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Connection between Lean Design/Construction and Construction Worker Safety

John Gambetese

Catarina Pestana

Oregon State University

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CPWR Small Study Final Report

8484 Georgia Avenue
Suite 1000
Silver Spring, MD 20910

PHONE: 301.578.8500
FAX: 301.578.8572

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(CPWR Small Study No. 13-10-PS)

FINAL REPORT

By:

John Gambatese, and Catarina Pestana
School of Civil and Construction Engineering
Oregon State University
101 Kearney Hall
Corvallis, OR 97331

For:

The Center for Construction Research and Training
8484 Georgia Avenue, Suite 1000
Silver Spring, MD 20910

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John A. Gambatese, PhD, PE
Oregon State University
101 Kearney Hall
Corvallis, OR 97331
Ph: (541) 737-8913
Email: john.gambatese@oregonstate.edu

Catarina Pestana, MSc
Oregon State University
101 Kearney Hall
Corvallis, OR 97331
Email: pestanaa@onid.oregonstate.edu

This small study aimed at investigating how lean design and construction practices are connected to and impact safety on construction sites. The research team identified production, contractual, and safety practices typically implemented during both the design and construction of architecture/engineering/construction (AEC) projects, and determined the extent to which each of the identified production practices adheres to the principles of lean design/construction and whether lean design/construction practices are particularly beneficial or detrimental to construction safety. The researchers carried out seven case studies of building construction projects that included conducting interviews of project personnel, visiting the project sites, and reviewing project documentation about the design and construction practices utilized to design and build the projects. Utilizing the knowledge gained from the case studies, the researchers also conducted a survey of Lean Construction Institute (LCI) members to obtain expert perspective from a wider segment of the industry on the connection of lean practices to safety. Based on the case studies and survey, the researchers assessed the extent to which lean practices impact construction safety risk and support commonly-implemented safety practices.

Key Findings:

- A variety of lean design and construction practices are being implemented on building construction projects that reflect the principles of lean production. The extent to which lean practices are implemented varies from company to company, and from project to project within a company.
- Improving production through the application of lean principles naturally leads to enhanced worker safety. Utilizing lean practices provides the ability to “make safety better.”
- The construction phase is recognized as the best opportunity to positively impact safety through the implementation of lean practices.
- Worker involvement in safety is viewed as the safety practice that benefits the most from the implementation of lean practices, and is particularly impacted by 5 S’s, standardized work, and LPS.

- Integrated project delivery concepts are tied closely to both lean construction and safety management practices. Management commitment, staffing for safety, and pre-project planning are safety management practices that are positively supported by contractual arrangements founded on lean principles (e.g., IPD).

Original Study Abstract:

Lean construction is an approach to construction management that aims to eliminate operational inefficiencies through a focus on optimizing production at the construction work face. Based on the principles set forth in the Lean Production approach to production management, also known as the Toyota Production System, lean construction extends the application of lean production principles to the delivery of projects in the architecture/engineering/construction (AEC) industry (Howell 1999; Koskela 1992). Common goals of lean construction practices on projects are to improve productivity, time on task, flow of work, and the value added to the final product with each work task. In the proposed small study, lean construction is investigated in conjunction with lean design. For the purposes of the study, lean design is identified as the application of lean production principles to production management during the design of AEC projects.

The specific aim of the proposed small study is to develop an understanding of the relationship between lean design and construction practices and the risk of worker injuries and fatalities on construction sites. By doing so, the research is intended to provide evidence of how to advance the practice of lean design/construction in order to enhance construction site safety while also improving the efficiency of delivering AEC projects. Given the AEC industry's current trend towards utilizing project delivery methods which integrate the design and construction disciplines, such as design-build, CM-at-risk, and Integrated Project Deliver (IPD), the research will be founded on a similar integrated lean design and construction viewpoint. Connection between construction safety risk and lean design and construction practices that are both independent and integrated across the project delivery lifecycle will be investigated.

Connection between Lean Design/Construction and Construction Worker Safety

Abstract

Lean construction is an approach to construction management that aims to eliminate operational inefficiencies through a focus on optimizing production at the construction work face. Common goals of lean construction practices on projects are to improve productivity, time on task, flow of work, and the value added to the final product with each work task. Likewise, lean design is identified as the application of lean principles to production management during the design of AEC projects. Based on the understanding that worker injury incidents and near misses are examples of waste as defined in lean construction, a small study was conducted to investigate the relationship between lean design and construction practices and the risk of worker injuries and fatalities on construction sites. Using a mixed methods approach of project case studies and a survey of construction personnel knowledgeable about lean construction, lean practices were found to be present on many construction projects to varying extent. Those involved in projects on which lean practices are present indicate that improving production through the application of lean principles naturally leads to enhanced worker safety. The greatest opportunity to implement lean practices for the benefit of worker safety is in the construction phase. With regard to safety practices, worker involvement in safety is viewed as the safety practice that benefits the most from the implementation of lean practices, and is particularly impacted by 5 S's, standardized work, and LPS. Lastly, management commitment, staffing for safety, and pre-project planning are safety management practices that are positively supported by integrated contractual arrangements founded on lean principles (e.g., IPD). The research findings suggest the need for further empirical research on the connection between specific lean practices and worker safety and health, and the promotion and dissemination of lean practices as another avenue for bringing attention to and improving construction worker safety and health.

Introduction

Lean construction practices are starting to be identified as beneficial for worker safety. Founded on the principles of lean production, lean construction practices are becoming more popular as the United States (US) construction industry continues to take steps to optimize production on construction projects (LCI 2013). Improving production is desired in order to reduce costs, shorten schedules, improve quality, increase competitiveness in the global marketplace, and ultimately improve a firm's economic standing. As a production management approach for project delivery, lean construction is implemented to maximize performance at the jobsite level by looking at construction as both conversions and flow, where only conversions add value to the final product (Howell 1999; Koskela 1992). Examples of lean construction practices that have been developed include implementing the Last Planner® System, utilizing pull schedule techniques and value stream mapping, and structuring production processes to maximize value to the final customer.

Lean practices also target activities that adds no value to the final customer and therefore are considered to be waste. There are seven basic types of waste: defects, waiting, transportation of goods, motion, inventory, over-production, and unnecessary process steps. “Make do” is often considered an eighth type of waste associated with the construction industry. Accidents and injury incidents are a major source of waste in construction that have high social and economic costs. Accidents introduce variability in the production process, resulting in major disruption of the workflow, which lean construction aims to stabilize.

Background and Literature Review

A recent example of the connection between lean construction and safety is when Turner Construction stopped work briefly on all of its projects in North America to give its employees and subcontractors a tutorial on lean construction and safety (Abaffy 2012). In the article, one subcontractor is quoted as saying that lean construction practices have led to a 50% reduction in injuries. Initial exploratory research has been undertaken to understand the connection between lean construction and jobsite safety. Antillón et al. (2011), for example, found that there is a significant amount of evidence of synergy between lean production practices and safety management practices. The researchers note in their paper that applying lean construction practices to safety management is a promising research area, and feel that it is unreasonable not to integrate or include safety with production planning. Based on the findings of a Brazilian study that addressed the lean production practice of autonomation, Saurin et al. (2008) state that this practice requires both workers and managers to constantly assess the trade-off between safety and production. However, Saurin et al. highlight that the effectiveness of this approach to construction safety has not yet been proven by empirical data. The Brazilian researchers emphasize the need for further research as follows: “Although it is widely accepted that safety should be integrated virtually into all managerial processes, it seems to be necessary to expand research efforts in this area” (Saurin et al. 2002). The researchers add that, “The integration of safety into the design phase would be a natural follow up for this research project.”

Saurin et al. additionally suggest an important step in the research; that is, to investigate how lean practices implemented throughout both the design and construction processes can affect safety. To date, the application of lean production concepts to the construction industry has focused primarily on the activities undertaken during the construction phase to construct the physical features of the project. Prior to the start of construction, however, much work is undertaken to plan and produce the design of the facility. The potential impacts that the design can have on construction, and especially on construction worker safety, are well known (for example, see: Weinstein et al. 2005; Gambatese et al. 2008; and Gambatese et al. 2007). Production management principles also apply to the production of the design. Consequently, lean concepts and practices can be applied to the design phase for improved performance in both design and in construction.

Research that focuses on lean design and construction practices is especially of interest given the construction industry's current movement towards integrated project delivery methods. Such methods are designed to integrate design and construction knowledge and tasks with the goal of developing and creating higher quality facilities in a more efficient manner. The proposed research aims to investigate whether and how an integrated approach involving lean practices across both design and construction can impact construction worker safety. The study findings can then be used to augment current lean practices to improve safety. The present study is also expected to provide recommendations for further study of how specific lean practices can be modified or developed to improve safety.

Research Objectives

The primary objective of this small study is to expand the general understanding of the relationship between lean design and construction practices and the risk of worker injuries and fatalities on construction sites. Four secondary objectives (SOs) were established to guide the research in attaining the primary objective for this study. The secondary objectives are:

SO#1: Identify the production practices typically implemented for the design and the construction of architecture/engineering/construction (AEC) projects;

SO#2: Characterize the typical production practices in terms of efficiency, work flow, value added, and integration across the design and construction phases;

SO#3: Determine the extent to which each of the identified production practices adhere to the principles of lean design and construction; and

SO#4: Determine whether lean design and construction practices impact the risk of construction worker injuries and fatalities, and which practices are particularly beneficial and detrimental to construction safety.

