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A Research Synthesis on the Interface between Lean Construction and Safety Management

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A RESEARCH SYNTHESIS ON THE INTERFACE BETWEEN LEAN CONSTRUCTION AND SAFETY MANAGEMENT

by

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ABSTRACT

Antillón, Eric Israel (M.S., Civil Engineering)

A Research Synthesis on the Interface between Lean Construction and Safety Management

Thesis directed by Associate Professor Keith R. Molenaar and Assistant Professor Mathew R. Hallowell.

Applying lean construction to safety management efforts is a promising research area and has been discussed widely in the construction community. Some researchers believe that the reduction of occupational hazards is a naturally occurring effect of the implementation of lean practices. Lean focuses on the reduction of waste and poor safety can be considered a source of waste. To further understand how lean practices affect project safety performance, an interaction matrix between lean construction and safety management practices was developed by performing a research synthesis, which was also validated by conducting structured interviews. The variables analyzed in this interaction matrix were elements from the last planner system and typical lean production tools, for example autonomation and standardization, and the most common safety management practices such as planning and staffing for safety. The interface between lean construction and safety management was systematically analyzed by assessing the conclusions from separate investigations addressing this issue. The results of this research indicate that there is a significant amount of evidence that serves as an aid to recognize the potential synergies when planning for lean and safety strategies. This evidence, along with the results obtained from the analysis of the interaction matrix, can also help to develop and integrate future production and safety management models.

A mis padres, mis hermanos, y mi novia.

Gracias a todos por su apoyo y amor incondicional.

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I. INTRODUCTION

The construction industry has long been reputed for its high accident rates when compared with other industries. It is one of the most dangerous industries worldwide consistently accounting for the highest fatality rates. The International Labor Organization (ILO) has made a conservative estimate claiming that at least 60,000 people are being fatally injured every year on building sites worldwide (ILO 2003). A recent report states that work-related death rates have decreased by 22 percent from 1992 to 2005 in the industry, while rates of reported nonfatal injuries and illnesses with days away from work dropped dramatically by 55 percent during this period. This report also states that the estimated direct and indirect costs of fatal and nonfatal construction injuries totaled $13 billion (2002 dollars) annually, and the medical expenses of nonfatal injuries alone cost more than $1.36 billion per year. Furthermore, in 2005 alone, the construction industry shared 1,243 (21.7 %) of the total 5,734 work-related deaths from injuries in the US, while making up only 8% of the overall workforce (CPWR 2008). Significant improvements in construction safety performance are still needed in order to reduce both the monetary and social impact this has on today's society.

Recent investigations have studied how safety performance is affected by the implementation of lean practices and have shown that they both improve the efficiency of production sites and result in favorable safety outcomes (Thomassen et al. 2003; Saurin et al. 2004b; Nahmens and Ikuma 2009; Leino et al. 2010). Lean production promotes the reduction of waste through the standardization of the workflow and reduction of workflow variability. Lean production allows for the opportunity to continuously improve in different areas that are identified as waste, or non-value adding activities, through the implementation of lean tools such as the Last Planner System. The minimization of waste in a production system is one of the cornerstones of lean production. Improved safety performance, such as fewer injuries and reduced fatality rates are a signal of a reduction of waste given that poor safety can undeniably be considered a source of waste. Accidents result in reduced efficiency of a process, resulting in non-value-adding events in a production system. Since lean principles aim at reducing waste, it would be adequate to assume that the reduction of occupational hazards is a natural occurring outcome of the implementation of lean construction principles (Howell et al. 2002).

1.1 Purpose of the Study

The purpose of this thesis is to investigate how the use of lean practices results in safer environments in construction projects. Recent studies have identified the safety outcomes that result from the implementation of lean practices. In one study, crews implementing the last planner had about 45 percent lower accident rates than crews in the same company performing similar work (Thomassen 2003). It has been suggested to implement lean strategies, such as Just-In-Time delivery, for safety management practices in order improve both safety performance and safety management efforts (Rosenfeld et al. 2009; 2010). A tentative description at this time for the relationship between the implementation of lean practices and safety might be that safety performance improves as a result of the inherent characteristics of lean construction. However, the underlying causes of the correlation between the lean practices that improve safety and how they lead to safer environments have yet to be explored. The topic is still in its infancy and needs to be addressed because it may help the industry improve productivity while at the same time improving safety performance.

1.2 Thesis Statement and Questions

It is hypothesized that the implementation of lean practices is directly related to the improvement of safety performance. Companies implementing lean practices in their work sites will have improved safety performance due to the inherent characteristics of lean construction. These characteristics, such as the stabilization of workflow and the use of optimal buffer sizing, encourage less material in the work area, an orderly and clean workplace, and overall increased task predictability and flow reliability. The application of lean strategies to safety management practices also enhances safety and promotes efficiency. The research performed for this thesis aims to address the existing synergy between the implementation lean construction practices and safety management practices and how this results in improved safety performance. The central question on which this thesis intents to expand on is:

How does the implementation of lean construction affect safety performance?

This question was further narrowed down into the following subquestions: (a) what specific tools and methods of lean construction improve safety management efforts? and (b) what is the correlation, if any, between the implementation of lean construction practices and safety performance?

The causes for the correlation between the lean strategies that improve safety performance and how they lead to safer environments have yet to be explored. This does not refer to a statistical correlation, but rather to a conceptual correlation referring to the relationship and dependency of lean construction and safety management. To further explore this correlation, it is necessary to provide in-depth conceptual evidence on the interface between lean construction and safety management. This will then serve as a basis for the development of future integrated production and safety management models that could be successfully implemented in the industry.

1.3 Thesis Objective

This thesis aims at providing new knowledge to the existing literature on the topic of how lean practices affect safety performance. Currently, the amount of empirical evidence on the hypothetical relationship is minimal given that some discussions seem to be biased by ideological viewpoints and also lack the support from empirical data (Saurin et al. 2006). Therefore, it is anticipated that a more in-depth discussion between these variables can provide a basis for the development of future production and safety management models, and future research. This investigation aims at improving safety effectiveness in the industry, while at the same time reducing non value-adding activities, or waste, which impedes labor efficiency in the work site and increases hazards. Safety managers, lean construction practitioners, and contractors in general could benefit from the results obtained by this study. The results can be implemented in the field by serving as an aid to recognize the potential synergies when planning for lean and safety strategies.

1.4 Research Methods

The research approach selected for this inquiry was a research synthesis. This approach closely examines previous studies related to the topic at hand, and combines qualitative data in order to seek conclusions from previous studies. This approach helps to recognize and understand the interface between lean construction practices and safety performance that has been recently identified. Empirical studies are also inferred as supporting evidence for the improved safety performance resulting from the implementation of lean construction. An interaction matrix has been developed with the aid of the research synthesis, from which the data was then analyzed adapting a morphological analysis approach. Following the data analysis, structured interviews were conducted with an expert panel to better understand and validate the synthesized interactions between lean construction and safety management.

1.5 Arrangement of the Thesis

This thesis is organized into 6 main chapters. Chapter I describes the purpose of the thesis, the thesis statement and investigation questions, its objective, and a brief overview of the research methodology implemented. Chapter II presents a thorough literature review of the existing body of knowledge concerned with the most fundamental groundwork for the key ideas pertaining to this thesis, from which a respective point of departure for the research was established.

Chapter III describes the research methodology implemented, which is adapted for the purpose of the specific objectives of this thesis, and establishes a research process to achieve the proposed objectives. In Chapter IV, the way in which the data is collected and how the appropriate data is selected is described, which provides the foundation for the analysis of the data by developing the interaction matrix to analyze. Chapter V analyzes the interaction matrix developed and validates the results and interactions identified with supportive evidence through structured interviews with an expert panel. And last, Chapter VI describes the conclusions that were reached and contributions that resulted from this study. The limitations to the research and recommendations for future research are also discussed in the last chapter.

II. BACKGROUND AND LITERATURE REVIEW

A literature review on the existing body of knowledge pertaining to the topics of interest was carried out. The literature review lays the necessary groundwork for the key ideas of this thesis, which are related mainly to lean construction and construction safety management, in order to build the 'bridges' between the two. Given this background, a reference to other studies closely related to the one being undertaken is provided in order to set the research problem within the ongoing dialogue in the literature and to establish a point of departure and the importance of this study.

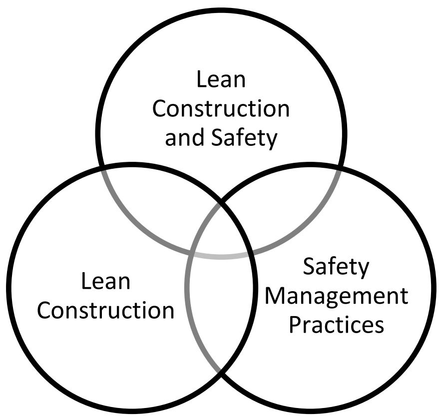


Figure II.1 - Topics Covered in the Literature review

The origins, concepts, processes, and expected outcomes of lean construction are reviewed in addition to specific strategies that may have a direct influence on safety management (i.e., the Last Planner System). Current safety management practices in the construction industry have also been covered. Accident causation models and accident prevention strategies are reviewed in order to understand the extent to which lean construction might affect safety performance. To establish the point of departure, several topics in the academic arena that discuss concurrent applications of lean construction and safety were covered. Some of the topics in these studies discuss issues such as how lean construction practices can be used to improve safety performance and enhance safety management efforts, and how safety management strategies can benefit from some of the inherent principles that lean construction employs, among others.

2.1 Lean Construction

> *"Lean is a way to design production systems to minimize waste of materials, time, and effort in order to generate the maximum possible amount of value." – Koskela et al. (2002, p. 221)*

Lean Construction refers to the application and adaptation of the underlying concepts and techniques of lean production as a new philosophy of production for construction. The industry has adapted this production model as a means to improve its performance and reduce the considerable amount of waste that tends to exist in the construction industry. Lean production focuses on the reduction of waste, increase of value to the customers, and continuous improvement. Several of these lean production concepts and techniques have been successfully implemented in the construction industry from which effective lean construction tools, such as the Last Planner System, have been developed. The origins of lean construction, its approach to project and construction management, and the most effective applications that have been developed thus far are discussed in this section.

2.1.1 Lean Origins

Lean production has emerged from the ongoing development of alternatives to mass production that began shortly after the 2^{nd} World War. Its primary foundation, however, has been accredited to the principles of the Toyota Production System, developed mainly by Taiichi Ohno (1988) and Shigeo Shingo (1988). Lean production focuses on eliminating wasted time and material from every step of the production process. This new production system contrasts its effects with the craft and mass forms of production. Attention is shifted to the entire production system instead of the narrow focus of craft production on worker productivity, and that of mass production on machine (Howell 1999). The Toyota production system eventually became known as the Lean Production System in the early 1990's. *The machine that changed the world* (Womack et al. 1990) popularized and made more easily accessible the concepts and techniques of lean production. The term 'lean' itself was so given in part to counterpose the new production system to 'mass' production (Ballard 2000).

Koskela's ground-breaking report (Koskela 1992) challenged the construction industry to explore and adopt the new concepts and techniques of this new production philosophy, lean production, in order to examine it as an alternative to the traditional production system for construction. Koskela elaborated upon this important contribution into what eventually became his final dissertation: *An exploration towards a production theory and its application to construction* (Koskela 2000). Based on the principles of lean production and its implementation in the construction industry, the last planner system, one of the most effective lean construction tools, gets established as an effective methodology that advantageously improves workflow efficiency by stabilizing it while protecting it from upstream variability. These concepts are what eventually gave birth to lean construction.

2.1.1.1 The Toyota Production System

The Toyota production system (TPS) is an integrated socio-technical system designed for manufacturing in the 1950's, it was designed specifically for the auto industry by the Japanese automotive company of the same name. TPS focuses on eliminating muda, which is the Japanese term for waste. However, in addition to the elimination of muda, muri (overburdening) and mura (variation) are also of important consideration.

Muda refers to *non-value adding activities*, which is the most familiar type of waste within the lean production paradigm. There are two types of muda: unavoidable waste, which are activities that add no value but seem to be unavoidable; and avoidable waste, which are also activities that do not add value, yet they are immediately avoidable (Womack and Jones 1996). Within these definitions, accidents and injuries in the construction industry can most definitely be considered avoidable waste.

Table II.1 - Types of Waste (adapted from Liker 2004)

Waste	Description
Overproduction	Producing too much, too soon, or more than needed (batch processing). This generates such wastes as overstaffing and storage and transportation costs because of excess inventory.
Defects	Production of defective parts or correction. Repair or rework, scrap, replacement production, and inspection mean wasteful handling, time, and effort.
Inventory	Excess raw material, WIP, or finished goods causing longer lead times, obsolescence, damaged goods, transportation and storage costs, and delay.
Overprocessing	Taking unneeded steps to process the parts. Inefficiently processing due to poor tool and product design, causing unnecessary motion and producing defects.
Transportation	Carrying work in process (WIP) long distances, creating inefficient transport, or moving materials, parts, or finished goods into or out of storage or between processes.
Waiting	Workers merely serving to watch an automated machine or having to stand around waiting for the next processing step, tool, supply, part, etc., or just plain having no work because of stockouts, lot processing delays, equipment downtime, and capacity bottlenecks.
Motion	Movement of people that does not add value such as looking for, reaching for, or stacking parts, tools, etc.
Intellect	Losing time, ideas, skills, improvements, and learning opportunities by not engaging or listening to employees.

Muri refers to the overburdening of people or equipment, things such as pushing a machine or person beyond natural limits, which may result in safety and quality problems. Mura refers to variation in a production process and typically results from irregular production schedules or fluctuating production volumes. This is mainly associated to the unevenness in production level. Mura is therefore fundamental to eliminating muda and muri, it is “the resolution of muda and muri” (Liker 2004, p. 114).

Based on these concepts of waste, several principles, methods, and tools were developed revolving around the primary goal of eliminating all waste, which has become the foundational work of lean production. A popular diagram that has been developed to visually describe this production system is the TPS house (Figure 2.2). The diagram consists of a house with two pillars and its foundation, representing the structure of the system; this diagram basically captures the essence of the system and how it all works together. The system will not stand without both of the main pillars and the pillars need to be on a stable foundation in order for the system to stand.

