction Firm | 1-5 years | 10-50 employees | Project Engineer/Assistant Project Engineer | Hydroelectric Facilities |
| 32 | Construction Firm | 16-20 years | 501-1000 employees | Project Manager/Assistant Project Manager | Data centers |
| 33 | Construction Firm | More than 20 years | 501-1000 employees | Executive | Commercial and institutional buildings |
| 34 | Construction Firm | More than 20 years | 251-500 employees | Project Manager/Assistant Project Manager | Residential buildings |
| 35 | Construction Firm | 6-10 years | 10-50 employees | Estimating | Commercial and institutional buildings |
| 36 | Construction Firm | 16-20 years | 251-500 employees | Project Manager/Assistant Project Manager | Commercial and institutional buildings |