Research Methods

Due to the nature of the secondary objectives established, the research was carried out using multiple methods. The research plan included three different phases to collect qualitative and quantitative data throughout the course of the study. During the first phase, project case studies were used as a strategy to collect and analyze empirical data, namely through interviews. The case studies allowed investigating contextual conditions that are difficult to gather through a survey or other means. The unit of analysis for the cases studies was construction projects. During this phase, the goal was to identify planning and production practices typically used on each project and to provide an initial idea of the extent to which the practices adhere to the principles of lean design/construction and are beneficial to enhancing construction safety. Further description of the case study process is provided below.

During the second phase of the study, an on-line survey of AEC industry professionals was conducted. The survey targeted sponsoring members of the Lean Construction Institute, and was designed to validate the results obtained from the first phase of the study. Additional description of the survey process is provided below.

The third phase of the study included analyzing the data received from the case studies and the industry survey. Based on the results of the analysis, this phase also included developing recommendations for practice and future research.

In addition, a literature review was carried out during all three phases to form a theoretical background for the study and findings. The literature review targeted contemporary academic and professional journals as well as reports from prior research related to the topic.

The connection between the research methods used and each of the SOs is as follows:

- SO's #1 and #2: A combination of literature review, project case studies, and interviews was deemed the most suitable for these secondary objectives. A literature review was initially carried out to identify common and recommended lean production principles and practices implemented during contractual planning, the design phase, and the construction phase of a project. Four project case studies were then identified and conducted within a large construction company located in the Pacific Northwest that showed particular interest in the research topic and supported the research developed herein. In addition, as part of the case studies, interviews were conducted with the company personnel to confirm the list of lean principles and practices that were identified from the literature review.
- SO #3: This secondary objective was met through interviews on four project case studies. Based on the contacts with those interviewed on the four projects, an additional three project case studies were identified with two other companies. The additional interviews, adapted to reflect the results of the initial four case studies, were conducted with personnel within the additional two companies.
- SO #4: This secondary objective was met using an on-line survey that targeted sponsoring members of the Lean Construction Institute (LCI). The intent of the survey was to validate the lean principles and practices that were identified as being both particularly beneficial and detrimental to construction safety.

Lean Principles and Practices Cited in Literature

Contrary to the traditional production conversion model, which focuses on local optima to improve overall performance, lean production focuses on improving the entire delivery system. Specifically, lean production aims at maximizing value to the customer while minimizing waste, facilitated through lean project delivery.

Koskela first introduced the view of a construction project as a production system when she proposed a shift from the traditional conceptual understanding of construction (Koskela 1992). As mentioned above, production systems are composed of a network of flows and conversions. Koskela claimed that a reduction or elimination of flow activities should represent the first focus of improvements. Once flow activities have been addressed, further changes should target improvements in the conversion activities.

In her work, Koskela proposed a set of eleven principles for the design and management of production systems in construction. These principles are:

1. Reduce the share of non-value-adding activities;
2. Increase output value through the constant consideration of customer requirements;
3. Reduce variability;
4. Reduce cycle time;
5. Simplify by minimizing the number of steps, parts, and linkages;
6. Increase output flexibility;
7. Increase process transparency;
8. Focus the control on the complete process;
9. Build continuous improvement to the process;
10. Balance flow and conversion improvements, practice benchmarking; and
11. Continuously improve the process.

The implementation of lean practices has repeatedly been reported to occur as a result of a shift in a company's approach to optimization of the project delivery system, and is rooted in a new approach in production management that includes work structuring and production control that stabilize the workflow (Ballard et al. 2001).

In the manufacturing industry, commonly-implemented lean production practices are well defined which facilitates their implementation in a somewhat uniform way. However, in the construction industry, the selection of techniques and tools implemented by each company is far from unique, and new tools and techniques are continuously being developed and/or adapted. In fact, the extent to which each company adheres to lean techniques and practices varies deeply from company to company, and greatly depends on the company's current production system status and the future status that it aims to achieve.

Implementing lean thinking requires companies to slowly and deeply change the company's culture and adhere to lean principles. This change cannot be accomplished by simply implementing practices and tools. Nonetheless, the implementation of practices and tools may help to facilitate this change. Furthermore, Nesensohn et al. (2012) argue that implementing lean thinking requires not only long-term thinking and vision, but also guidance on how to achieve it. The researchers propose that this guidance should include deciding what practices to benchmark, which also allows for assessing the extent to which the industry is advancing towards a lean system (Etges et al. 2012).

Based on the Koskela's conceptualization of production management as the management of transformation/flow/value, Ballard et al. (2001) developed guidelines for the design of production systems that maximize value for the client and minimize waste throughout the processes that focused on improving entire delivery system (e.g., design, assembly, use).

Lean delivery systems represent a shift in the traditional delivery systems (e.g., design-bid-build, and CM/GC) to a more integrated and collaborative delivery approach that engage all participants through the project lifecycle. Frequently identified as integrated project delivery (IPD) or integrated form agreement, Howell and Lichtig (2008) argue that this type of contractual agreements enables:

1. Impeccable coordination that permits stable and predictable workflow while allowing innovation and continuous improvement;
2. Approaching projects as production systems that bring opportunities to redesign the production system of both the design and the construction; and
3. Seeing projects as collective enterprises, which align project-wide performance with shared financial risks and rewards.

IPD-like contracts intend to share risk and rewards amongst project team members with the goal of improving quality and efficiency, and reducing litigation. The process involves designers and constructors (including major subcontractors) working together from the start of the project and freely sharing information as the design is developed. In addition, subcontractors and fabricators may participate in the design of some parts of the project in order to create designs that lead to efficient and high quality construction. All of the project team members share the risks and rewards. Projects containing the following characteristics are identified as representing projects with IPD (Cohen 2010):

- Key participants bound together as equals – teams jointly manage the project and there is no hierarchy for decision-making.
- Shared financial risk and reward based on project outcome – a contractual tie between profit based on agreed outcome and limitations on change orders

- Liability waivers between key participants – participants take responsibility for the project rather than for their part of the work, enabling rapid, direct, and continuous communication.
- Fiscal transparency between key participants – allows open communication, no hidden agenda.
- Early involvement of key participants – Key parties are contractually engaged earlier allowing for coordination and constructability to be addressed during the development of the design rather than during the construction process Also allows for diversity of opinions and perspectives and a better understanding of the systems and processes in the early phases of the project enabling innovation and creativity.
- Jointly developed project target criteria – project goals are developed jointly and enforceable for the project. The project goals are the basis for determining project success and compensation.
- Collaborative decision making – major decisions are made jointly and "closer to sources of knowledge and information".

A review of literature on lean construction provided a list of lean tools and techniques that have been developed and are currently implemented in practice both during the design and the construction phases.

For the design phase, Ballard and Zabelle (2000) present an approach for the management and development of lean designs which consists of the following six steps:

1. Organize cross-functional teams
2. Peruse a set-based strategy
3. Structure design work to approach the lean ideal
4. Minimize negative iteration
5. Use Last Planner® System for production control
6. Use technologies that facilitate lean design

Ballard and Zabelle (2000) and Tommelein et al. (2002) present lists of tools and techniques available for managing and producing lean designs. Table 1 summarizes the most commonly-used lean design practices that were cited in the literature.

***Table 1*: Summary of Lean Design Practices**

Lean Design Practice	Description
Target-value Design	Collaborative design process involving designers, builders, suppliers, estimators, and owners to collaboratively produce a design that provides the best target value.
Last Planner System®	Production control of design activities based on commitments through the consistent use of techniques such as pull planning, make-ready look-ahead planning with constraint analysis, weekly work planning based upon reliable promises, and learning based upon analysis of the planning system (plan percent complete and reasons for variance).
Deferring decisions to the last responsible moment	Least commitment strategy preventing premature decision making and rework.
Pull Scheduling	Minimize design negative iterations by developing a plan using pull techniques – the work is planned based on the request of a downstream customer.
Frequent team communications	Incomplete design outputs are communicated often to the other disciplines. Enables concurrent design and reduces design batch size.
Design alternatives	Designing a range of possible solutions that is then shared with other participants on the project to enable concurrent design.
Simultaneous product and process design	The design phase employs 3D modeling that integrates product and process design, i.e., is capable of modeling assembly, commissioning, operations, and maintenance of the facility.
Waste reduction	Reduce design waste by using specialty contractors that are knowledgeable about construction and quality impacts to produce detailed designs rather than design specialists.
Early involvement of specialty contractors	Specialty contractors participate in decision-making during early design phases.
Cross-functional Teams	Cross-functional teams with all stakeholders understanding and participating in key decisions. The decision-making process is conducted with cross-functional teams that include participants from all the relevant disciplines.