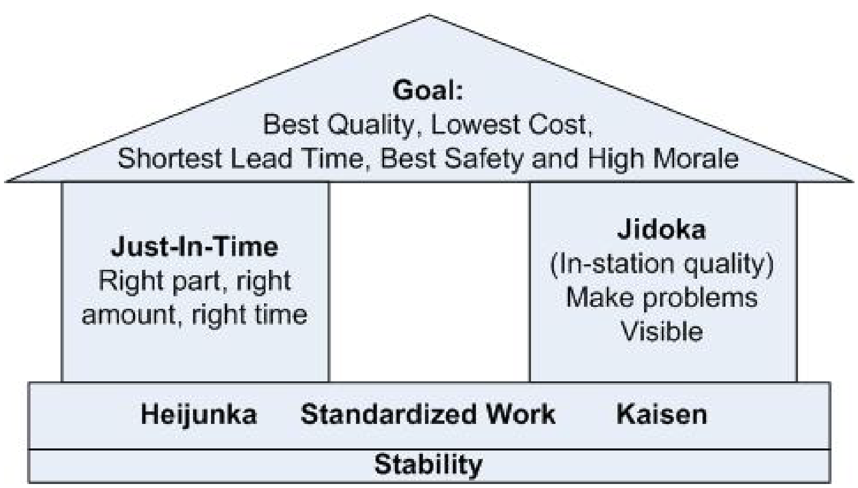


Figure II.2 - TPS House (adapted from Liker 2004)

The main objective of TPS is to produce the products that the client demands with the best quality, lowest cost, shortest lead time, best safety and high morale. In order to accomplish such goals, two main methods, which are represented by the two pillars in the TPS house, must be implemented in the production process. One pillar represents the method *Just-In-Time* (JIT), which is a set of tools and techniques that allows a company to produce and deliver products in small quantities, with short lead times, to meet specific customer needs. JIT allows for "the delivery of the right items at the right time in the right amount" (Liker 2004, p. 33). JIT has evolved from the known "pull system," an inventory or material flow system in which the consumer requests a product and "pulls" it as opposed to the traditional "push system" in which the seller "pushes" the product so that the consumers buy it. The second pillar represents the concept of *Jidoka* – the Japanese term for *autonomation* or "automation with a human touch." This concept consists on never letting a defect pass into the next station within a production process allowing machines or workers to stop production whenever something unusual or defective is detected, either automatically or manually (Liker 2004). These pillars rely on using tools such as visual management and the well-known 5S toolkit, among others.

The foundation, which must be stable, accomplishes stability through the continuous use the following techniques: *Heijunka*, or *production leveling* is used to level out the volume and mix of items produced so that there is little variation in production, thus controlling the type of waste associated with variation in production (mura); *Standardization* refers to using stable, repeatable methods everywhere to maintain the predictability, regular timing, and regular output of processes, thus controlling the overburdening of people or equipment (muri); and *Kaisen*, the Japanese term for *continuous improvement*, is another important technique that simply consists on making incremental improvements, no matter how small, and achieving the lean goal of eliminating *all* waste that adds cost without adding any value (muda) (Liker 2004).

2.1.1.2 Lean Production

The publication of *The Machine that Changed the World* (Womack et al. 1990) captured the attention of production practitioners and researchers worldwide. The concept of lean production became widely used for referring to the set of principles that make up this new production system. “Lean production is ‘lean’ because it uses less of everything compared with mass production – half the human effort in the factory, half the manufacturing space, half the investment in tools, half the engineering hours to develop a new product in half the time” (Womack et al. 1990, p. 13). Later on, Womack and Jones (1996) concisely summarized the principles of lean production in *Lean Thinking* in which the authors argued that “a lean way of thinking allows companies to specify value, line up value-creating actions in the best sequence, conduct these activities without interruption whenever someone requests them, and perform them more and more effectively” (Womack and Jones 1996, p. 15). In a nutshell, it can be said that lean creates flow and eliminates waste. Lean thinking has been summarized in the following five principles, which are the core concepts of lean production according to Womack and Jones (1996):

1. Precisely specify **value** by specific product
2. Identify the **value stream** for each
3. Make value **flow** without interruptions
4. Let the customer **pull** value from the producer (Use a pull logistic)
5. Pursue **perfection**

Craft production is characterized by the use of highly skilled workers and simple but flexible tools to make exactly what the consumer asks for, one item at a time. The problem with craft production is that the goods produced cost too much. As a consequence, mass production was developed as an alternative at the beginning of the twentieth century. Mass production, on the other hand, uses narrowly skilled professionals to design products made by unskilled, or semiskilled, workers tending expensive, single-purpose machines. This in turn allows for the production of standardized products, without adjustment to what the costumer asks for, in very high volumes, the main advantage of mass production. As a consequence, the consumer gets lower costs but at the expense of variety. Lean production, however, combines the advantages of craft and mass production by avoiding the high cost of the former and the rigidity of the latter. Also, teams of multiskilled workers are employed in lean production and use highly flexible, increasingly automated machines to produce volumes of products in enormous variety (Womack et al. 1990).

Table II.2 - Characteristics of Production Systems (Deflorin and Scherrer-Rathje 2008)

	Craft Production	Mass Production	Lean Production
People	Highly skilled workers	Unskilled or semiskilled workers	Teams of multiskilled workers
	High percentage of tacit knowledge	Narrowly skilled professionals to design products	Cross trained so that they can fill in for each other
	Technical expertise career path	Engineers with specific specialties, career enhancement is displaying genius in a single area of product, process, or industrial engineering	Career path were restructured for engineers so that rewards go to strong team players
Machines	Simple but flexible tools	Expensive, single purpose machines	Highly flexible and increasingly automated machines
Goal	One item at a time	High volume	Large volumes
	Customization	Standardized products	High variety

Given that lean production was initially designed for manufacturing, trying to implement manufacturing tools in the construction industry might have implications. Several authors have identified significant peculiarities that distinguish construction production from manufacturing production and other industries (Nam and Tatum 1988, Carassus 1998, Koskela 2000). Construction is a *One-of-a-kind production* – in construction customers play a key role throughout the project allowing for a great level of customization, and the differing site conditions and surroundings shape the uniqueness of each particular project and its needs; *On-site production* – construction production is site-position manufacturing and is carried out at the final site of the constructed product as opposed to fixed-position manufacturing in which the constructed product can be moved after assembly; and a construction project organization is usually a *temporary organization* – in construction, the completion of activities is highly interrelated and complicated, and temporary organizations are designed and assembled for the purpose of the particular project, which makes construction projects characteristically complex, unique, and dynamic systems. Despite these differences between construction and manufacturing, the core inherent purpose of lean construction, like in lean production, is to eliminate waste. To eliminate, or reduce waste in construction, the management of flows, which entails management of systems and processes along with production processes, is something that is of important consideration given its significant function in reducing waste (Ballard and Howell 1994).

2.1.2 Production Theory of Construction

The application of the theory of production has been applied to construction. The most prominent work in regards to the application of the new production system in the construction industry can be found in Koskela (1992; 2000), from which several foundational concepts and principles of lean construction have been established. To understand how this theory can be applied, it is important to analyze what a theory of production does first; an explicit and adequate theory of production must have the following functions (Koskela 2000, p. 25):

- It must provide an *explanation* of observed behavior
- It must provide a *prediction* of future behavior
- It must give *direction* in pinpointing sources for further progress
- It must allow *testing* of the theory to prove its validity

Koskela (2000) explains how production processes have been conceived in three different perspectives throughout the years: as *transformation*, in which inputs are simply converted into outputs, as the *flow* of materials and information, and as a process for *generating value* for costumers. The conventional production theory has dominated the construction industry, which consists of the transformation model of production. Koskela (1992) argued that replacing this traditional model with a new model, which consists of both transformations and flows, was required in order to reduce waste. This new production theory of construction is based on the conceptual realization that there are transformations and flows in all production systems, including construction. The principles of the theory of production describe this conceptual realization, and the tools and methodologies "embody the respective concepts and principles and convert the theory into practical action" (Koskela 2000, p. 21).

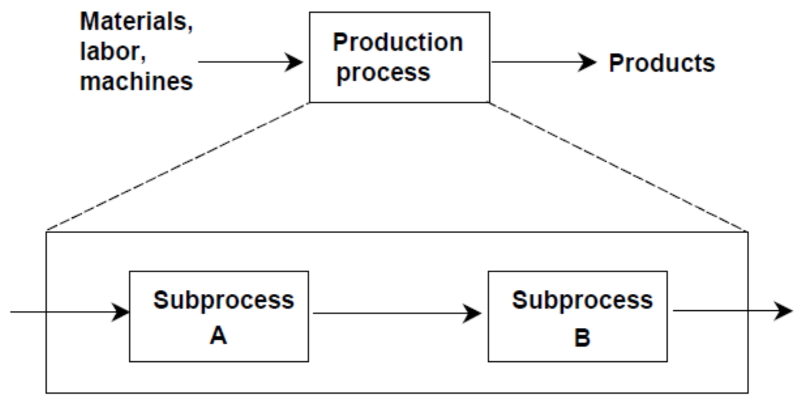


Figure II.3 - Production as a Transformation Process (Koskela 2000)

The transformation model of production views the production process as a number of discrete steps, each independently adding to the value of the final product. In its simplest form, it is basically the transformation of inputs to outputs. Flows in the construction industry, however, have often been ignored and even deteriorated by these traditional managerial concepts. The flow view of production categorizes production as a series of activities where some are *value-adding activities* and some are *non-value adding activities* (waste). The improvement of these flows therefore means to either eliminate the latter or reduce them in order to make transformations more efficient. With this model, flows are classified into four main types of activities: transformation, inspection, waiting, and movement, where transformations are the only value-adding activities.

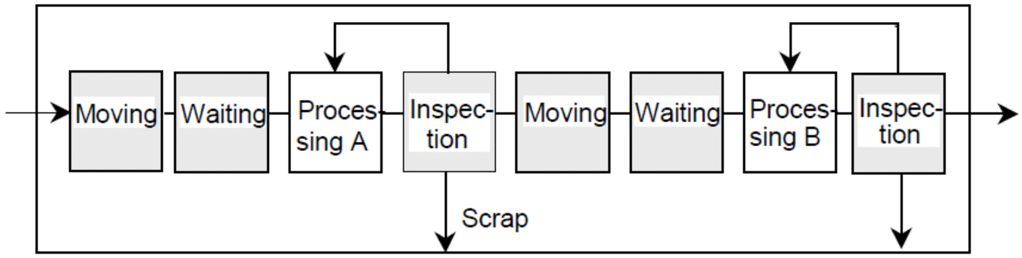


Figure II.4 - Production as a Flow Process (Koskela 2000)

The third model of production, *Value Generation*, views production as a means for the fulfillment of customer needs, hence the generation of value for the costumers. This comes from looking at production from a more broad perspective, which is that the fabrication of raw materials into finished products of different kinds is in for the fulfillment of certain human wants. Given these three different viewpoints regarding production, Koskela's seminal report proposed a new production management theory in construction and presented the TFV theory of production for construction: as Transformation, as Flow, and as Value Generation.

Table II.3 - Conceptual Summary of the TFV Theory of Construction (Koskela 2000)

	Transformation	Flow	Value Generation
Conceptualization of Production	As a transformation of inputs into outputs	As a flow of material, composed of transformation, inspection, moving and waiting	As a process where value for the customer is created through the fulfillment of the customer's requirements
Main Principles	"Getting production realized efficiently"	"Eliminating the share of non-value-adding activities"	"Improving customer value"
Associated Principles	- Decomposition - Cost Minimization - Value	- Reduce Cycle Time - Reduce Variability - Simplify - Increase Transparency - Increase Flexibility	- Requirements' Capture - Requirements' Flow-Down - Comprehensive Requirements - Ensure Capability - Measure Value
Practical Contribution	Taking care of what has to be done	Taking care of what is unnecessary is done as little as possible	Taking care that customer requirements are met in the best possible manner
Suggested name for practical application	Task Management	Flow Management	Value Management

Given the background on the three main views of production, it can now be observed that the mass form of production has been based primarily on the transformation model of production, whereas lean production adapts the flow model of production, that is, it consists of transformation activities and flow activities. This realization adopts the "reduction of cost through elimination of waste" as the core principle of lean production, from which many principles were developed. Adopting the third concept of value generation, the principles introduced by Koskela (1992) are presented at a high level of abstraction so that they may be adopted by other production systems. These are taken to be the main principles of lean production that are applied in construction, and are therefore taken to be the fundamental principles of lean construction. The principles can be found in Appendix A.

Koskela (2000) identified seven input flows, or preconditions, that unite and generate a task result. The realization that tasks depend heavily on flows, and the progress of flows in turn is dependent on the realization of tasks, is one of the reasons for the consideration of tasks and flows in parallel in production management. The seven preconditions needed for a construction task to be successfully carried out, also referred to as "the preconditions for soundness," are:

- The right *information*, such as construction designs, so that proper planning can be accomplished
- The right *components and materials* needed to perform the task
- Sufficient *workers (manpower)*
- The right *equipment*
- Proper *space*, such as an accessible building site, which also reduces the risk of accidents
- Having *connecting works* ready, meaning the completion of previous activities
- Having the *external conditions* of the construction site ready, such as approvals from local authorities.

Tools such as the last planner aim at leveling control of these flows, as will be discussed next, which may cause variability propagation in the system and consequently the cause of variability penalties, such as lower utilization of resources and lost production on site (Koskela

2000). These seven preconditions therefore facilitate the availability of sound production processes reducing variability propagation.

Workflow variability significantly affects the performance of construction trades and their successors. In a construction process, resources produced by one trade are typically prerequisites for the next trade. Throughput, project completion, and waste is affected by variations in flow, thus reducing workflow variability in the construction industry is of extreme importance. Reliable workflow establishes buffers to shield crews from workflow variability (Tommelein et al. 1999). Buffers allow two activities to proceed independently while the variation in output from the upstream operations does not affect the performance of the downstream operation (Howell and Ballard 1994). In other words, buffers serve as a shield against the negative impact upstream variability could cause to the production line and they also increase flow reliability. There are several types of buffers, such as inventory buffers (raw material, WIP, subassemblies, stock, safety stock), time buffers (lags, pacing mechanisms), and capacity buffers (excess of labor and equipment). Horman and Thomas (2005) have investigated how inventory buffers in construction affect labor performance and discussed how the use of inventory buffers can also cause management problems. Large buffers might lead to congestion which impedes performance, however, when material stocks are too low, this results in stopped, slowed, or disrupted production. In theory, optimal levels of inventory buffering would reduce congestion, which as a result, would also reduce hazards.

2.1.3 The Last Planner System

Based on the principles of lean production and its implementation in the construction industry, the Last Planner System of production control (LPS) has been established as an effective methodology that advantageously improves workflow efficiency by stabilizing the workflow in construction sites while protecting it from variability. LPS focuses exclusively in the flow model of construction discussed in the previous section; as the author himself explains, LPS "had evolved to roughly its current form, with a clear conceptual basis in production theory *a la Koskela* and an explicit and self-conscious objective of managing work flow" (Ballard 2000, p. 1-7). By stabilizing the workflow, it is possible to reduce in-flow variability and to work behind a "shield" between the downstream operations and the upstream variability, thus helping in the improvement of downstream operations by reducing uncertainty and unpredictability (Howell and Ballard 1994). LPS reduces waste by rapidly reducing uncertainty and producing more predictable and reliable workflow.