Similarly, research has identified lean practices that are particularly applicable to the construction process. A review of literature on lean construction provided a list of lean tools and techniques that have been developed and are currently implemented in practice. Nesensohn et al. (2012) present a list of 20 best practices applied in lean construction. The practices presented by Nesensohn et al. were the practices initially considered in the present study and were adapted as the study evolved. A summary list of common practices, along with descriptions of the practices, is provided in Table 2 (LCI 2013; Lean Lexicon 2008).

***Table 2*: Summary of Lean Construction Tools and Techniques**

Lean Tools and Techniques	**Description**
5 S's	An approach to maintain order in the workplace. It includes: • Sort: Removing clutter and unused items. • Set in Order: Arranging the work in a manner that makes jobs easier to do; defining a place for everything • Shine/Sweep: Making it easy to keep the area clean. • Standardize: Making and maintaining the locations designated with set in order. • Self-Discipline/Sustain: Keeping the 5 S's in place.
5 Whys	A problem solving technique that enables root cause analysis by asking repeatedly why an issue has occurred until it is not possible to identify another cause and the core of the problem – the core of the problem – has been found. The number five is an arbitrary number to remind looking past the surface under multiple layers and deeper into the problem until the root cause is found.
Andon	A system to notify management, maintenance, and other workers that assistance is needed.
First-run Study	Trial execution of a process in order to determine the best way to perform the process.
Integrated Project Delivery (IPD)	A project delivery method that aims at aligning interests, objectives, and practices amongst the key project stakeholders.
Just-in-Time (JIT)	Producing or delivering the right amount of parts or product at the right time and the right place as needed for production.
Kaizen	A discrete, continuous improvement process usually most effective when integrated with an overall improvement strategy.
Kanban	A signal that gives instructions to pull materials or parts in a certain amount.
Kitting	Creating sets of parts that are consolidated and delivered to a work area as a unit. The kit helps to prevent errors.
Last Planner® System (LPS)	A collaborative planning approach based on commitments through the consistent use of techniques such as pull planning, make-ready look-ahead planning with constraint analysis, weekly work planning based upon reliable promises, and learning based upon analysis of the planning system (plan percent complete and reasons for variance).
Lean Project Delivery System	Organized implementation of lean principles and tools and techniques.
Look Ahead Planning	Making work-ready by identifying and removing constraints to allow matching the work that should be done with the work that can be done.
Phase Plan or Pull Plan	A plan developed by the teams responsible for doing the work through pull techniques – the work is planned based on the request

	of a downstream customer.
Plan Percent Complete (PPC)	The "number of assignments completed on the day stated" divided by the "total number of assignments made for the week".
Poka yoke	A mistake proofing technique that keeps processes from producing errors.
Standard Work	A defined and documented production process that specifies the work to be done and the sequence of operations for a worker.
Reason for Variance	Systematic identification of the factors that prevent assignments from being completed as promised.
Value Stream Mapping	A diagram that represents the steps involved for the material/equipment/workers and information flows needed to bring a product from request to delivery.
Weekly Work Plan	Detailed plan developed based on commitments – identifies promised task completions agreed upon by the "last planners" (performers).
Work Structuring	Designing the production system to determine who does what, when, where, and how.
Workable Backlog	An activity or assignment that is ready to be performed, but is not assigned to be performed during the active weekly work plan if need arises.

Safety Principles and Practices Cited in Literature

Compared to that available related to lean design and construction, the literature on construction safety principles and practices is quite extensive and too wide-ranging to summarize in this small study report. The most applicable principles and practices relevant to this small study are summarized here. The principle of safety management that is perhaps the most applicable relates to how to control safety hazards. The "hierarchy of controls" or "order of precedence" is a guide to follow to provide a safe environment for workers that addresses the expected safety hazards and risk to workers. Manuele (1997) presents this order of precedence as follows, with the items listed from 1 to 5 in order of decreasing priority, reliability, and effectiveness:

1. Design to eliminate or avoid hazard,
2. Design to reduce the hazard,
3. Incorporate safety devices after the fact,
4. Provide warning devices, and
5. Institute training and operating procedures.

The above list indicates that it is best to eliminate the hazard if possible, as doing so will remove the risk associated with the hazard. In addition, the reliability of the control in regard to assurance that workers will not get injured increases with the higher level of action taken. If it is not possible to eliminate the hazard, mitigation measures that are lower in the list may be employed with a corresponding assumption of risk due to their lower reliability and effectiveness. Taking no action will expose those who interact with the design to uncontrolled risk.

Many different practices are employed on projects to mitigate safety risk. In the design phase, Prevention through Design (PtD) aims to design out the hazards before they appear on the site. The National Institute for Occupational Safety and Health (NIOSH) defines PtD for all industries and for all phases of a project's lifecycle as: "Addressing occupational safety and health needs in the design process to prevent or minimize the work-related hazards and risks associated with the construction, manufacture, use, maintenance, and disposal of facilities, materials, and equipment" (NIOSH 2013). During construction, recommended practices engage workers, supervisors, and management personnel within a company, and target worker behavior, worksite conditions, and construction operations. For example, the Construction Industry Institute (CII) identifies the practices shown in Table 3 as high-impact safety practices and recommends their implementation on projects.

Table 3: **Safety Best Practices (created from Hinze 2002)**

Safety Practice	Description
Demonstrated management commitment	Sincere management commitment conveyed to the worker level. For example: top management participates in investigation of recordable injuries; company president/senior management reviews safety performance report; and home office performs safety inspections on the project.
Staffing for safety	Safety personnel are properly allocated to the project to ensure that the safety needs of the projects are being satisfied, training programs are carried out, and daily safety support for the field personnel is properly provided.
Pre-project planning	Project safety analysis is conducted prior to the beginning of the project. For example: constructability reviews are carried out, and site-specific safety programs are developed.
Pre-task planning	Pre-task safety plans are integrated into the daily work routine (job hazard analysis and specific task plan developed to eliminate hazards).
Safety education	Formal jobsite orientation and training of every worker and is carried out periodically and as the jobsite conditions change. The training focuses on the needs of the individual trainees, whether they are field workers, supervisors, or managers.
Worker involvement	Workers are actively engaged in the implementation of safety practices. For example: observations of worker behavior, and input through worker safety perception surveys and/or worker participation on safety committees.
Evaluation and recognition/reward	A technique used to reward workers' commitment to safety that aims at improving safety performance.
Subcontract management	Subcontractors are included in the safety orientation and training, safety planning, and remaining safety efforts
Accident/incident investigations	Accidents/incidents (including near misses) are reported, root cause investigated, and results shared with workers.
Drug and alcohol testing	Implementation of an alcohol and substance abuse program that includes randomly testing workers for substance abuse and implementing rehabilitation programs.

Initial Contact and Preliminary Interviews

The researchers made preliminary contact with personnel in companies that were targeted to participate in the study. The companies initially targeted for case studies are listed as members of the Cascadia Lean Construction Institute (LCI) Community of Practice, and included a construction company and a design firm (both initially listed as industry partners in the research proposal). When making initial contact with the companies, both showed interest in participating in the research study. However, after further communications and discussions, only the construction company (Company A) continued to be willing to participate in the study. Innumerous attempts to engage the design company in the research study turned out unsuccessful. As a result, no data could be obtained from the design firm for the study.

Initial interviews were conducted with the Assistant Director and Director of Company A's production system. The Director was previously the company's safety director. The initial interviews were designed to further explain the research objectives and scope, and determine how best to integrate the research team with the company's personnel and projects in order to perform the research study.

Selection of Case Studies

The research team and Company A identified four projects conducted by the company that were deemed to be good candidates as case studies. Specifically, the projects were those on which lean practices were implemented to some degree, currently in progress or recently completed, located in the Pacific Northwest, and involved the construction of buildings. The researchers contacted two other construction companies, Company B and Company C, with projects and offices located in the Pacific Northwest. Three additional ongoing projects from Company's B and C were added to the initial pool of case studies. The designers on each case study project were also contacted, but again with no success.

Figure 1 depicts the research design for the study. As shown in the figure, the case studies are intended to provide empirical evidence regarding the extent to which lean design and construction practices are typically included in projects and integrated. The case studies were also designed to support the industry survey with regard to the impact of lean practices on construction safety.

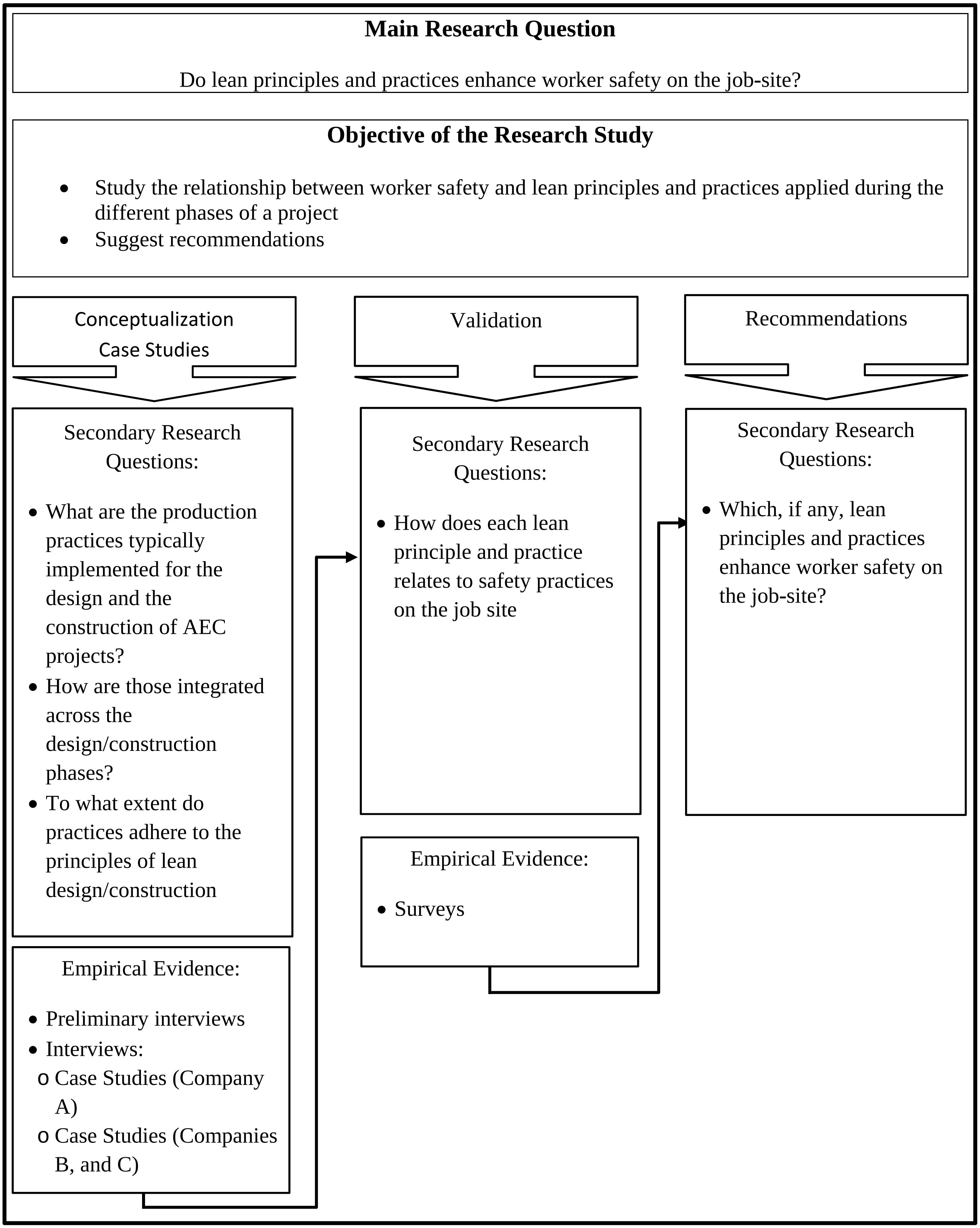

Figure 1: Research Design

Description of Participating Companies and Cases Study Projects

The case study projects selected within Companies A, B, and C consisted of building construction projects located in the Pacific Northwest. Details about each company and each project are provided below.

Company A

Six interviews were conducted with personnel in Company A, which ranks as one of the largest contractors in the US with ten offices in the states and one in Canada. The company is known for its expertise in green/sustainable construction, and virtual design and construction (VDC). The types of projects which the company builds are primarily educational buildings, commercial buildings, industrial facilities, and health care facilities.

Company A has a zero injuries program that has been in place since the late 1990's. In 2013, the company reported no lost worktime injuries and 21 recordable incidents in approximately 5,000,000 man-hours worked. The company started its lean journey in 1996 and has been actively applying lean practices company-wide since 2012. Its initial lean efforts started when the company established a production system lean office and temporary site services that assist all projects with equipment and consumable supplies.

Provided below is a list of the selected case study projects along with summary information about each project.

<u>Case Study 1</u>

- Commercial building (hotel/office)
- Approximately 300,000 square feet, 11 stories plus 3 levels of below-grade parking
- Project location: State of Washington
- Project start date: June 2013
- Expected completion date: May 2015
- Percent design completion at time of case study: 90%
- Percent construction completion at time of case study: 25%
- Construction cost: $90 million
- Construction contract type: guaranteed maximum price (GMP)
- Ownership: private
- Labor status: union/merit shop
- Lean practices applied: Yes

Case Study 2

- Student Center (recreation and fitness facilities including a full-size gym, weight and cardio equipment, basketball court, indoor track, and space for student programs, organizations, and events)
- 73,000 square feet of space
- Project location: State of Washington
- Project start date: December 2013
- Expected completion date: December 2014
- Percent design completion at time of case study: 85%
- Percent construction completion at time of case study: 25%
- Construction cost: $17.2 million
- Contract type: design-build
- Ownership: private
- Labor status: union/merit shop
- Lean practices applied: Yes

Case Study 3

- Library (renovation of a library including student spaces for quiet study and group work, two active learning classrooms, a technology studio, an innovative writing and research center, and new staff offices)
- 55,000 square feet of space
- Project location: State of Washington
- Project start date: May 2011
- Completion date: September 2012
- Percent design completion at time of case study: 100%
- Percent construction completion at time of case study: 100%
- Construction cost: $11 million
- Contract type: Similar to integrated project delivery (IPD)
- Ownership: public
- Labor status: union/merit shop
- Lean practices applied: Yes

Case Study 4

- Water reclamation facility expansion (new influent pump station, headworks building, aeration basin, odor control, and site improvements)
- Project location: State of Oregon
- Project start date: May 2008.

- Completion date: May 2011
- Percent design completion at time of case study: 100%
- Percent construction completion at time of case study: 100%
- Construction cost: $42 million
- Contract type: guaranteed maximum price (GMP)
- Ownership: public
- Labor status: union/merit shop
- Lean practices applied: Yes

Company B

Six interviews were conducted with personnel in Company B, which is a construction contractor that operates mainly in the Pacific Northwest (Oregon, Washington, and Idaho). The company has experience constructing a variety of types of buildings and facilities including high tech, commercial retail, cultural, education, government, and healthcare.

The company has a zero injury program in place. Even though it implements a handful of lean practices on some projects, implementation is not done company-wide. In addition, implementation of lean practices is not conducted in a systematic and consistent manner on every project.

Provided below is a list of the selected case study projects along with summary information about each project.

<u>Case Study 5</u>

- Student Experience Center (structural steel-framed facility that includes a craft center, student offices, and television and radio studios)
- 96,000 square feet of space, 4 stories plus basement
- Project location: State of Oregon
- Project start date: March 2013
- Expected completion date: January 2015
- Percent design completion at time of case study: 100%
- Percent construction completion at time of case study: 70%
- Construction cost: $42 million
- Contract type: Construction manager/general contractor (CMGC)
- Ownership: public
- Labor status: union/merit shop
- Lean practices applied: No

Case Study 6

- Cultural Center
- 3,500 square feet of space, 1 story
- Project location: State of Oregon
- Project start date: June 2014
- Expected completion date: December 2014
- Percent design completion at time of case study: 100%
- Percent construction completion at time of case study: 40%
- Construction cost: $1.8 million
- Contract type: Construction manager/general contractor (CMGC)
- Ownership: public
- Labor status: union/merit shop
- Lean practices applied: No

Company C

Two interviews were conducted with personnel in Company C, which is a large construction contractor with offices in Oregon, Washington, Arizona, and South Carolina. The company has experience constructing a variety of different types of buildings and facilities including healthcare, education, and athletic facilities.

Company C has a zero harm program in place (zero injury, zero near misses, zero loss or changed lives at the end of each day). The company implements lean practices on selected projects in a systematic and consistent manner.

Case Study 7

- Sports Medicine Center (clinical sports medicine facility)
- 17,030 square feet of space, 2 stories
- Project location: State of Oregon
- Project start date: January 2014
- Expected completion date: November 2014
- Percent design completion at time of case study: 99%
- Percent construction completion at time of case study: 85%
- Construction cost: $4.5 million
- Contract type: design-build
- Ownership: private
- Labor status: union/merit shop
- Lean practices applied: No

LCI Survey

In addition to the project case studies, a survey of LCI members was also conducted. The survey targeted owners, designers, and constructors that are listed as sponsoring members of the LCI group. The objective of the survey was to determine their perspectives on the extent to which the lean design and construction practices implemented in the case study projects impact construction safety. The survey asked how each lean principle and practice relates to safety practices on a jobsite. The survey was developed considering the analysis of the preliminary interviews, the case studies, and the results of the literature review on both lean practices and safety best practices. The survey document included three different sections:

1. The impact of integrated project delivery contractual principles on high-impact safety practices recommended by CII;
2. The extent to which lean design practice empowers/enables prevention through design (PtD) and safety constructability reviews; and
3. The impact of each lean practice on each of the safety practices.

Results and Analysis

This section of the report presents the results and analysis of the different phases of the research: the preliminary interviews, the case studies, and the online surveys.

Preliminary Interviews

As described above, initial interviews were conducted with the Assistant Director and Director of Company A's production system. A researcher met with the interviewees at their offices in Seattle, WA. During the interviews, the researcher recorded the questionnaire responses and also asked follow-up questions for clarification and further information where needed.