The Center for Excellence in Production Management (GEPUC) from the Pontifical Catholic University of Chile in Santiago, is a multidisciplinary center with the purpose of carrying out systematic actions in research, development, implementation and monitoring of improvements in the industry. GEPUC was founded back in 2000 when a group of engineers and academics observed several cases of foreign firms that had successfully increased their productivity and competitive levels through the implementation of the new project management methods that had emerged from the lean production philosophy. GEPUC has been implementing these lean construction practices emphasizing the last planner system in the Chilean industry since then. Some of its implementation and the impacts observed can be found in Alarcón et al. (2008) for further details. There was a great deal of collaboration with GEPUC and undergoing research from the Pontifical Catholic University during the data gathering phase of this thesis. Given the expertise of GEPUC, an adaptation of its applied LPS model (GEPUC 2010) along with the literature review on LPS (Ballard 1994, Howell and Ballard 1994, Ballard 2000), has been used to further expand on the interaction between the elements of LPS and safety management.

LPS adds two levels of planning between the master plan and the work execution planned by the last planner. The added levels of planning basically work as filters that produce reliable workflow while protecting the production from upstream uncertainty and variability (Figure 2.5).

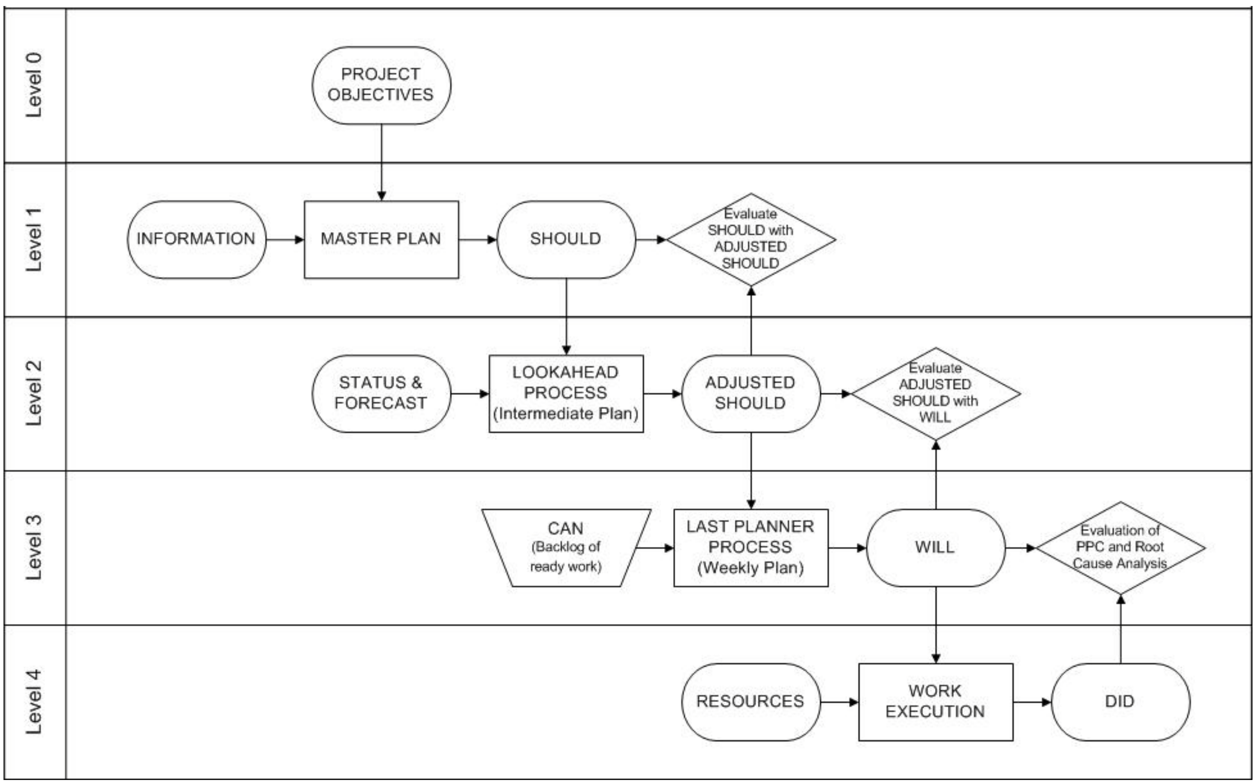


Figure II.5 - The Last Planner System (adapted from Howell and Ballard 1994)

The added levels of planning, referred to as levels 2 and 3 here, are the intermediate plan, also known simply as the 'Lookahead' process, and the weekly plan known as the last planner process. The lookahead process consists of a planning window, typically of about 4 weeks, in which constraint analyses are completed in order to provide a workable backlog for the next planning phase. In LPS, the last planner is the person or group that is accountable for the completion of assignments at the operational level and produces the assignments to be completed. The last planner produces weekly work plans to control the workflow. The term "assignments" stresses the communication of requirements from the last planner to the crew. These products of crew level planning are also commitments to the rest of the organization. They say what WILL be done, and (hopefully) are the result of a planning process that best matches WILL with the ADJUSTED SHOULD within the constraints of CAN (see Figure 2.5). Unfortunately, last planner performance is sometimes evaluated as if there could be no possible difference between SHOULD and CAN (Ballard 1994). The main tool in LPS that is used to control and improve workflow performance is the Percent Planned Completed (PPC) measurement. If an assignment fails to be completed, an analysis of the root causes for nonconformance with the plans must be carried out in order to develop a future plan and prevent it from happening in the future (Ballard 2000). The PPC, along with the root cause analysis are monitored weekly in order to provide a measure of plan reliability. The complete planning system of LPS is discussed in detail in Ballard (2000), while the details of the elements of the LPS to be analyzed in this study can be found in Appendix B.

2.1.4 Section Summary

This section has provided a summary of the origins of the new philosophy of production for construction, whose foundation rests on the underlying concepts and techniques of lean production and the principles of the Toyota Production System. Koskela’s ground-breaking report (Koskela 1992), which discusses the need for a new production system of construction, has been considered to be the catalyst for the lean construction movement that began in the early 1990’s and has continued to grow. Based on the principles and concepts of lean construction, the last planner system (Ballard 2000) gets established as one of the most effective and successful lean construction methodologies that have been develop thus far. Given the purpose of lean construction practices, which aim at improving production planning decisions by increasing predictability and reducing variability, similarly, safety management could benefit from this. The next section discusses the current state of safety management in the construction industry.

2.2 Safety Management

Many safety management practices have been developed over the years with the purpose of improving working conditions in order to reduce hazards and the amount of work-related accidents in the construction industry. The current safety performance for the construction industry is covered in this section, along with the most prevalent accident causation theories in the construction industry and safety management practices. Other aspects of safety management, such as safety culture and climate, and the way in which safety performance is currently measured are also reviewed in this section.

2.2.1 Construction Safety Performance

The majority of the construction workforce is made up of unskilled laborers, with many others being classified by several skilled trades, such as carpenters, electricians and plumbers among many others. In industrialized countries, construction workers make up 5 to 10 percent of the workforce and over 90 percent are male. In many countries, this work is typically left to migrant workers, whereas in others it is a relatively well-paid position and an avenue to financial security (Weeks 1998). Construction projects involve complex and dynamic environments with many concurrent activities, especially in larger projects. Throughout the life of a project, different workers will be exposed to a wide variety of health hazards, exposures which may also differ from day to day or even by the hour. Accidents and illnesses that result from work-related activities cause a great deal of harm and human suffering to the victims, family and the people around them. In addition to the pain that might result, accidents also result in costly events both to society and the firms that experience these accidents. The quantification of accidents is not an easy thing to do, and in fact, some of the costs, such as the human suffering that may result from an accident are unquantifiable (ILO 2003).

Given these inherent characteristics of the construction industry, it continues to be one of the most dangerous industries consistently accounting for the highest fatality rates worldwide. In 2008, the US construction industry had a fatality rate (number of fatal occupational injuries per 100,000 full-time equivalent workers) of 9.7, when the all worker average fatality rate was 3.6 (Figure 2.6). The number of fatalities for the industry in the US declined 20 percent, from 1,204 cases in 2007 to 975 cases in 2008. In 2008, this number represented 19 percent of the total reported fatalities (BLS 2009; 2010). The number of fatalities in the construction industry in the US had stayed consistently over 1100 since 1997 (ILO 2010). Falls and electrocutions have been identified as the leading causes of fatal injuries in the construction industry, whereas being struck by an object, falls to lower levels, and over exertion in lifting remain the leading causes of nonfatal injuries in the construction industry (CPWR 2008). The dynamic and unpredictable construction tasks and environments, combined with the high production pressures and workload, create a high likelihood of errors, which leads to accidents (Mitropoulos et al. 2007). Safety performance in the construction industry has improved in the past two decades, but it has reached a plateau, as these recent statistics provided suggest (ILO 2010; 2009; BLS 2010; 2009; CPWR 2008). These costs related to work-related accidents could be reduced with the right tools. The construction industry still needs a significant amount of improvement in safety performance to reduce both the monetary and the social impact that it has in today's society.

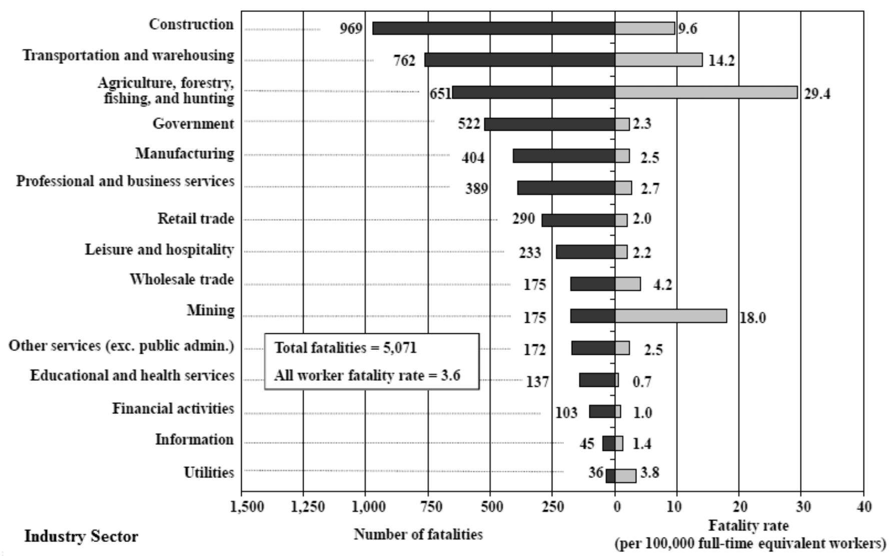


Figure II.6 - Number and Rate of Fatal Occupational Injuries in 2008 (BLS 2009)

2.2.2 Accident Causation Theory

In order to prevent accidents it is essential to understand the factors and processes that cause accidents. Understanding the causes of accidents can lead to the development of effective accident prevention strategies. An accident may be described as the result of a chain of events in which something has gone wrong, resulting in an undesired conclusion. These undesired conclusions result in injuries, fatalities, loss of production or damage to property and assets. Accident causation is extremely complex and must be understood adequately in order to improve accident prevention. Safety still lacks a theoretical base and thus it cannot be regarded as being a science yet (Jorgensen 1998). Throughout the years, many researchers have been working towards understanding and managing safety and accident prevention better, and consequently try to develop effective means to improve safety performance. Some of the most influential researchers have developed several prediction theories of accident causation although none has been universally accepted yet (Raouf 1998). However, some of the most influential accident causation models, which will be discussed briefly, have been the foundation of effective accident prevention strategies.

2.2.2.1 The Human Error Factor

Human error has been classified as an inappropriate or undesirable human decision or behavior that reduces, or has the potential for reducing effectiveness, safety or system performance and it has also long been a major contributing factor in accident causation in the construction industry (Saurin et al. 2004a). In fact, Saurin et al. (2005) suggests that the remaining and most difficult to tackle accidents are now those in which human errors play a major role. James Reason's seminal work on human error (Reason 1990) made significant distinctions as to how to view human error. Reason suggested human error can be viewed through a person approach or a system approach. The former approach focuses on the errors of the individual, such as the unsafe acts, errors and procedural violations which arise primarily from aberrant mental processes (forgetfulness, inattention, poor motivation, carelessness, negligence, recklessness). The latter approach on the other hand focuses on the conditions under which the individual works. In the system approach, errors are seen as the consequences rather than the cause of the accident (Reason 2000). Reason (1990) has classified unsafe acts into errors and violations. Errors can be (1) slips and lapses, which are "skill-based" errors and occur with little or no conscious thought, (2) mistakes, which involve the intentional behavior yet the wrong plan execution during unskilled behavior, or (3) perceptual errors, which result from misinterpretation of an actual plan. Violations can be either (1) routine violations, which simply depart from the rules and are often tolerated by supervision, or (2) exceptional violations, which are neither typical of the individual nor accepted by management.

Countermeasures used in the person approach are things such as poster campaigns that appeal to people's sense of fear, writing another procedure, disciplinary measures, threat of litigation, retraining, naming, blaming, and shaming among others. Countermeasures used in the system approach are based on changing the conditions under which the individual works rather than trying to change the human conditions. The person approach often fails to isolate unsafe acts from the system context by focusing on the individual origin of errors (Reason 2000). For these reasons, as will be discussed further, several investigations (Howell et al. 2002, Mitropoulos et al. 2005, Rosenfeld et al. 2010) have looked into moving away from viewing the human error from the person approach, otherwise referred to as behavior-based approaches, and develop new safety management strategies with the system approach.

2.2.2.2 Early Theories

The accident proneness theory, one of the older theories, maintains that within any given group of workers, some of them will be more prone to being involved in accidents. The theory further holds that accidents do not happen at random or by chance, but rather that some people simply have innate characteristics that make them more prone to accidents than others (Hinze 1997). Heinrich (1931) developed the so-called domino theory, in which he proposed that 88 percent of all accidents are caused by unsafe acts of people, ten percent by unsafe actions and two percent by “acts of god.” This two percent can be further explained by another simple theory know as the pure chance theory, which basically says that any worker has an equal chance of being injured in an accident and that there exists no way to intervene in order to prevent it (Raouf

1998). The domino theory states that all accidents happen in a five-factor accident sequence. One factor triggers the next one, as toppling dominoes lined up in a row would, eventually “toppling” the injury or damage domino. The five factors proposed by Heinrich are the following: (1) ancestry and the social environment of the worker, (2) the worker fault, (3) the unsafe act altogether with mechanical or physical hazard, (4) the accident, and finally (5) the damage or injury.