Following the completion of the interviews, the researchers conducted content analyses of the interview responses. The interview results indicate that the implementation of lean practices is related to a shift in the company's approach to the optimization of the production system. This shift typically results from a need to adapt to different owner requirements and challenging site and project characteristics. For example, there might be a limited layout area, or a complex project in which integration among the trades on the project must occur within a small window in order to deliver the project on time. The interviewees identified improvements in productivity as the primary reason for the implementation of most of the lean tools and techniques used.

Nonetheless, improvements in occupational safety and health for the workers, reducing the potential risk of worker injuries and fatalities on construction sites, improving the quality of the work and the end product, and the reduction of costs, were reported as "natural and unplanned consequences" of the implementation of the lean practices. In particular, some lean practices were perceived as highly beneficial to worker safety, (e.g., housekeeping and standardized work operations).

The implementation of lean practices for the contractual planning, design, and construction phases, support the implementation of the company's Zero Injury Program. According to the interviewees, real improvements in worker safety are linked to the company's safety program. Lean, however, has the ability to "make it better". As the interviewees see it, better planning and standardized work, both lean concepts, allow for quickly identifying deviations from the standard that may negatively impact safety.

Along with adding value for the owner, the application of lean tools and techniques focus on the elimination of waste. Excessive motion and repetitive movement were identified as the types of construction waste that contribute the most to potential risk of worker injuries and fatalities on construction sites.

Case Studies

As indicated above, case studies were conducted on a total of six construction projects. The extent to which lean practices were implemented on each project was different between projects and between companies. Company A applied lean practices as part of its lean journey on all of the Company A projects studied. However, Companies B and C only applied some practices that may be considered lean, but did not apply them in a systematic and consistent manner. As a result, analyses of the case study data were conducted at two different levels: (1) at the project level (Company A projects only); and (2) at the company level (Company A and Companies B/C).

At the project level, the analysis relies on the data collected from the four cases study projects conducted at Company A. The company provided information on both the lean practices used during the construction phase and OSHA recordable injuries and near misses that had occurred on each project to date. Companies B and C provided input on the relationship between lean practices and safety on the jobsite. However, Company B did not disclose safety information, and Company C reported zero OSHA recordable injuries and zero near misses. Therefore, comparisons at the project level utilized the projects from Company A only. While the number of projects included in the comparison analyses was low (4 projects) and limits generalizing the results to other projects, being constructed by only one company eliminated company-specific confounding factors in the analysis.

At the company level, the analyses relied on comparisons between Company A and Companies B and C combined. As mentioned above, Company A has formally integrated lean construction into its project management processes, while Companies B and C are not as engaged in lean practices. This difference provided an opportunity to compare Company A to Companies B and C based on safety performance and thus potentially distinguish the impacts that lean practices have on worker safety.

Company A

The survey questionnaire asked two questions about the interviewee's knowledge related to lean and construction. One question asked the interviewee to rate his/her knowledge of lean design and construction. Another question asked the interviewee to rate his/her knowledge of traditional construction practices. Both questions used a nominal scale from poor to excellent to rate their knowledge. Tables 4 and 5 present the responses related to knowledge of lean practices and traditional construction practices, respectively.

***Table 4*: Knowledge of lean design and construction – Company A (n = 5)**

Knowledge Area	None (0)	Poor (1)	Fair (2)	Good (3)	Very Good (4)	Excellent (5)	Mean Response
Lean Design	0	0	1	3	1	0	3.0
Lean Construction	0	0	0	4	1	0	3.2

***Table 5*: Knowledge of traditional construction practices – Company A (n = 5)**

Knowledge Area	None (0)	Poor (1)	Fair (2)	Good (3)	Very Good (4)	Excellent (5)	Mean Response
Traditional construction practices	0	0	1	1	1	2	3.8

The results reveal that those interviewed generally feel that they have a "good" level of knowledge of both lean design and lean construction practices. With regard to traditional construction practices, on average the respondents rate themselves as having a higher level of knowledge compared to lean practices.

In Company A, when asked their level of support regarding implementing lean practices on different projects, all of those interviewed indicated that they support implementation on all projects. However, those interviewed did not all agree on the value of implementing lean practices to projects. Table 6 shows the interviewee responses when asked about the value of lean practices to different phases of a project lifecycle. As can be seen from the table, those interviewed feel that more value is realized in the construction phase. This result may be affected in part by the fact that those interviewed are more closely tied to construction compared to planning and design.

***Table 6*: Value of implementing lean practices during different phases of a project – Company A (n = 6)**

Project Phase	None (0)	Little (1)	Some (3)	High (5)	Mean Response
Contractual Planning	0	1	1	4	4.0
Design Phase	0	0	1	5	4.7
Construction Phase	0	0	0	6	5.0

On each Company A case study project, the researchers asked about the types of lean practices implemented during both design and construction. The lean design practices implemented are shown in Table 7, and Table 8 shows those practices implemented during construction. Those interviewed were construction personnel. While there responses regarding the construction phase are based on firsthand knowledge, their responses regarding lean design practices are based on secondhand knowledge of the design team and design processes used. The results reveal that several practices are used during both design and construction. They are: Just-in-time, Standardized work, Kitting, and Last Planner® System.

***Table 7*: Lean practices implemented during design phase – Company A (n = 6)**

Lean Practice	# of Responses
Just-in-time	2
Standardized work	2
Kitting	1
Value stream mapping	1
Last Planner® System (LPS)	3

***Table 8*: Lean practices implemented during construction phase – Company A (n = 6)**

Lean Practice	# of Responses
5 S's (Housekeeping: Sort, Set in, Shine, Standardize, Sustain)	3
Just-in-time	1
Kaizen	2
Poka-Yoke (error proofing)	1
Standardized work	3
Kitting	3
Pre-fabrication	1
Last Planner® System (LPS)	3

As part of the collection and review of project documentation, the researchers recorded the number of OSHA recordable injuries and the number of near misses on each project. This incident data is shown in Table 9 along with the specific lean practices applied during the construction phase on each project and some project characteristics of interest to the analysis. It should be noted that the size of the projects vary (measured in terms of both square feet and dollars), and the percent completion is not the same for all projects. Case study Project #2 is different than the other three projects in that the number of lean practices implemented is less. The number of recordable injuries and near misses is less for Project #2 compared to the other projects, however, the percent complete is less than for Projects #3 and #4, and the size is less than Project #1. It should be noted, though, that project size and percent complete are factors that can impact safety performance. Additional case study projects are needed to confirm any noticeable trend with confidence.

***Table 9*: Safety-related incidents and lean construction practices implemented on each case study project – Company A**

		Case Study Project			
		1	**2**	**3**	**4**
	Number of OSHA recordable injuries	1	0	1	4
	Number of near misses	5	3	9	>15
Lean Practices	5 S's (Housekeeping: Sort, Set in, Shine, Standardize, Sustain)	x		x	x
Lean Practices	Just-in-time	x			
Lean Practices	Kaizen			x	x
Lean Practices	Poka-Yoke (error proofing)	x			
Lean Practices	Standardized work	x		x	x
Lean Practices	Kitting	x		x	x
Lean Practices	Pre-fabrication		x		
Lean Practices	Last Planner® System (LPS)	x		x	x
	Construction % complete	25%	25%	100%	100%
	Size (square feet)	300,000	73,000	55,000	--
	Construction cost ($ millions)	$90	$17.2	$11	$42

Those interviewed provided additional details about the injury incidents and near misses on each case study project. Summary details of each are shown below:

<u>Case Study 1</u>:

- One OSHA recordable injury: Hand laceration while hammering formwork that could have been prevented by the use of lean practices.
- Five near misses: Could not have been prevented by the use of lean practices.

<u>Case Study 2</u>:

- Zero OSHA recordable injuries

- Three near misses: Two could have been prevented by better implementation of lean practices, in particular 5 S's and LPS.

Case Study 3:

- One OSHA recordable injury: Laceration with sharp object while cleaning debris; preventable with better implementation of 5 S's and 5 Whys.
- Nine near misses: All preventable by better implementation of lean practices, in particular 5 S's and LPS.

Case Study 4:

- Four OSHA recordable injuries: Two avoidable with the use of lean practices, in particular better implementation of 5 S's and LPS.
- More than 15 near misses: Two avoidable with the use of lean practices, in particular better implementation of 5 S's and LPS.

The results above show no particular trend between the lean practices applied and the number of injuries and near misses on the jobsites. Still, the interviewees reported that four out of the six OSHA recordable injuries, and 11 out of the 32 near misses, could have been prevented by the implementation, or better implementation of some lean practices, in particular, 5 S's and LPS.

During the case study interviews, the researchers asked each participant their views about the impact that the lean construction practices have on worker safety. Figure 2 shows the lean construction practices that the interviewees rated as having high impact on worker safety. The figure shows the mean rating of each lean practice in terms of its impact on safety. Note that 5 S's and standardized work practices were rated highly; these practices allow for the identification of issues as they occur. Pre-fabrication, which permits the work to be performed under controlled conditions, was also rated highly. Andon and Kaizen, both rated highly, are practices that enhance worker involvement. Lastly, LPS relates to the reliability of the planning system.