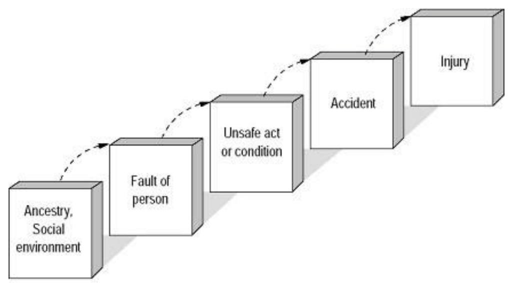


Figure II.7 - The Domino Theory

The multiple causation theory, which is also known as the two-component model, was developed by Petersen (1971). The theory holds that there are contributory factors and a combination these is what typically gives rise to accidents. There are two main groups in which these factors can be grouped into. There is the behavioral component (unsafe acts), which are factors pertaining to the worker such as, improper attitude, lack of knowledge and skills, and/or inadequate physical and mental conditions. All of this result in not using proper PPE or not paying close attention to a task, for example. The other component is the environmental component (unsafe conditions), which are things such as working near dangerous zones (heights, mechanical equipment), improper guarding of other hazardous elements, and degradation of equipment through the use and unsafe procedures (Raouf 1998).

Another well-known theory is the distraction theory developed by Hinze (1997). This theory focuses on the fact that production pressures can distract workers from hazards and increase the probability of accidents. Productivity is constantly compromised when the distraction due to hazards is high. Figure 2.8 shows the concept of this theory being applied to a work condition with numerous hazards. If there is a strong focus on productivity, there is a strong focus on high task achievement. In order to be productive, the worker must focus on high task achievement and the worker's focus on distractions must be minimal. The presence of hazards is considered to be a distraction for a worker. Given this conditions, if there is low focus on hazards then there is a higher probability of an injury occurrence. Work task achievement (the focus on productivity) will stop altogether once an injury occurs. Hazards are typically physical conditions with inherent qualities (unsafe conditions) that can cause harm; however, there are also other sources of hazards such as, the mental state of the worker – if the worker is not in the proper frame of mind when work is being performed. A worker might be mentally distracted with other thoughts that might preoccupy the worker's mind (i.e. death of a parent, dinner plans, etc). This theory presents an approach that has started to move away from the typical person approach for safety management, to the system approach.

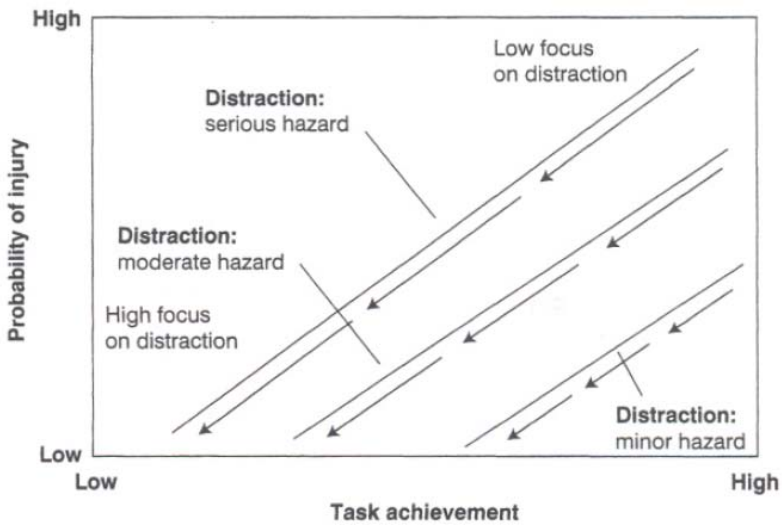


Figure II.8 - The Distraction Theory (Hinze 1997)

2.2.2.3 Cognitive System Engineering

The framework developed by Rasmussen et al. (1994), which is modeled within the paradigm of cognitive systems engineering (CSE), provides a broader view of the relationship between an individual and the work environment in which the individual works. CSE is "a cross-disciplinary approach for the design of complex socio-technical systems, being concerned with how joint cognitive systems (which are human machines ensemble that cannot be separated) perform, rather than cognition as a mental process" (Hollnagel and Woods 2005). CSE applications to safety management have been mostly related to high-risk operations in complex systems, such as aviation and power plants, therefore construction can also benefit from the same approach given construction's dynamic and complex nature (Saurin et al. 2007). It seems that an opportunity for a significant breakthrough in construction lies in devising innovative approaches to systematically integrate safety and lean based on the CSE theory (Saurin et al. 2006). Rasmussen's model maintains that workers tend to migrate closer to losing control for two reasons: (1) production pressures for increased efficiency and (2) tendency for least effort as a response to increased workload. Figure 2.9 shows the migration of work towards loss of control based on Rasmussen's work behavior model. Howell et al. (2002) identified three zones of worker operation: the "safe zone," where the worker's behavior is within the boundaries of safe performance, the "hazard zone," or 'near the edge' where work is no longer safe, and the "loss of control zone," where control is lost and irreversible.

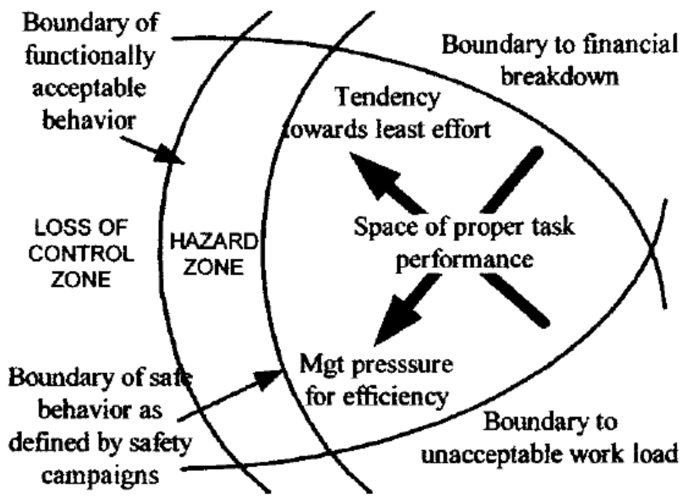


Figure II.9 - Rasmussen's Work Behavior Model (Mitropoulos et al. 2005)

The idea that an error is a deviation from normal practice makes sense in well-structured systems where a correct sequence can be identified, however, this is more difficult to accomplish in construction given the complex, dynamic conditions that characterize the construction industry (Howell et al. 2002). Using Rasmussen's approach, which suggests that learning to work close to the loss of control boundary can improve safety, contradicts traditional safety management practices; however, this new strategy recognizes that organizational and individual pressures push people to work 'near the edge,' meaning that people learn to work near the boundary of safe performance. This is a strategy that attempts to adjust current safety management practices with production management practices, such as those incorporating lean construction, thus adjusting to a more realistic framework in today's construction conditions.

2.2.2.4 The Systems Model

Mitropoulos et al. (2005) presented a new systems model of construction accident causation, which builds on Rasmussen's model previously discussed. The model is based on a "descriptive" rather than "prescriptive" model of work behavior (Figure 2.10). The traditional approach to accident prevention has focused exclusively on prescribing and enforcing "defenses," which are physical and procedural barriers that reduce the workers' exposure to hazards (Mitropoulos et al. 2005). Violations of these defenses are called "unsafe conditions" and "unsafe behaviors." Through the use of this traditional approach, management commitment and policies prevent unsafe conditions, while workers' training and motivation prevent unsafe behaviors. The model takes into account actual production behaviors, as opposed to the normative behaviors and procedures that workers "should" follow. Mitropoulos et al. (2005) identified the reduction of task unpredictability and the increase of error management capabilities as important directions to further improve accident prevention. Reducing task unpredictability reduces unexpected tasks, hazardous situations, interruptions and "short-term" production pressures, all of which reduce the likelihood of errors.

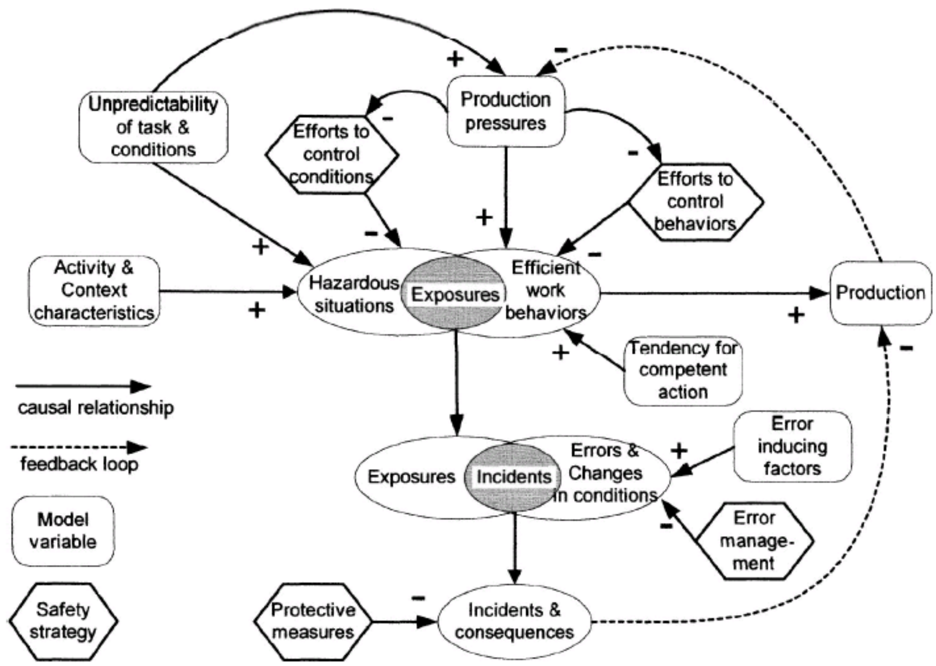


Figure II.10 - Systems Model of Construction Accident Causation (Mitropoulos et al. 2005)

2.2.2.5 Resilience Engineering

Resilience engineering is concerned with how organizations manage unexpected events and how people in these organizations manage and cope with these events. This term has recently been used to refer specifically to the CSE applications on safety management. Further, using resilience engineering, safety is not viewed as a system property but rather as something that a system *'does'* and not something that it *'has'*. Safety is therefore a reflection of how a system performs. Viewing safety through resilience engineering suggests that understanding failure in order to prevent its reoccurrence is more profound when it is understood how safety is created by the people in workplaces that continually experience changing hazard sources, as it is in the construction industry, and inevitably compromise between safe and productive actions all the time (Schafer et al. 2008). Furthermore, as suggested in *Managing the Unexpected*, resilience is about being concerned with cures just as much as managers are typically concerned with prevention, "to be resilient is to be mindful about errors that have already occurred and to correct them before they worsen and cause more serious harm" (Weick and Sutcliffe 2007, p. 68).

2.2.3 Safety Culture and Climate

The concept of 'safety culture' has developed since the 1987 OECD Nuclear Agency report (INSAG 1988) attributed the cause of the infamous 1986 Chernobyl disaster to the poor safety culture at the power plant. The report made notable observations on several errors and violations of operating procedures prior to the disaster, which were considered evidence of a poor safety culture. The term has been loosely used to describe the corporate atmosphere, or culture, in which safety is understood to be, and is accepted as, the number one priority (Cooper 2000). Furthermore, based on several of definitions regarding safety culture that abound in the academic arena, it can be best described as the organizational values and norms that affect the workers' overall attitudes and behavior in relation to an organization's safety performance. Given the current poor safety performance of the construction industry, the industry's poor safety culture could be one of the causes, which implies that it must be improved in order to improve the industry's current safety performance (Mohammed 2003).

The terms safety 'culture' and 'climate' have been used interchangeably, however, climate refers explicitly to the perception of the workers in regards to the value of safety in the work environment. Mohammed (2003) argues that safety culture is concerned with the determinants of the ability to manage safety (a *top-down* organizational attribute approach), and safety climate is concerned with the workers' perception of the role safety plays in the workplace (a *bottom-up* perceptual approach). The top-down approach includes observable measures such as management commitment, participation and accountability, procedures and policies, communication, etc. On the other hand, the bottom-up approach includes a different set of observable measures such as workers' constructive involvement, proactive reporting, individual attitude, group behavior, working relationships with supervisor and co-workers, etc (Mohammed 2003). Safety climate is dependent on the prevalent safety culture, and therefore it can be considered a product of the safety culture of an organization.

2.2.4 Accident Prevention Strategies

In 1993, CII released its report titled *Zero Injury Techniques* (CII 1993) which presented the results from a safety study that had identified five strategies as the most successful accident prevention techniques being used to achieve the "zero accident" objective. The implementation of these techniques should allow companies with good construction safety programs to improve their safety performance, and thus achieve zero or near zero accidents on construction projects. These five strategies are the following:

- *Pre-Project/Pre-Task planning for Safety* – Planning for safety, either for a task or a project consists on a systematic review of the scope of an activity or project, which is focused on identifying potentially hazardous tasks, conditions, toxic or hazardous materials, or special training and procedures required to perform certain tasks. The intent is to identify those hazards that exist and to develop a safe, cost-effective plan to perform the work (Hinze 2002).

- *Safety Orientation and Training* – The activities that are typically carried out as safety training and orientation should include both the owner and the contractor personnel. This is the typical "safety first step" given to an employee before going out on the job site and it is also given to all personnel, including visitors, who wish to spend field time on the project site. All the information that's necessary to stay safe and protect themselves and others from injury is provided in these meetings (Hinze 2002).

- *Written Safety Incentive Programs* – An incentive program may be established exclusively to reward safety performance by personnel or as part of a broader project incentive program, which may include schedule, cost and quality. These are designed to influence worker actions and encourage safer work performance. Incentives are typically monetary awards or gift awards that are given to the workers as a reward for a predetermined amount of good safety performance (Hinze 2002).

- *Alcohol and Substance Abuse Programs* – Given the well understood and accepted association between substance abuse and injury occurrence, alcohol and substance abuse programs such as drug screenings are vital to improved safety performance. Other measures may include random testing and post-accident testing as well (Hinze 2002).

- *Accident/Incident Investigations* – Accident and incident investigations send a strong message of management concern to all employees. Failure to do so also sends a message of disinterest for employees' safety and well-being. The purpose of an investigation is to find out the cause of accidents, which may result in recommendations to prevent accidents in the future from happening again and adjust any safety management strategies as necessary (Hinze 2002).

This study was followed by a validation study (Hinze and Wilson 2000) to examine changes made since its publication. The validation study was conducted by the National Center for Construction Education and Research and the M. E. Rinker Sr. School of Building Construction at the University of Florida, which concluded that the these strategies played significantly improve safety performance and play a vital role. These techniques were further extended to follow-on this project and identify the current best practices in the construction industry (Hinze 2002). The results of this study identified nine key practices, or areas, that contribute to improved safety performance. These practices are noted as follow:

- Management commitment
- Staffing for safety
- Planning: pre-project and pre-task
- Safety education: orientation and specialized training
- Worker involvement

- Evaluation and recognition
- Subcontract management
- Accident/incident investigations
- Substance abuse program

Within these practices, specific safety strategies are included, for example, safety committees and perception surveys are strategies implemented as part or worker involvement practices. This study concluded that the biggest change encountered since the first report on zero injuries was published (CII 1993) is the area of worker involvement in the safety process. All of these nine areas of safety identified significantly improve safety, each on different, yet effective ways. Specific details about each of these nine main practices can be found in Appendix D; this is a list of the most common safety management practices identified to be used for the analysis in this thesis project, as will be explained in Chapter 4.