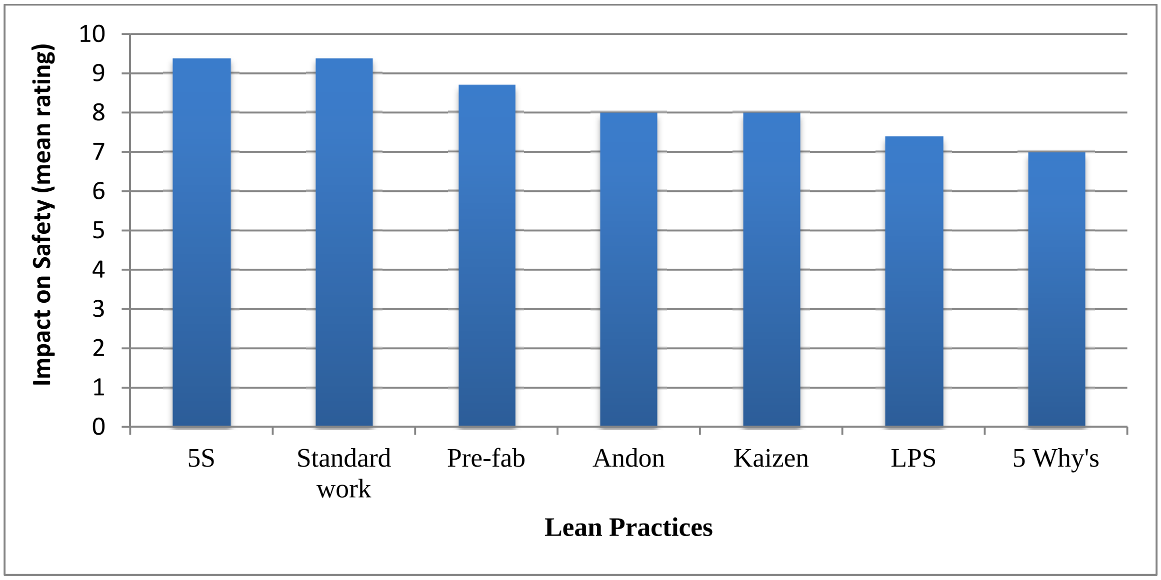

***Figure 2*: Impact of lean practice on project safety – Company A (n = 6; 0 = no impact, 1 = minimal impact, and 10 = significant impact)**

<u>Companies B and C</u>

Companies B and C, as indicated above, stated that implementation of formal lean practices was not taking place on the case study projects. The researchers surmised, however, that some of the practices actually implemented on the projects may be similar to the formal lean practices identified, although referred to by a different name. Therefore, the interview questions were restructured slightly (more general reference to the lean practices) to try to capture how companies perceive worker safety is impacted by lean practices.

Tables 10 and 11 present the interviewee's responses to the questions about their knowledge of lean practices and traditional construction practices, respectively. The low mean responses regarding lean design and lean construction is lower than that in Company A, and expected given the lack of implementation of lean practices on Company B and C projects. The knowledge of traditional construction practices is similar to that reported by the Company A interviewees.

***Table 10*: Knowledge of lean design and construction – Companies B and C (n = 8)**

Knowledge Area	None (0)	Poor (1)	Fair (2)	Good (3)	Very Good (4)	Excellent (5)	Mean Response
Lean Design	4	2	1	1	0	0	0.88
Lean Construction	4	1	0	3	0	0	1.3

Table 11: **Knowledge of traditional construction practices – Companies B and C (n = 8)**

Knowledge Area	None (0)	Poor (1)	Fair (2)	Good (3)	Very Good (4)	Excellent (5)	Mean Response
Traditional construction practices	0	1	2	2	1	2	3.1

Figure 3 shows the lean construction practices that the interviewees rated as having high impact on worker safety. Note that the results are consistent with the results obtained for the Company A case study projects. 5S's and standardized work practices are believed to have higher impact. These are followed by the ability to notify management that assistance is needed and to stop the work when issues arise (Andon), and then pre-fabrication. First run studies were rated as having the same impact as continuous improvement events.

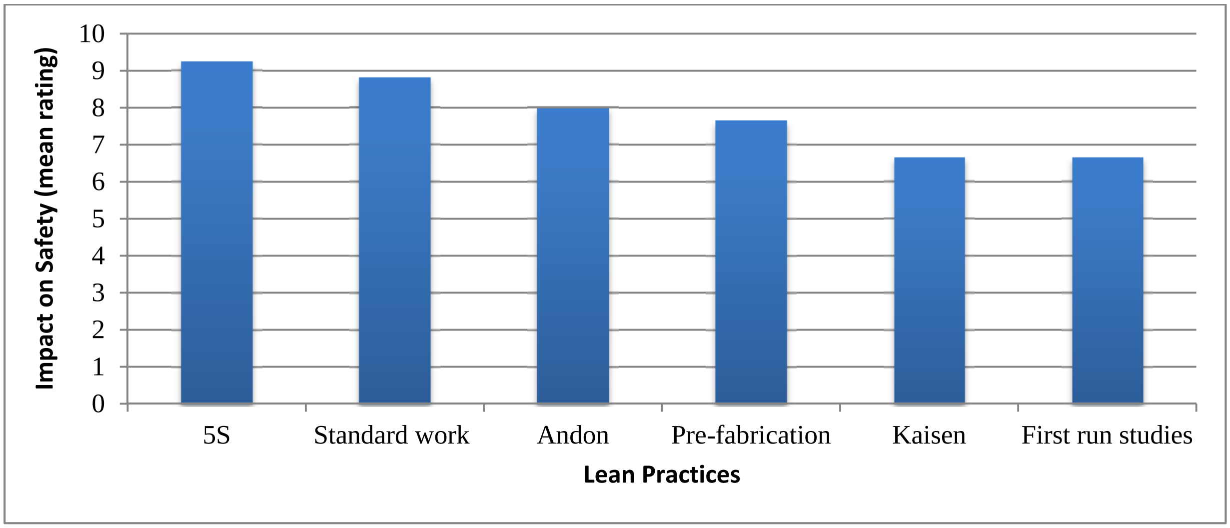

Figure 3: **Impact of lean practice on project safety – Companies B and C (n = 8; 0 = no impact, 1 = minimal impact, and 10 = significant impact)**

In the analysis, the researchers placed particular focus on Last Planner® System (LPS) practices. Figure 4 shows the LPS practices that the interviewees rated as having high impact on worker safety. Similar to Company A's projects, the practices that were rated as having higher impact are related to collaboration of the project team members, i.e., multi-functional teams for the definition of the work to be done during the look-ahead plan and constraint analysis.

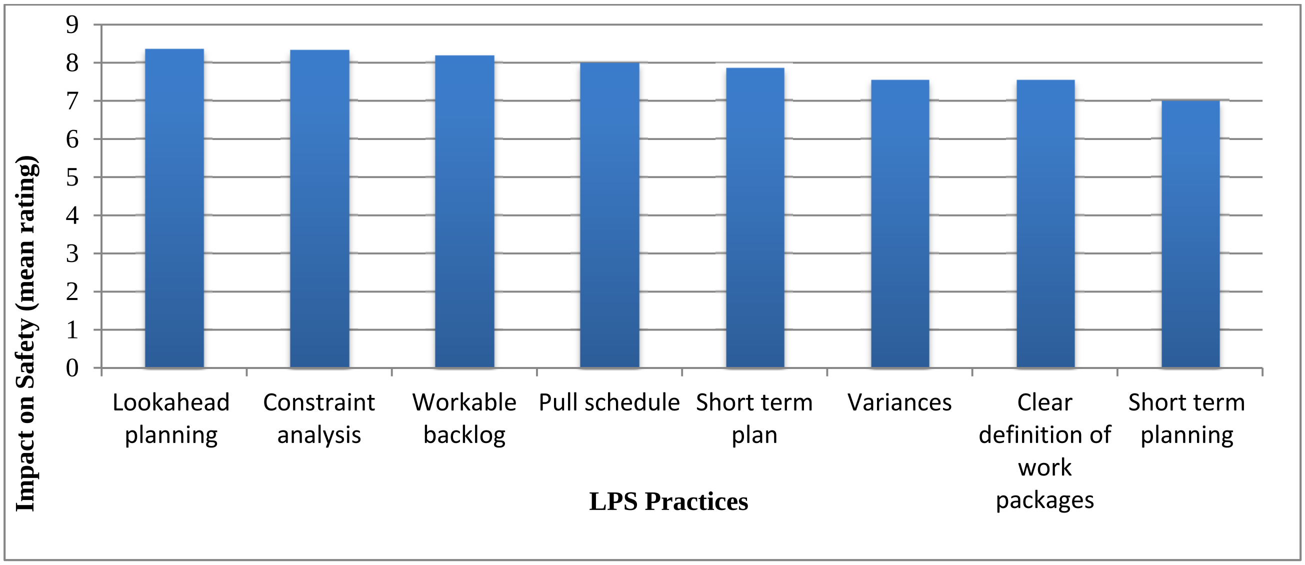

***Figure 4*: Impact of LPS practices on project safety – Companies B and C (n = 8; 0 = no impact, 1 = minimal impact, and 10 = significant impact**)