2.2.5 Safety Performance Measurements

Measuring safety performance allows companies to make decisions concerning the impact that their safety management efforts have on their safety performance. Measurements are useful to evaluate the efficiency of a process, which in this case is the implementation of accident prevention strategies, or safety management practices, as they are referred to in this thesis from now on. Safety performance measurements can determine if safety performance is: (1) acceptable, meaning that no change in operations would appear needed; (2) improving, which could be a possible indication that interventions are working; (3) declining, meaning that additional interventions are needed; or (4) unacceptable, an indication that interventions must be implemented (Hinze 2009). As a universal measure, incident rates are typically what is used to measure safety performance within a company. These rates are typically based on the number of *recordable* incidents that a company has experienced per every 100 full-time employees. A recordable incident includes all work-related deaths, illnesses, and injuries which result in loss of consciousness, restriction of work or motion, permanent transfer to another job within the company, or that requires some sort of medical treatment of first-aid (RIT 2008).

2.2.5.1 Lagging Indicators

To date, most safety performance measurement systems have been preoccupied with the negative consequence of site accidents rather than proactive prevention strategies. These safety performance measurements are often referred to as reactive safety indicators, or lagging indicators, for they are measurements of *only* past performance, the end result of a process. These measurements are reactive in nature given that they only record incidents that have already occurred and they may also cause incidents and near-misses to go unrecognized (Mohammed 2003). The advantage of this lagging indicators is that the historical data that is typically reported is accurate, or nearly so. The disadvantage of these indicators, however, is that by the time one realizes that safety performance is at an unacceptable level, workers will already have been injured. There is also the issue of under-reporting, given that a great deal of attention is paid to such single measures (Hinze 2009). Various types of incident rates are used throughout the industry. Table 2.4 shows the most common lagging indicators used in the construction industry today along with the typical form in which they are measured; OSHA’s specific performance measurements are also included to provide a reference for the discussions throughout this thesis. OSHA’s standard base rate of calculation is based on a rate of 200,000 labor hours, which is equivalent to 100 employees, who work 40 hours per week, and who work 50 weeks per year (OSHA 2004).

Table II.4 - Safety Performance Lagging Indicators

Indicator	Description	Measurement
Incident Rate	The number of recordable incidents for every 100 workers.	$\frac{Total\ Incidents * 100}{Total\ Workers}$
Risk Rate	The number of lost work days per recordable incidents for every 100 workers.	$\frac{Total\ Lost\ Days * 100}{Total\ Workers}$
Severity Rate	The average number of lost work days per recordable incident.	$\frac{Total\ Lost\ Days}{Total\ Incidents}$
Severity Index	The number of lost work days per recordable incidents with respect to a million man-hours worked.	$\frac{Total\ Lost\ Days * 1{,}000{,}000}{Total\ Manhours}$
Frequency Index	The number of recordable incidents with respect to a million man-hours worked.	$\frac{Total\ Incidents * 1{,}000{,}000}{Total\ Manhours}$
OSHA - Recordable Incident Rate (RIR)	The number of OSHA recordable incidents for every 200,000 man-hours worked.	$\frac{Total\ Incidents * 200{,}000}{Total\ Manhours}$
OSHA - Lost Work Day (LWD) Rate	The number of lost work days per OSHA recordable incident for every 200,000 man-hours worked.	$\frac{Total\ Lost\ Days * 200{,}000}{Total\ Manhours}$
OSHA - Lost Time Case (LTC) Rate	The number of OSHA recordable incident cases resulting in lost work days for every 200,000 man-hours worked.	$\frac{Total\ LTC\ Incidents * 200{,}000}{Total\ Manhours}$
OSHA - Days Away/Restricted and/or Transfer (DART) Rate	The number of OSHA recordable incident cases resulting in Days Away (lost work days), Restricted days or a Transfer within the company for every 200,000 man-hours worked.	$\frac{Total\ DART\ Incidents * 200{,}000}{Total\ Manhours}$

2.2.5.2 Leading Indicators

There's recently been a shift within this paradigm from reactive, lagging safety indicators, to proactive, leading safety indicators. Leading indicators can monitor the state of safety within a project without having to wait for the system to fail in order to be able to identify its weaknesses and then take the corrective actions necessary (Razuri 2007). These indicators focus on the safety process, as opposed to the end result. Lagging indicators document historical data of safety performance, while leading indicators are used as predictors of safety performance. If an indicator predicts poor safety performance, it would not be necessary to wait to see if the prediction is correct, instead, the corrective action would be taken to increase the probability of good performance. While lagging indicators tend to be accurate and objective, the disadvantage of using leading indicators is that they are generally more vague, less accurate and certainly not as subjective. No single leading indicator of performance measurement can foretell all aspects of the safety performance to be realized, thus only when taken as a group can they provide a sense of the level of performance to be expected (Hinze 2009). Razuri (2007) identified five noteworthy safety performance leading indicators, while Sossford (2009) built upon these and added several more that were acquired through interviews. Table 2.5 below shows a list of the leading indicators identified. The complete planning definitions and description of each specific indicator are discussed in detail in Razuri (2007) and Sossford (2009).

Table II.5 - Safety Performance Leading Indicators (Razuri 2007, Sossford 2009)

Indicator	Objective	Measurement
Incidents	To provide an incentive for workers to report incidents.	$\frac{Total\ Incidents\ Reported}{Total\ Workers}$
	To relate incidents reported to the actual number of accidents occurred.	$\frac{Total\ Incidents\ Reported}{Total\ Accidents\ Occurred}$
5S	To implement the 5S philosophy in order to improve safety.	Average 5S Index
IPA	To measure the amount of substandard actions and conditions on the site.	$\frac{\sum Substandard\ Actions\ \&\ Conditions}{Total\ Labor\ Mass}$
PSW	To measure the percentage of safe work packages carried out as the main performance measure used to evaluate safety effectiveness.	$\frac{\sum Work\ packages\ safely\ carried\ out}{Total\ work\ packages\ assigned}$
JHA	To implement Job Hazard Analysis for all work packages.	$\frac{Total\ JHA's}{Total\ Workers}$
Safety Training	Management	$\frac{Total\ training\ hours}{Total\ Manhours\ (monthly)}$
	Management	Total number of inspections
	Management	$\frac{Training\ sessions\ carried\ out}{Training\ sessions\ planned}$
	Workers	$\frac{Total\ training\ hours}{Total\ Manhours\ (monthly)}$
	Workers	% of workers trained

2.2.6 Section Summary

This section has provided a summary of the most important aspects of safety management for the construction industry. The current state of construction safety performance was covered, in which some of the inherent characteristics of the industry were discussed, as well as the most recent statistics on the matter. Accident causation theory and the most influential models were reviewed, including the most recent models that depart from the typical person approach for safety and implement the system approach. Safety culture and climate are also covered in this section, which have been recently identified as possible causes of the industry’s poor safety performance. Last, the most recent reports that have summarized the most common safety management practices and how safety performance is measured today were discussed. Now that the foundational concepts of lean construction and safety management have been covered, the next section discusses how safety management has been recently studied within the lean construction paradigm.

2.3 Lean Construction and Safety

"Every method available for man-hour reduction to reduce cost must, of course, be pursued vigorously; but we must never forget that ***safety*** *is the foundation of all our activities" – Taiichi Ohno (Liker 2004, p. 34).*

Lean strategies encourage less material in the work area, an orderly and clean workplace, and systematic workflow, therefore, it could be expected that standardizing, systematizing and regularizing production leads to better safety (Nahmens and Ikuma 2009). Poor safety is considered a form of waste because from a lean perspective, incidents that disrupt the flow of work or lead to injuries are waste (Howell et al. 2002); furthermore, injuries are costly not only in terms of human suffering, but also in terms of worker compensation costs, lost time, lost productivity, and higher employee turnover (Saurin et al. 2004b). Safety should not be treated as a separate subject from production, for it is an integral part of every production process; safety depends on every action, material, and person used in a work process (Nahmens and Ikuma 2009). Typical production planning decisions, which determine what will be done, when, how and by whom, are the basis to establish preventive measures (Saurin et al. 2004b). As Leino et al. (2010) explains, based on these beliefs, safety shall be treated as another one of the performance variables targeted by production management along with cost, time, and quality. From a lean perspective, safety management is about managing uncertainty (Leino et al. 2010). Over the past decade, several researchers in the construction industry have shifted their attention to topics pertaining to lean construction and safety. There have been significant investigations and proposed initiatives, many of which have been thoroughly reviewed in this investigation and discussed in the previous section (Howell et al. 2002; Mitropoulos et al. 2005; Schafer et al. 2008). These investigations address several issues as to how safety is affected by the implementation of lean practices and vice versa, and how they might benefit from one another.

A wide range of themes within these investigations has emerged in recent years pertaining to topics on how safety is affected by the implementation of lean practices and vice versa. Alves and Tsao (2007) identified and categorized major research areas in lean construction to provide a perspective as to what lean construction meant back in 2006. This study was carried out by analyzing the keywords that were listed in all of the seven conference proceedings for the International Group for Lean Construction (IGLC) from 2000 to 2006, which consisted of a total of 357 papers. Ghosh and Young-Corbett (2009) similarly undertook a significant review of the IGLC proceedings from 1998 to 2008 with the objective of finding out how researchers have looked into managing safety within the lean construction paradigm. Four main themes have emerged based on the literature pertaining to the intersection of lean construction and safety management. Table 2.6 displays the relevant investigations that have been reviewed in this literature review. In the same table, this thesis (Antillón 2010) is also shown to portrait where it intends to contribute within the existing body of knowledge, and to provide a referential point of departure. Managing safety within the lean construction paradigm is being undertaken through the following four themes: (1) through production planning and control; (2) developing new approaches to construction safety; (3) forecasting risk levels for workers as a function of time; and (4) using performance measurements to improve safety (Ghosh and Young-Corbett 2009). With the aid of these reviews, the investigations that have been thoroughly analyzed are discussed within one of these relevant themes.

Table II.6 - Emerging Research linking Lean Construction and Safety

Emerging Themes	Authors														
	Howell et al. (2002)	Abdelhamid & Everett (2002)	Thomassen et al. (2003)	Surin et al. (2004a)	Saurin et al. (2004b)	Saurin et al. (2005)	Mitropoulos et al. (2005)	Saurin et al. (2006)	Mitropoulos et al. (2007)	Razuri et al. (2007)	Schafer et al. (2008)	Nahmens and Ikuma (2009)	Rosenfeld et al. (2010)	Leal (2010)	Antillón (2010)
Safety through Production				x	x		x	x							x
New Approach to Construction Safety	x	x		x		x	x	x	x		x				x
Forecasting Risk Levels													x		
Performance Measurements			x							x		x		x	

2.3.1 Safety through Production

Saurin et al. (2004b) proposed a safety planning and control (SPC) model that integrates safety management to the production planning and control process (Figure 2.11). Several concepts used in LPS, such as work packaging, were incorporated into safety management. A Percentage of Safe Work packages (PSW) was used as the main performance measure used to evaluate safety effectiveness, something fairly similar to the PPC performance measure. PSW's were considered safe when no failure in the conception of safety plans were detected, there were no failure in their implementation and no accidents or near misses were also observed. Other concepts used in LPS such as look-ahead planning for safety were also implemented in this model. The results of this study indicate that lean management strategies could be extended to safety management in order to improve safety performance based on both proactive and reactive indicators. The authors have devised and implemented the SPC model in six construction projects in Brazil. The projects were carried out by the same contractor between the years of

2001 and 2006. Saurin et al. (2004b) present a detailed description of the SPC model, while a discussion on its impact on human error control is reported by Saurin et al. (2004a).

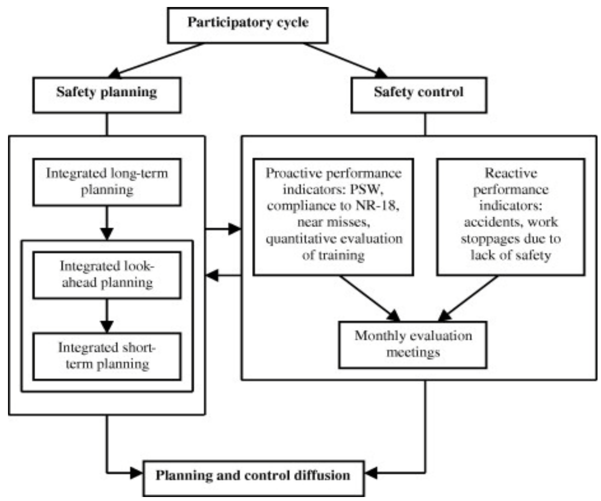


Figure II.11 - Overview of the SPC Model (Saurin et al. 2004b)

2.3.2 New Approach to Construction Safety

Saurin et al. (2006) identified autonomation and visual management as two lean methods used to detect variability, which contribute to detect migrations and to make boundaries of safe work visible. From a lean production perspective, typically autonomation means that either operators or machines are given the autonomy to stop production whenever something unusual is detected, such as a defective product. In lean construction, the worker is given the autonomy to stop work or ask for help when the worker notices a problem, such as a bad rule or no rule situation. The problem then becomes visible to everyone and consequently it can be eliminated. Visual management can be extended for safety purposes using things such as safety signs and boards displaying current accident rates, and allowing all workers to identify the boundaries for safe performance and compare the expected safety performance (Saurin et al. 2006). This investigation also commented on the lack of in-depth conceptual discussions on the interfaces between safety management and lean production principles and practices, and more importantly the lack of support from empirical data.

Mitropoulos et al. (2007) examined how production practices consistent with lean principles affect the chances of construction accidents. The production practices were examined by an exploratory field study which indicates that a focus on reducing uncertainty, errors and rework (waste), and matching skills to task demand reduces the chances of construction accidents while increasing productivity. Several of the other investigations that have suggested new theoretical approaches to construction safety (Howell et al. 2002; Mitropoulos et al. 2005; Schafer et al. 2008) were discussed in the previous section.

2.3.3 Forecasting Risk Levels

Rosenfeld et al. (2010) developed a structured method for hazard analysis for construction called "Construction Job Safety Analysis" (CJSA), which focuses on addressing the dynamic work environments that make managing construction site-safety more difficult. CJSA was developed with a lean approach to safety management in mind, by determining the likelihood of occurrence of loss-of-control events in order to more efficiently plan safety management efforts to the places and times where they are the most effective, thus enhancing safety by being less wasteful and more efficient. In other words, this approach in a way aims at developing a 'lean' safety management model. The development of this method was inspired by the CHASTE (Construction Hazard Assessment with Spatial and Temporal Exposure) approach (Rosenfeld et al. 2009) which is a conceptual model that basically enables forecasting of safety risks in construction for different trades, taking into consideration the dynamic interdependence of different trades in projects that endangers workers by activities performed by others. This approach allows safety managers to “level risk,” something similar to resource leveling, which again, as with the implementation of CJSA, ensures the effective allocation of safety management efforts *when* and *where* they are needed. From a lean perspective, this is basically transforming the traditional “push” approach for safety management into a more effective, and less wasteful “pull” approach.

Just-In-Time (JIT) is a lean method that may be extended to safety management practices. Griffy-Brown (2003) has emphasized the role of redundant capacity to reduce significant risks, which is referred to as the Just-In-Case (JIC) approach as opposed to JIT. JIC stresses the need for preparedness against uncertain environments and encourages the use of appropriate buffers to avoid worse situations, which for safety this would be a significant accident such as a fatal injury. A worse situation (a fatal injury) would then result more costly than keeping redundant capacity (the allocation of safety management efforts), thus adopting the JIC approach to safety management. JIT logistics in the construction industry have shown significant benefits, however, it has been very difficult to implement given that more reliable work planning is required than what can normally be provided in construction (Bertelsen 2002). This is the reason why JIC would be a better approach to the adoption of the JIT principle in construction, which is still similar but somewhat modified.

2.3.4 Performance Measurement

Thomassen et al. (2003) reported the experience and results that MT Højgaard, one of the largest Danish contracting firms, had in projects implementing LPS. The results, which are the main findings from their 2002 annual report on lean construction, show a significant safety performance improvement on sites implementing LPS; these projects had an overall accident rate of about 45 percent lower than the other projects (Table 2.7). It was suggested that the reason why the implementation of such lean tools had significantly reduced accident rates was because: (1) they facilitate the availability of sound activities, which are accomplished by meeting all of the preconditions for sound production, and makes it easier to stay in a space of "non-chaos" consequently reducing hazards; and (2) LPS also implements a fundamental strategy that allows for a system to be more maneuverable, that is, the bottom-up approach to planning which allows for the foreman (the last planner) and others that are actually working at the site to play a significant role in planning (Thomassen et al. 2003).

Table II.7 - Accidents and Accident Rates for MT Højgaard (Thomassen et al. 2003)

MT Højgaard	Last Planner Sites	Non-Last Planner Sites
No. of working hours	305,604	580,371
No. of accidents	12	41
Accident Rate (%)*	7.85	14.13

* Accident Rate = Number of accidents / 200,000 working hours

A recent investigation (Leal 2010) focused on the implementation of LPS in industrial mining projects with the goal of quantifying and understanding the impact of its implementation on several performance variables for these types of projects. Of those variables, safety performance showed remarkable results. This investigation consisted of three case studies where LPS was implemented on different industrial assembly projects for a Chilean mining company during the years 2008 and 2009. Concurrently, two other projects for the same company that did not implement LPS were also analyzed as the non-LPS case studies. As shown on Table 2.8, the three LPS cases achieved the zero accident goals, while the non-LPS cases resulted with some accidents and the accident rates were even higher than the company's historic average accident rate. Leal (2010) proceeded to evaluate the magnitude of the impact LPS has on achieving project objectives from the workers' perspective. While customer satisfaction and productivity resulted on the top project objectives, with the largest impact magnitude from the workers' perspective, quality and safety were the lowest two objectives.

Table II.8 - Results of Safety Indicators for Industrial Mining Projects (Leal 2010)

Case	Frequency Index*	Accident Rate*	Severity Index*	Risk Rate*
LPS Case 1	0.00	0.0 %	0.00	0.0 %
LPS Case 2	0.00	0.0 %	0.00	0.0 %
LPS Case 3	0.00	0.0 %	0.00	0.0 %
Non-LPS Case 1	10.00	0.8 %	160.00	10.0 %
Non-LPS Case 2	1.30	0.6 %	5.00	2.0 %
Historic Average	3.01	0.4 %	31.56	3.4 %

* See Table 2.4 for the details of the safety performance measurements

Nahmens and Ikuma (2009) conducted a large-scale survey of industrialized homebuilders to determine if the use of lean construction, specifically the use of Continuous Improvement (CI) programs, is associated with improved safety metrics in the industrialized housing industry. It was hypothesized that builders using the lean components of CI programs would have improved safety, as measured by fewer OSHA - DART cases. The results obtained from the investigation indicate that homebuilders using CI programs have incidence rates that are lower than those without, which supports the theory of safety improvement with the use of at least one lean component. The results from this study also suggested that lean practices may need to be used in conjunction with formalized safety programs to significantly reduce more severe cases. In Razuri et al. (2007), 14 best safety practices that correlate closely with safety performance were analyzed through a survey study in Chile. The results indicate that there is a positive correlation between the number of safety best practices implemented and the project injury rate (PIR). The results also identified the most effective practices for the future implementation of a management model that integrates production and safety management. Several of the practices identified could be integrated with some lean practices, such as LPS. Among the safety practices identified as the most effective were safety training for management and workers, safety committees, safety tasks analysis by the crews, and behavior-based safety programs.

2.3.5 Section Summary

This section has covered the most relevant and recent studies that have studied the intersection between lean construction and safety. From these studies, there seems to be four main themes through which this is interaction is being undertaken: through production planning and control, developing new approaches to construction safety, forecasting risk levels for workers as a function of time, and using performance measurements to improve safety. Given this, a point of departure can now be established, in which the importance of this study and what it intends to accomplish is specified.

2.4 Point of Departure

An in-depth literature review has been carried out for the existing body of knowledge concerned with lean construction, construction safety management and topics pertaining to the intersection between the two. In this manner, the most fundamental groundwork for the key ideas pertaining to this thesis has been laid down. Lean construction, which implements a new approach for production management for the construction industry, has recently been discussed widely in the construction community and has continued to gain interest as a promising research area. Given that lean focuses on the reduction of waste and poor safety can undeniably be considered a source of waste, it is hypothesized that the implementation of lean practices results in improved safety management efforts, which in turn results in the improvement of safety performance. Given this, the central question that this thesis intents to address is:

How does the implementation of lean construction affect safety performance?

More specifically, this thesis focuses on addressing the following two questions: (a) what specific tools and methods of lean construction improve safety management efforts? and (b) what is the correlation, if any, between the implementation of lean construction practices and safety performance?

It is evident that many of the new proposed approaches to construction safety within the paradigm of lean need to be further assessed and are topics that are still in their infancy, and there is a lack of in-depth conceptual discussions on the interface between lean construction and safety management. The hypothetical relationship that exists between lean practices and safety performance needs to be further addressed. This will provide a basis for the discussion of the strong correlation, which may or may not exist, between lean practices and safety performance in construction. A framework that reiterates the interactions between aspects of lean construction and safety management would enable an in-depth conceptual discussion on this interface. The results from this can provide evidence to promote and demonstrate the value of lean construction in construction safety, yet another aspect of significant importance to construction projects, and can also help to develop and integrate future production and safety management models.

III. RESEARCH METHODOLOGY

A research methodology approach known as a research synthesis was applied in this thesis. This approach closely examines previous studies related to the topic at hand and it was used to combine qualitative data related to the interface between lean construction and safety management. This helped to recognize and understand the interface between lean and safety. Empirical studies were also inferred as supporting evidence for the interactions identified and how the implementation of lean results in improved safety performance. This chapter describes why this research method approach has been chosen, the data collection process, data analysis process, and the validation process. A research method developed at the Centre for Integrated Facility Engineering (CIFE) at Stanford University, known as the CIFE 'Horseshoe' Research Method (Fischer 2006), was adapted to map the research process. The sections that follow align with Figure III.1 starting on the upper left corner around to the lower left corner.

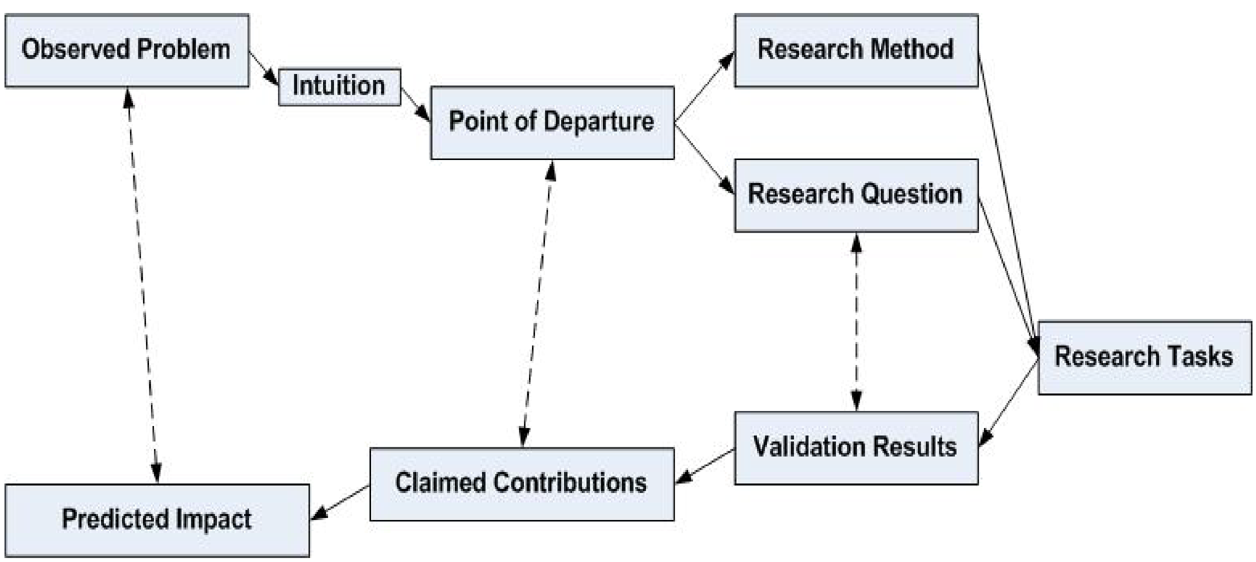


Figure III.1 - Map of the Research Process (adapted from Fisher 2006)

3.1 Observed Problem, Intuition and Point of Departure

This study builds on the previous studies of the interface between lean construction and safety management. The scope of this study has been narrowed down to address the relationship between the implementation of lean construction practices and improved safety performance. The hypothesized relationship is best described as a correlational relationship, which means that the implementation of lean practices and safety performance perform in a synchronized manner (Trochim 2006). More importantly, as the literature review suggests, it seems as if there is a positive, direct relationship between lean practices and safety performance. Building on intuition, the least formalized step in the CIFE horseshoe, and the literature review, it seems as if there is a lack of an in-depth conceptual discussion on the interface between lean construction and safety management, which may help to further understand how lean construction results in safer environments, and therefore address the observed problem. Given the well-defined hypothesis and the need for an in-depth conceptual discussion, this has clarified the areas that the research needs to focus on as a theoretical starting point, or point of departure.

3.2 Research Method and Question

The research method applied in this thesis was a research synthesis. Many terms such as 'literature review', 'research review', and 'systematic review' are often used interchangeably with the term 'research synthesis' to label the activities performed by this research method. In order to clarify the purpose of its use in this thesis and any discrepancies that might arise in regards to it, a research synthesis "seeks to summarize past research by drawing overall conclusions from many separate investigations that address related or identical hypothesis. The research synthesist's goal is to present the state of knowledge concerning the relation(s) of interest and to highlight important issues that research has left unresolved" (Cooper 2010, p. 4). Typically a literature review will attempt to do some or all of the following: to integrate what others have done and said, to criticize previous scholarly works, to build bridges between related topic areas and to identify the central issues in a field. For this thesis, these topics are lean construction and safety management. The literature review in this thesis was very helpful in identifying the gaps within the ongoing dialogue in the literature, which helped to establish the given point of departure for the research work.

The question being addressed in this thesis is the following: how does the implementation of lean construction affect safety performance? This is dealt with through the analysis of the interaction between specific tools and methods of lean construction and safety management practices. With the aid of the research synthesis, an interaction matrix was developed from which the interface between aspects of lean construction and safety management were analyzed. In addition to the qualitative procedures of the research, quantitative data from previous empirical studies were statistically inferred in order to seek the necessary evidence to support the interactions identified.

3.3 Research Tasks

The research tasks for this research problem include the data collection process, data analysis process, and the research validation process. The data collection was accomplished through the use of the above mentioned research synthesis and using a coding sheet to comply with the internal validity of the research. From the studies collected, an interaction matrix was then developed. The data analysis process for the analysis of the developed interaction matrix implemented a morphological analysis approach. The results obtained from the analysis of the interaction matrix were then validated conducting structured interviews with an expert panel.

3.3.1 Data Collection

As part of a research synthesis, retrieving the adequate studies to analyze must meet certain criteria in terms of the quality of the studies and the relevance to the main research problem being addressed. Using several tools and methods suggested by handbooks on implementing research synthesis (Cooper 2010, Cooper et al. 2009) along with other research design guides (Creswell 2009, Trochim 2006), an adequate data collection process has been developed to meet the objectives of this study and ensure consistency and validity of the research process.

Retrieving the appropriate literature required a significant amount of judgment on the quality and relevance of the studies collected. Given the inherent characteristics of the research and its qualitative nature, in order to comply with the internal validity of the research, the studies collected and analyzed were coded, so as to evaluate the studies synthesized. Many of these studies were identified during the literature review phase of the thesis. If another researcher tried to implement a similar method as the one being implemented in this study, similar results and conclusions shall be reached. Using the tools and steps suggested by Cooper (2010, p. 84), a coding sheet was developed to gather information about each study collected in the synthesis. With the aid of this coding sheet, a preliminary evaluation of the quality and relevance of each study was performed to determine if the research study should be included or excluded from the synthesis. With a relatively small number of studies involved in this research synthesis, the aspects of each study to code and how the quality and relevance of each study were assessed was relatively simple. The following table is an example of the details about each study that was considered before deciding to include it in the synthesis and how information was gathered:

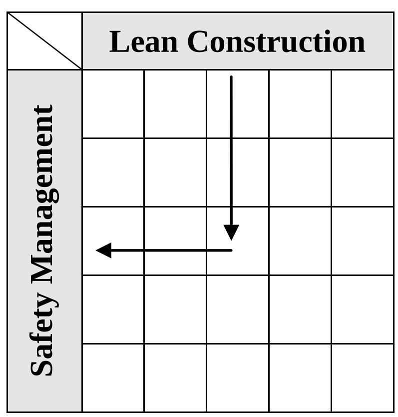
Table III.1 - Coding Sheet Example

Research Synthesis Coding Sheet	
Report (author and year):	Saurin et al. (2004b)
Type of research report:	Professional Conference Research Presentation
Details:	
Research problem or hypothesis:	To adopt some of the main requirements for effective production planning and control for safety management.
Method for studying the research problem or hypothesis:	Action research
Main conclusions or results:	The results indicated that several concepts and methods successfully used in the Last Planner System could be easily extended to safety management.
Quality:	
Is the research method suitable for studying the research question or hypothesis?	The research method was suitable because of the need to devise and test the SPC model in a real construction environment.
Is there a problem in implementing the research in this study? If yes, how?	No
Relevance:	
Is the information or research problem relevant to the synthesis question? If yes, how?	Yes, because the discussion of integrating safety with production planning into a single management model in this study was done taking into account several concepts of lean construction such as LPS.