Companies A, B, and C: General comments about lean practices

Those interviewed on all of the case study projects were asked to provide additional comments regarding lead design and construction practices and their impacts on projects and worker safety. The comments received are summarized below:

- Housekeeping:
  - Reduces confusion, extra steps, and on-the-spot decisions
  - Less motion; decreases in trip and fall hazard
  - Clean work area improves morale
- Standardized work:
  - Reduces confusion, extra steps, and on-the-spot decisions
  - Less motion; identifies sequence of work; defines what is normal; no overproducing
  - Promotes knowing what you are doing
  - Able to take variables out of the equation; worker does the same thing day in and day out
  - Less room for errors
- Pre-fabrication:
  - Controlled environment
  - Reduce motion
- Use of an alert system when assistance is needed (Andon)
  - Increases labor comfort level to stop the work when appropriate
- Kaizen:
  - Makes workers think about how they can work safer

- Decision making during the short term planning includes form supervisors, foremen, and subcontractors:
    - Allows identifying tasks in advance and performing pre-task planning
    - Enables predictable workflow
    - Ability to look at potential safety hazards
    - Enables planning and scheduling of work around other trades and before the task is performed
    - Establishes a smoother schedule, less juggling between trades, and fewer safety hazards
- Analysis of physical flows: material, equipment, and workers:
    - Not having too many people, too much equipment, and too much material makes the workplace safer
    - Helps to identify areas where clutter can be reduced
- Look-ahead planning meetings includes participation of subcontractors:
    - Let subcontractors know what else is happening on the site which improves their awareness on the site and enables coordination of the work
- Clear definition of work packages:
    - Workers know exactly what they are supposed to be doing

LCI Survey

The on-line survey questionnaire was sent via e-mail to the 93 LCI sponsoring members that are listed on the LCI website. Similar to the case studies, the focus of the survey was to ask how lean practices impact safety practices. The research team received 15 responses (1 owner, 1 designer, and 13 constructors) (16% response rate). Of the 15 responses received, 12 had some answers blank and were not fully complete (1 owner, 1 designer, and 10 constructors). The designer respondent reported that he is not applying lean practices and the remaining sections of the survey were not completed.

Tables 12 and 13 present the responses regarding the respondents' knowledge of lean design and construction practices and traditional construction practices, respectively. The results reveal that knowledge of lean construction practices is more prevalent than that of lean design practices. The respondents rated their knowledge of traditional construction practices to range from good to excellent, except for the one owner respondent who indicated having no in-depth knowledge of traditional construction practices.

***Table 12*: Knowledge of lean design and lean construction – LCI survey (n = 14)**

Knowledge Area	None (0)	Poor (1)	Fair (2)	Good (3)	Very Good (4)	Excellent (5)	Mean Response
Lean Design	0	1	4	5	3	1	2.9
Lean Construction	0	1	2	3	4	4	3.6

***Table 13*: Knowledge of traditional construction practices – LCI survey (n = 14)**

Knowledge Area	None (0)	Poor (1)	Fair (2)	Good (3)	Very Good (4)	Excellent (5)	Mean Response
Traditional construction practices	1	0	0	2	3	8	4.1

One question on the survey asked the extent to which the respondent supports the implementation of lean practices on all projects. As can be seen in Table 14, the majority of the respondents fully support implementing lean practices in all projects. The remaining respondents indicate that they support implementing lean practices on some projects. A similar question targeted the phase in which the respondents see value in implementing lean practices. The majority of respondents believe that there is high value in implementing lean during all project phases (see Table 15).

***Table 14*: Level of acceptance of lean practices – LCI survey (n = 14)**

Response	% of Respondents
I fully support implementing lean practices on all projects	78.5%
I support implementing lean practices on some projects	21.5%

***Table 15*: Value of implementing lean practices during different phases of a project – LCI survey (n = 14)**

Project Phase	None (0)	Little (1)	Some (3)	High (5)	Mean Response
Contractual Planning	0	0	1	13	4.9
Design Phase	0	0	1	13	4.9
Construction Phase	0	0	1	13	4.9

When asked if implementing lean practices during the different phases of a project have any impact on worker safety on the job-site, the majority of the respondent (86%) reported that implementing lean practices during the construction phase of the project highly impacts worker safety. The perceived benefit to worker safety from implementing lean practices during contractual planning and design was less (36% for contractual planning, and 43% for design phase).

***Table 16*: Impact on worker safety from implementing lean practices during the different phases of a project – LCI survey (n = 14)**

Project Phase	None (0)	Little (1)	Some (3)	High (5)	Mean Response
Contractual Planning	0	3	6	5	3.3
Design Phase	0	1	7	6	3.7
Construction Phase	0	0	2	12	4.7

As described above, best practices for contractual planning are consistent with the principles of lean production. One section of the survey explored the impact of IPD contractual planning practices on safety practices. Figure 5 shows the respondents' views of the impact that contractual planning practices can have on safety. All of the respondents indicated that there is positive impact (the survey allowed for indicating either positive or negative impact) by all contractual planning practices. No responses were received that indicated high positive impact. Only one contractual practice – Liability waivers between key participants – was viewed as having minimal impact on all safety practices.

It is interesting to note that management commitment, staffing for safety, and pre-project planning are the safety practices that seem to gain more with IPD-related contractual agreements. Early involvement of key participants is the principle that most affects management commitment and pre-project planning.

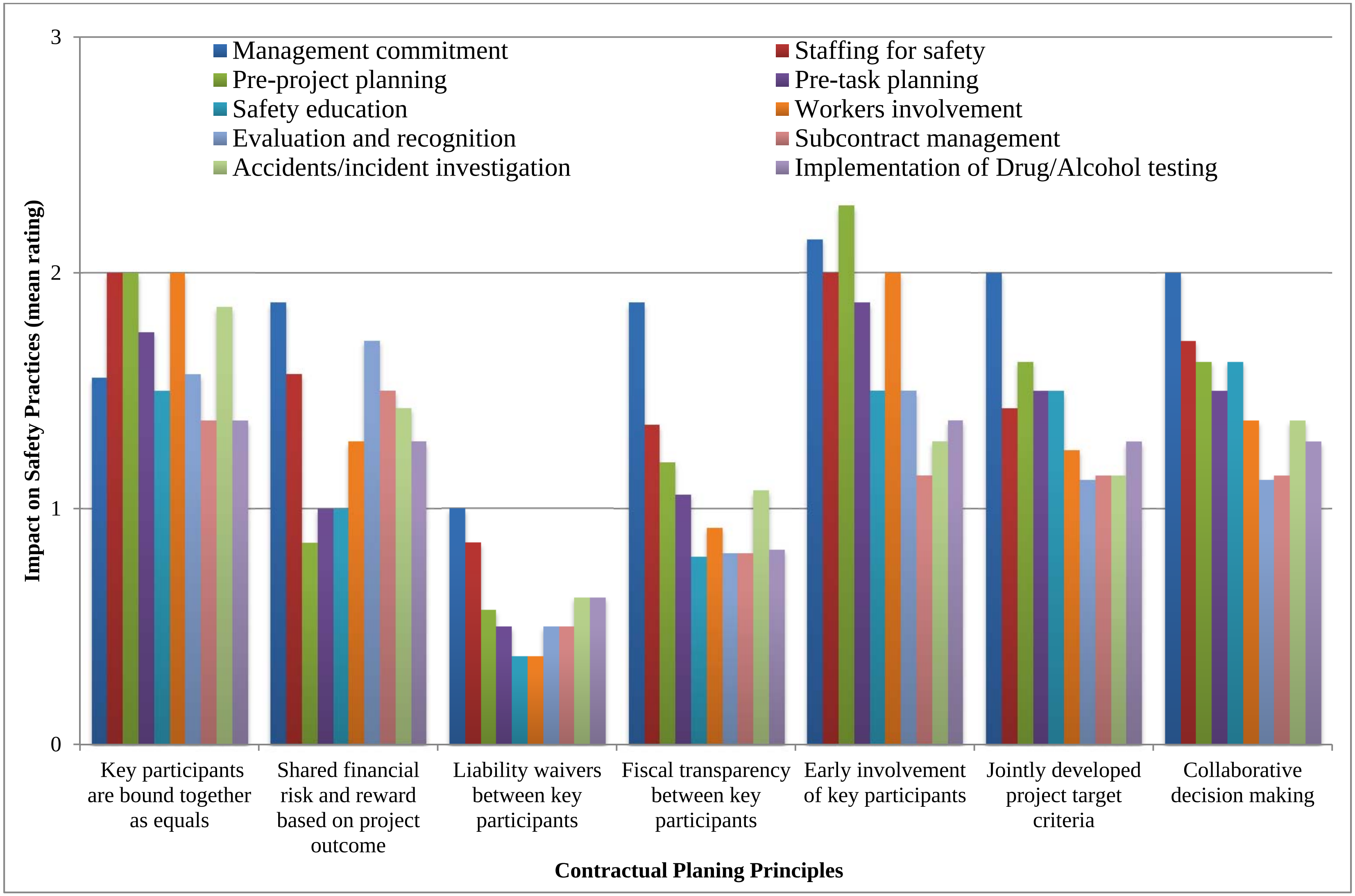

***Figure 5*: Impact of lean contractual planning principles on safety practices – LCI survey (n = 14; 0 = no impact, 1 = minimal positive impact, 2 = some positive impact, and 3 = high positive impact)**

3D modeling that integrates product and process design and early involvement of specialty subcontractors in the development of the design are some of the practices that the research team would expect find as highly enabling PtD and safety constructability reviews. However, only one designer responded to the survey and submitted an incomplete response (discontinued the survey). As a result, the research team was not able to determine the extent to which lean design practices are perceived to empower/enable PtD and safety constructability reviews.