The information of each report can easily be referenced in the bibliography for the complete details. The type of research studies collected were mainly from two research venues, they were either from a professional conference research presentation paper or a peer-reviewed journal publication, in which the latter passes through a much stricter peer review than the former (Cooper 2010). The most important details about each study collected were the problem being addressed, how it was addressed, and what conclusions or results were drawn from it. This provided enough information to determine whether or not the report had similar or related information that could be used to determine how lean construction affects safety performance. Last, assessing the quality and relevance of the report were vital to ensure that the research synthesis used the appropriate data.

Previous studies that have considered the interaction between lean construction and safety were the main type of data collection. The advantages of using this type was data was that it enabled the possibility of obtaining not just the results from similar studies, but also the language and words of the authors of these studies, which represents data that has given a thoughtful input and a great deal of attention to compile. The data was thoroughly collected in an iterative process to develop a fine framework, more specifically an interaction matrix that encompasses across all of the possible interactions between the lean construction methods identified to analyze and the most common safety management practices. This helped in determining where current research efforts focus, where they are needed, and also to seek conclusions from the interactions identified.

Table III.2 - Interaction Matrix Sample



3.3.2 Data Analysis

The approach taken to develop and analyze the proposed interaction matrix adapted a closely related analysis approach known as a morphological analysis. This approach was inspired by a similar study to the one being undertaken (Martinez et al. 2009), which in the same way integrated the principles of sustainable construction (green building) and lean construction to develop a "Green-Lean" conceptual integration. Similarly, another study (Sacks et al. 2010) has analyzed the interaction between lean construction and Building Information Modeling (BIM), from which its analysis approach was also adapted with the mentioned morphological approach.

Morphological analysis was developed by Zwicky (1969) based on the analysis of the *morphology* of the structural interrelations studied by other fields of science such as anatomy, geology, botany and biology. The term morphology comes from classical Greek (*morphe*) and it means *shape* or *form*, therefore, it refers to the study of the shape and arrangement of parts of an object (i.e. concepts or system of ideas) and how these parts "conform" to create a whole (Ritchey 2002). Zwicky proposed to generalize and systematize the concept of morphologic investigation to other fields of science, "to study the more abstract structural interrelations among phenomena, *concepts* and *ideas*, whatever their character might be" (Zwicky 1969, p. 34). This method helps to identify and investigate the total set of possible relationships or configurations contained in a given complex problem (Ritchey 1998). It is a general method for structuring and analyzing complex problem fields which are 1) inherently non-quantifiable; 2) contain genuine uncertainties; 3) cannot be causally modeled or simulated in a meaningful way; and 4) require a judgmental approach (Ritchey 2002). In summary, the morphological analysis approach helped to establish the total set of possible *interactions* in the interaction matrix which could then be systematically analyzed.

3.3.3 Research Validation

As a research validation strategy, structured interviews with an expert panel were conducted. These interviews were useful in providing the necessary feedback for the results of the analysis of the interaction matrix. By showing the results to the experts, they were asked whether the approach and results made sense and if the important concepts in the domain made sense. Stratification of the population before selecting the expert panel was applied, given that a significant amount of knowledge and experience with the proposed topic was required in order to provide significant feedback and judgment of the findings. In order to conduct the interviews, the selected expert panel members were certified as “experts” by qualifying each member as such. The objective of the validation was to obtain an unbiased representative sample by selecting the members strategically. For this reason, information about each panelist was collected to objectively confirm the status of each member as an expert either in the field of construction safety or as a lean construction practitioner, based on their academic and professional experience. The details of the validation process are further expanded upon on Chapter 5.

3.4 Validation Results, Claimed Contributions and Predicated Impact

The validation results serve as a basis to determine the reliability and accuracy of the results from the analysis. Also, they are helpful in identifying other potential research areas that might have gone unnoticed. As part of the claimed contributions, the tested and validated results extend prior work and contribute new concepts to theory. These concepts help to further understand the potential synergy between lean construction and safety, which may be helpful in integrating future production and safety management models, which could improve safety management efforts.

3.5 Research Process Summary

In the early stages of the investigation, the research problem was first formulated. Once the research problem was identified, the specific thesis objective and research question were developed based on intuition. An in-depth literature review was then carried out to provide a point of departure for the research work and to show how it intends to contribute to the existing body of knowledge. The most adequate research method approach was then identified to design the structure of the research process (CIFE Horseshoe) and establish the main research tasks needed to complete the proposed objective and answer the research question. The three main research tasks are: the data collection process, the data analysis process, and the research validation.

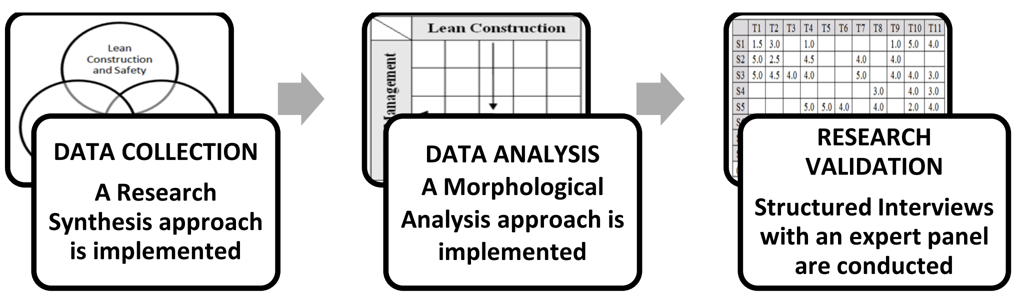


Figure III.2 - Main Research Tasks

IV. DATA COLLECTION

The data for this research were previous studies that have addressed similar or related topics to the interaction between lean construction and safety management. In order to analyze this relationship it was important to define the variables that were to be collected. A research synthesis may involve several threats to validity unless proper procedures are taken to minimize bias. Therefore, in order to address these issues, the measures discussed in the research methodology as part of the data collection process were implemented. Having established an appropriate data collection process, the development of an interaction matrix in which the main variables were evaluated and analyzed was then developed. This chapter discusses the data collection process implemented and the development of the main interaction matrix analyzed, which becomes the focal point of analysis in this thesis.

4.1 Data Collection Process

The main variables collected and analyzed were the aspects of lean construction and the most common safety management practices. As stated in the introduction, the hypothesis specified the potential link between these variables based on previous observations. Both variables have conceptual definitions that were extensively covered in the literature review. In providing operational definitions, the most prominent principles and tools of lean construction were thoroughly synthesized from previous studies and seminal work. The most common safety management practices were also synthesized from past studies and seminal work that have addressed the issue. The distinction between the different principles and tools of lean construction, and the safety management practices will be further discussed in following sections.

4.2 Interaction Matrix

Lean construction reduces uncertainty and increases predictability resulting in reliable work, as covered in the literature review. This reduces the potential for safety hazards, which may improve safety performance. As described in the literature review, companies make decisions regarding the impact of their safety management efforts based on their safety performance. Therefore, the tools identified have been evaluated to see how their implementation affects the most common and effective safety management practices. This allowed making inferences about how this results in safer environments. This next section summarizes and explains how the variables have been collected, integrated, and synthesized to develop an interaction matrix in which the interface between lean construction and safety management can be analyzed. The aim of such interaction matrix is to systematically analyze the interface between lean construction and safety management.

4.2.1 Lean Construction Principles

The principles of lean construction have been synthesized, as part of the literature review, in order to comprehend how lean construction has evolved. The Transformation-Flow-Value (TFV) understanding of construction suggested by Koskela (2000), introduced in the literature review, has been referred to as the foundational concept on which lean construction has evolved. One of the central elements of lean construction is the reinterpretation of the form in which production in construction is understood. Production in the construction industry is reinterpreted from the conventional production model to the TFV model when implementing lean. Given this, the principles of lean construction have been synthesized from seminal reports (Koskela 1992;

2000). Appendix A shows a list of the main principles suggested by Koskela (1992) along with a detailed description of what each principle implies.

4.2.2 Lean Construction Tools

There are several tools that have evolved since the beginning of the application of lean production in the construction industry. These tools continue to evolve as more knowledge and experience develops. The way in which the main tools of lean construction have been identified is by trying to develop a list of the most prominent and exhaustive tools that are being implemented in today's construction industry and that might also impact safety management practices. A total of 11 tools were analyzed at first, which are made up of the elements of the last planner system and lean production tools originally implemented by the Toyota production system.

4.2.2.1 Elements of the Last Planner

The last planner system of production control (LPS) is being implemented by several companies worldwide. Given the success of implementing LPS as a lean construction tool and the means to realize many of the principles defined in the last section, many studies regarding the impact of lean construction on safety have focused exclusively on LPS (Thomassen et al. 2003, Saurin et al. 2004, Leino et al. 2010).

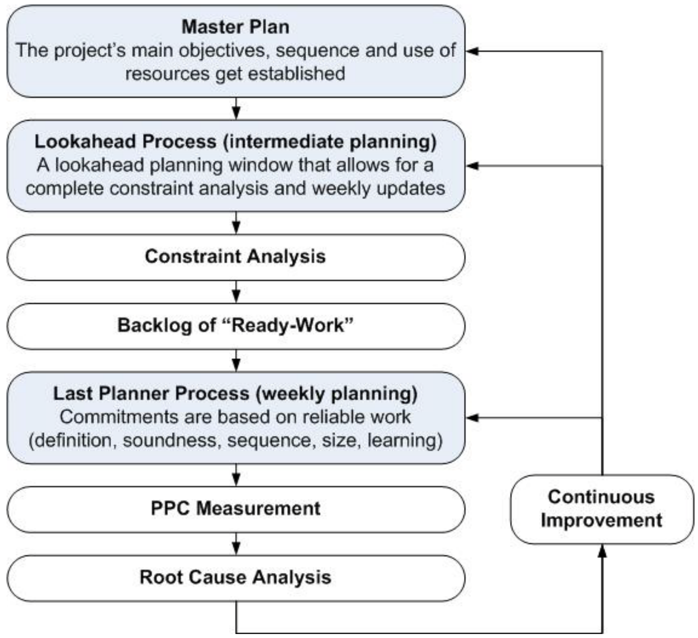


Figure IV.1 - Implementation Sequence of LPS Elements (adapted from Leal 2010)

In Appendix B, a concise summary and description of the most important elements of LPS has been synthesized from Ballard's seminal work (Ballard 2000) and in collaboration with GEPUC through the adaptation of its applied LPS model (GEPUC 2010). The lookahead process and the last planner process, as it has been described in detail in the literature review, can be thought of as the two overarching processes for two different planning levels. The constraint analysis, backlogs of ready-work, PPC measurements and the root cause analysis can be thought of as the most important tools within these overarching processes. For the purpose of the analysis, and to explicitly define each specific element within the interaction field, all of these six different elements have been included.

4.2.2.2 Lean Production Tools

The roots of lean construction evolved from the concepts of the Toyota production system, the system that eventually became known as the lean production system. Lean production consists of the main methods, or tools, that gave birth to this new production theory. Appendix C shows a list of the most common lean production tools that have been identified as the main concepts and techniques that have given birth to this new production system. Many of the most common lean production tools, such as 5S, poke-yoke, and Deming's PDCA cycle among others, have been initially taken to be associated tools that may implement many of the main lean production tools that have been identified. For example, using 5S, standardization, continuous improvement, visual management and autonomation are all implemented.

4.2.3 Tools versus Principles

At this point, it is important to distinguish between the principles and the tools of lean construction. This distinction also complements the analysis of the *interaction* between lean construction tools and safety management practices. Given the definition of a principle, a lean construction *principle* is the fundamental proposition that serves as the foundation for the lean chain of reasoning; in other words, it is the end in itself. A lean construction *tool* on the other hand, is the device used to accomplish that particular principle, or more specifically, the means to this end (Merriam-Webster 2010). Given this, an integration matrix was then developed to provide a basis for the understanding of the relationship between lean construction principles and tools, in which these relations can be explored.

Table IV.1 - Integration Matrix of Lean Construction Principles and Tools

Tools \ Principles		Reduce Waste	Reduce Cycle Time	Reduce Variability	Simplify	Increase Flexibility	Increase Transparency	Focus Control	Build CI	Balance Improvements	Benchmarking	Meet Customer Reqt's
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**P11**
Lookahead Process	**T1**											
Constraint Analysis	**T2**											
Backlog of Ready-Work	**T3**											
Last Planner Process	**T4**											
PPC Measurement	**T5**											
Root Cause Analysis	**T6**											
Just-In-Time	**T7**											
Autonomation	**T8**											
Production Leveling	**T9**											
Standardization	**T10**											
Continuous Improvement	**T11**											

This two-dimensional matrix integrating lean construction principles and tools would require another in-depth analysis of each relation identified, however, the focus of this thesis lies on the interaction matrix to be presented next. The purpose of developing such a matrix was to visually clarify and imply how if certain tools impact safety management practices, then its associated principles are also related. If certain principles are constantly being related to specific tools, this integration matrix will help to further expand on the issue. Overall, this might be a consideration for future research. Similarly, another interaction matrix between lean construction principles and safety management practices could be developed. However, the objective of this thesis is to provide the evidence for the potential synergy between lean construction tools, the means, and safety management, as it is more applicable to developing and/or integrating future production and safety management models.

4.2.4 Safety Management Practices

A summary of the most common and effective safety management practices, which are the strategies being implemented in the industry nowadays, has been compiled from several studies (CII 1993, Hinze 2002, Razuri et al. 2007, Hallowell and Hinze (In Press)). There are eight main practices that have been identified for the analysis. Each practice might contain a set of similar prevention strategies. The most prevalent safety management practices that have been identified are listed with a description of each specific practice in Appendix D, in which the other similar prevention strategies associated with each practice are also listed.