Figure 6 shows the respondent's views regarding the impact of lean practices on safety practices. The figure reveals that all lean practices that were previously identified as being implemented during construction were subsequently identified as positively impacting safety practices, with worker involvement standing out as the safety practice that most benefits from the implementation of lean practices. The implementation of LPS was found to be most beneficial to management commitment, pre-project, and pre-task planning. Safety education, evaluation and recognition, and implementation of drug/alcohol testing seem to be the safety practices that benefit the least from the implementation of lean practices during the construction phase of the project.

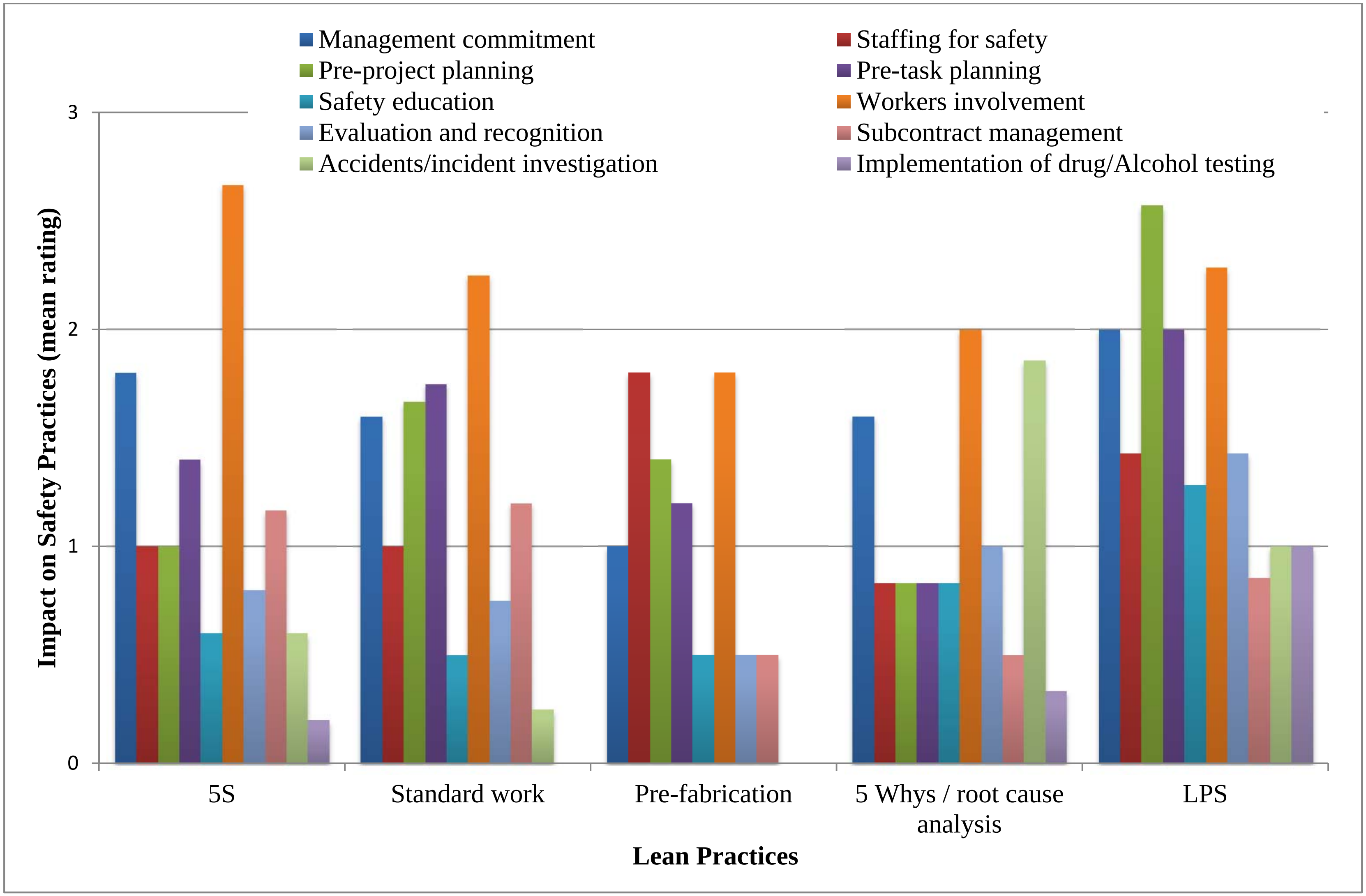

***Figure 6*: Impact of lean practices on safety practices – LCI survey (n = 14; 0 = no impact, 1 = minimal positive impact, 2 = some positive impact, and 3 = high positive impact)**

Conclusions and Recommendations

As a production management approach for project delivery, lean practices aim to maximize project performance while reducing waste. From a lean perspective, all accidents, including near misses, and injury incidents represent waste. Therefore, eliminating accidents and injury incidents is a way of making a project more "lean". Likewise, the increase in worker safety on jobsites was reported as a "natural and unplanned consequence" of the implementation of lean practices. That is, improving production through the application of lean principles naturally leads to enhanced worker safety. Utilizing lean practices provides the ability to "make safety better." This positive impact of lean practices on worker safety was recognized by the participants in the case studies and survey.

A variety of lean design and construction practices are being implemented on building construction projects that reflect the principles of lean production. The extent to which lean practices are implemented varies from company to company. Similarly, within a company, implementation of lean practices is not necessarily consistent across all of the company's projects. The extent of implementation depends on project-specific features and owner requirements. With regard to safety, however, all companies place great emphasis on worker safety on all projects and typically employ a wide variety of safety management practices.

Knowledge of lean practices greatly depends on the extent to which lean principles are promoted and formally implemented by a company. Companies that incorporate formal lean principles into their project management process will see greater understanding of lean practices amongst their personnel. Some companies implement construction practices that mimic lean practices but do not formally recognize them as lean practices. However, the resulting positive impacts to both production and safety are not dependent on whether the practices are consciously identified as being lean.

Some lean practices are applicable to, and feasible for, implementation during both design and construction. Examples of those practices that are used during both design and construction are: Just-in-time, Standardized work, Kitting, and Last Planner® System. Project teams have learned how to integrate these practices throughout both design and construction to benefit the entire project. As the delivery of AEC projects tends more and more towards the use of integrated project delivery methods, utilization of these integrated lean practices is likely to increase throughout the industry.

With respect to the unique phases of projects, the construction phase is recognized as the best opportunity to positively impact safety through the implementation of lean practices. The following are additional findings related to different project lifecycle phases:

- Contractual planning:
    - Management commitment, staffing for safety, and pre-project planning are safety management practices that are positively supported by contractual arrangements founded on lean principles (e.g., IPD).
    - Early involvement of key participants is the integrated contractual principle that most affects management commitment and pre-project planning for safety.
    - “Liability waivers between key participants” as an aspect of the contractual arrangement was judged to have minimal impact on all safety practices.
- Construction phase:
    - Worker involvement in safety is viewed as the safety practice that benefits the most from the implementation of lean practices, and is particularly impacted by 5 S’s, standardized work, and LPS.
    - LPS is most beneficial to management commitment to safety, pre-project planning, and pre-task planning.
    - Lean practices have minimal impact on safety education, evaluation and recognition programs, and the implementation of a drug/alcohol testing program.

The research findings reveal that greater attention to and use of lean design and construction practices will positively impact safety performance. Therefore, efforts to promote lean design and construction across the AEC industry in the US are recommended. These efforts could be a joint effort of national safety organizations and the Lean Construction Institute. The efforts would be mutually beneficial. That is, lean practices promote better safety performance, and improving safety leads to fewer injuries and near misses, thus eliminating waste and making workers more productive (i.e., more lean). Lean practices that would be especially important to target are those that are integrated across both design and construction such as Just-in-time, Standardized work, Kitting, and Last Planner® System. These practices can be tied to and support NIOSH’s current national initiative on prevention through design (PtD) which also connects both design and construction.

The findings also suggest that further research be undertaken as well. A study that permits a larger sample size (both in the number of case studies and number of survey participants), and a more diverse sample, would provide more confidence in the results and allow for testing the impacts of factors related to the project and the lean practices implemented. Future empirical studies that evaluate the safety impacts of specific lean practices would be beneficial. Those that would be of particular interest for further study are: Just-in-time, Standardized work, Kitting, and Last Planner® System. The results of such studies would help guide the selection of lean practices on projects to optimize the impact on safety. Lastly, construction worker safety and health could be enhanced through research efforts to develop new lean design and construction practices that target eliminating worker injuries and fatalities. Such practices could be promoted and disseminated under the flag of lean construction as another avenue for bringing attention to and improving construction worker safety and health.

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