4.2.5 The Morphological Problem

A similar study to the one being undertaken here (Martinez et al. 2009) integrated the principles of sustainable construction (green building) and lean construction using the morphological analysis approach discussed in the research methodology (Zwicky 1969, Ritchey 1998; 2002). Similarly, the complete analysis of this complex problem field can be thought of as a three-dimensional matrix, or a “morphological box,” consisting of three variables; the safety management practices (S-axis), the lean construction tools (T-axis) and the lean construction principles (P-axis).

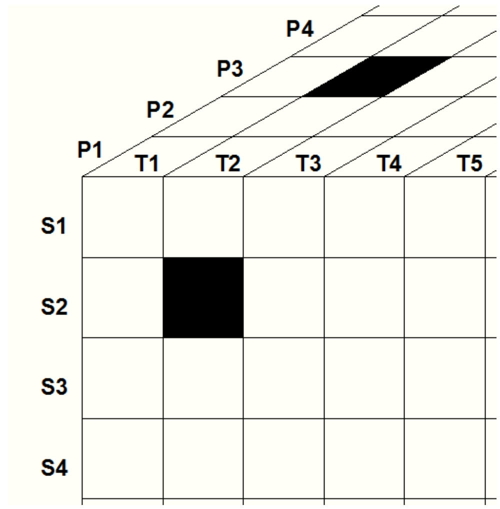


Figure IV.2 - The STP "Morphological Box"

Taking into account how the tools are the means for the realization of the principles of lean construction, and how together they can affect the safety management practices, this three-dimensional matrix consists of 968 cells (11x11x8) in which each cell contains 3 conditions; for example, Staffing for Safety is affected by the Lookahead Process because it Reduces Variability (S2-T2-P3). In Zwicky terms, this morphological field contains all of the possible relationships involved, given the defined parameters thus far. However, for the purpose of this thesis, the discussion of the interaction matrix between the lean construction tools and the safety management practices is the extent of the analysis. The interaction matrix analyzed in this study, evaluates the interaction between lean construction and safety management using the tangible characteristics of lean so as to make the findings applicable. In other words, it focuses on looking at the means to achieve lean, and how this interacts with safety management practices.

Table IV.2 - Interaction Matrix

Lean Construction Tools / Safety Management Practices		Last Planner System						Lean Production Tools				
		Lookahead Process	Constraint Analysis	Backlog of Ready-Work	Last Planner Process	PPC Measurement	Root Cause Analysis	JIT	Autonomation	Production Leveling	Standardization	Continuous Improvement
		T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**T11**
Management Commitment	**S1**											
Staffing for Safety	**S2**											
Planning for Safety	**S3**											
Safety Education	**S4**											
Worker Involvement	**S5**											
Evaluation and Recognition	**S6**											
Subcontractor Management	**S7**											
Accident Investigation	**S8**											

4.3 Chapter Summary

The data collection process discussed in this chapter establishes the main interaction matrix to analyze in this study and provides the necessary background and information on its development. The synthesis of the lean construction principles, tools, and the safety management practices that are included in this interaction matrix is also discussed in detail. All of the synthesized material discussed in this chapter can be found in appendices A through E.

V. DATA ANALYSIS AND RESEARCH VALIDATION

Implementing the data collection process established in the last chapter, and retrieving the appropriate studies for the research synthesis, the main interaction matrix was then analyzed. Each interaction in this matrix was analyzed adapting the morphological analysis approach. It is important to emphasize once again the fact that this study analyzes the impact of lean construction on safety management, and not the impact of safety management on lean construction. Unless significant impacts of safety on lean were identified, then such inferences were included in the explanations of the specific interactions identified (Appendix F). This chapter discusses the data analysis process implemented followed by the analysis of the interaction matrix. Following the analysis, a validation of the interaction matrix and the interactions identified in the analysis was also conducted.

5.1 Data Analysis Process

In order to analyze the interface between lean construction and safety management, an argumentation to evaluate the interactions identified was first developed. Martinez et al. (2009) developed a "logical argumentation" to evaluate the interaction of the principles of sustainable construction and those of lean construction to check for consistency among the relations identified. Similarly, such a logical argumentation was adapted to rate the degree of dependency, meaning how direct each relation is, of the interactions in which evidence was found. As articulated in the literature review, it is suggested that the relationship between the implementation of lean practices and safety management practices is a direct relationship. Given this description between the variables analyzed, the following logical argumentation has been adapted to analyze the interactions:

Direct Relation (D): an argument that shows a *near or immediate dependency* of a safety management practice with respect to a lean construction tool. It can also be defined as the greater degree of incidence that the implementation of a lean construction tool has on a safety management practice.

Indirect Relation (I): an argument that shows a *distant or future dependency* of a safety management practice with respect to a lean construction tool. It can also be defined as the lesser degree of incidence that the implementation of a lean construction tool has on a safety management practice.

No Evidence ( ): an argument that shows that *no relation* exists or it has not been visualized yet (it lacks the evidence).

The hypothesis suggests that lean construction tools and safety management practices have a positive correlational relationship, thus a direct relation, therefore, such an argumentation and analysis aims at determining how direct the relationships are. Each potential interaction in the interaction matrix (see Table 5.1) was given a logical argument, either *direct relation* (D) or *indirect relation* (I), if evidence from the research synthesis was found on the interaction. With the available evidence, the interaction was then evaluated to determine whether a direct or indirect relation was the most appropriate based on the evidence and applying the reasoning of the logical arguments discussed. If the interaction lacks the evidence, then a *no evidence* (blank) argument was assigned.

Furthermore, with the validation of the interactions and the input of the participants, these interactions were checked. The extent of this study was rather to identify the most important and obvious interactions, provide the supporting evidence from the research synthesis, and identify the most significant interactions in the interaction matrix developed. The interaction matrix initially identified a total set of 88 possible interactions. A similar matrix in Appendix E displays an index number correlated with the interactions found in the evidence, to identify the explanation of each interaction along with its supporting evidence, in Appendix F.

5.1.1 Interaction Results

Table V.1 - Interaction Matrix

Lean Construction Tools / **Safety Management Practices**		**Last Planner System**						**Lean Production Tools**				
		Lookahead Process	Constraint Analysis	Backlog of Ready-Work	Last Planner Process	PPC Measurement	Root Cause Analysis	JIT	Autonomation	Production Leveling	Standardization	Continuous Improvement
		T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**T11**
Management Commitment	**S1**	I	I		I					I	D	D
Staffing for Safety	**S2**	D	D		D			D		D		
Planning for Safety	**S3**	D	D	D	D			D		D	D	I
Safety Education	**S4**								I		D	I
Worker Involvement	**S5**				D	D	I		D		I	I
Evaluation and Recognition	**S6**					I	I					I
Subcontractor Management	**S7**	D	D		D						I	
Accident Investigation	**S8**						D				D	

* **(D)** *Direct Relation*, **(I)** *Indirect Relation*, **( )** *No Evidence*

With the analysis process established and implementing the logical argumentations just discussed, the interactions were then analyzed. The following section discusses each tool identified in order (T1-T11) and lists the most salient interactions identified per tool with the safety management practices. Refer to the interaction matrix provided to guide the discussion of the analysis. For the details on the specific sources of evidence, refer to appendices F and G.

5.1.2 Last Planner System (T1-T6)

There are several similarities and distinctions within the interactions that were identified between the elements of the last planner system and the safety management practices. Planning and Staffing for Safety, Subcontractor Management, and Worker Involvement are said to be the most related to the last planner, whereas the Lookahead Process, Constraint Analysis, and the Last Planner Process (weekly planning) have the most impact on safety management practices.

5.1.2.1 Lookahead Process - Intermediate Planning (T1)

The lookahead process defines what can be done after analyzing what the master plan has determined that needs to (or should) be done within a given time period, typically four weeks (i.e. the four-week lookahead). Saurin et al. (2004b) explains how project-specific safety objectives, plans and policies can be incorporated in the lookahead planning process, directly incorporating planning for safety (S3). Several of the strategies implemented by LPS can be easily extended to safety planning, thus directly affecting the effectiveness of safety programs. One of the main goals of the lookahead process is to shape the work flow sequence and rate. In terms of pre-project planning for safety, this allows to establish more reliable project-specific safety resources for a given time period during a project and thus staff for safety (S2) accordingly. The participation of upper management (S1) and subcontractor representatives (S7) in the lookahead meetings can also be easily accomplished. Management can indirectly show their commitment to safety planning by participating in these meetings and the subcontractors' participation in the planning process can also be a direct benefit to their safety plans.

5.1.2.2 Constraint Analysis (T2)

Constraint analyses determine what must be done for a given work assignment before execution. By freeing any constraints identified, this allows to execute the assigned task. A constraint analysis can systematically include safety constraints, such as the job hazard analyses, directly incorporating pre-task planning for safety (S2) as part of the constraint analysis process. By performing safety constraint analyses similarly as part of the production planning, risk can also be predicted better, which in turn allows safety management to allocate, or staff (S3), safety resources accordingly. Subcontractors (S7) can also benefit by participating in the constraint analysis in order to prevent hazards and accidents within their crew. The constraint analysis is typically part of the lookahead process, which explains the similarities to the lookahead relations. However, for the purpose of the analysis LPS has basically been presented at a finer granularity to be able to acquire more detailed information on the interaction with safety management.

5.1.2.3 Backlog of Ready-work (T3)

A workable backlog consists on having a list of the tasks that have gone through the constraint analysis and are ready to be performed with the assurance that everything is indeed workable. This idea can be easily extended to safety planning (S3) as well. A checklist of soundness requirements that an assignment must go through is usually what determines whether the assignment can be considered workable or not. As explained in the literature review, there are seven preconditions needed for a construction task to be successfully carried out (*information*, *materials*, *manpower*, *equipment*, *space*, *connecting works*, and *external conditions*) and safety could be easily be included as part of these preconditions.

5.1.2.4 Last Planner Process - Weekly Planning (T4)

At this planning level, the actual workers, such as the foreman and other people working on site (the last planners), play a significant role in planning. Similarly to the lookahead level of planning, upper management (S1) and subcontractors (S7) could participate in these meetings. Worker involvement (S5) is directly incorporated at this level to determine what CAN actually be done (what WILL be done) in terms of the previously defined tasks with the workers' perception of the work reliability. This is often referred to as a bottom-up perceptual approach which can also be extended to safety by allowing the workers to determine whether a task is reliable in terms of safety, directly incorporating planning for safety (S2), which can also be extended to staffing the adequate safety personnel (S2). This also allows identifying potential hazards that might have otherwise gone undetected by using the worker's perception of safe work.

5.1.2.5 PPC Measurement (T5)

The Percent Plan Complete (PPC) measurement consists on systematically comparing the plans committed to the plans executed in a project. This measures the extent to which the front line supervisor's commitment (WILL) was realized and becomes the reliability performance indicator, thus incorporating the workers (S5). The safety planning and control (SPC) model proposed by Saurin et al. (2004b), which integrates safety management to the production planning and control process (Figure 2.11), extends this concept to safety performance measurement in order to evaluate safety effectiveness. Using a similar measurement for safety the percentage of safe work packages (PSW) carried out is measured, which can directly evaluate worker's safety performance (S6). A typical evaluation and recognition strategy for safety management is an incentive program, which encourages workers to perform safe work behavior. This PSW measurement could also be used as part of the evaluation for worker's performance, in addition to using the PPC measurements as well.

5.1.2.6 Root Cause Analysis (T6)

Following the PPC measurement and having determined the nonconformance of assignments, the root causes for nonconformance with the plans are tracked and analyzed in order to develop future plans and prevent them from happening in the future, similarly to accident investigations (S8). Similarly, investigating root causes for accidents or near misses, which may or may not be the root causes for nonconformance with the assignments, safety management may proactively devise effective preventive measures. As Saurin et al. (2006) suggests, when root cause analyses are carried out, similarly causes for successful performance and safe work behavior (S6), rather than just causes for non-conformance might also influence workers perspective on safety by recognizing "causes for conformance." Taking into account the workers feedback (S5) on root causes for accidents or near misses are valuable resources to evaluate hazards and devise the preventive measures, which may be disseminated to the workers to develop successful prevention strategies.

5.1.3 Lean Production Tools (T7-T11)

It is evident that the five lean production tools identified can interact with many of the safety management practices given their inherent characteristics. Even though specific evidence for many of these interactions does not currently exist, through a deductive and judgmental reasoning approach based upon the literature, many of the interactions analyzed offer an opportunity to further explore the interactions. Each tool has a relatively larger impact on certain safety management practices than others. Standardization and Continuous Improvement are the two tools that impact the most safety management practices, based on the evidence.

5.1.3.1 Just-In-Time (T7)

The concept of delivering the right items, at the right time, in the right amount, can be extended for safety management purposes in the same manner. The delivery of the right safety resources, such as appropriate safety personnel and personal protective equipment, at the right time, when risk levels are higher for example, and in the right amount, can directly impact safety planning and staffing for safety (S2, S3). As Rozenfeld et al. 2010 suggests, tools implementing the JIT concept, such as CHASTE (Rozenfeld et al. 2009), helps to forecast safety risks and therefore management can allocate safety resources when and where they are needed, leveling safety risk. Instead of allocating safety management efforts with the traditional "push" approach, a more effective and less wasteful "pull" approach implementing JIT can significantly impact planning and staffing for safety.

5.1.3.2 Autonomation (T8)

Autonomation grants workers the autonomy to stop production when something unusual is detected, which may disrupt the production process. In terms of production management, this refers specifically to detecting a defective product and stopping the line before allowing the defect to pass into the next station in the production line. Autonomation in itself applies the same concept that worker involvement (S5) strategies for safety implement, that is, the use of the worker's perception and input for evaluating the aspects of safety programs. Therefore, autonomation can directly be extended to worker involvement in such a way that workers can stop production whenever they feel in danger. Proper safety training (S4) for workers to recognize such hazards is also essential for autonomation to impact safety management. As Saurin et al. (2006) suggests, the appropriate training for workers to make the right judgment when they feel in danger would help in maintaining a desired level of risk or risk averseness.

5.1.3.3 Production Leveling (T9)

Production leveling in construction refers to matching the available resources (material, manpower) to the production demands on a jobsite. By leveling production, variation in production is reduced consequently controlling any type of waste associated with inconsistencies in production scheduling (mura). These inconsistencies typically arise from fluctuations in production scheduling causing unevenness and overburdening of workers (muri), or machines, and therefore resulting in hazardous situations. Through proper production leveling the appropriate resources can be matched to production demands without exceeding the capabilities of the workers. This reduces the chances of construction accidents while at the same time increasing productivity (Mitropoulos et al. 2007). This impacts planning and staffing for safety strategies (S2, S3), and also shows management’s commitment (S1) to try and improve safety performance while at the same time reducing waste from a lean perspective.

5.1.3.4 Standardization (T10)

Standardization implies that all work be highly specified in terms of timing, content, sequence and outcome, and thus standardized procedures often include safety hazards in their content. This also implies that procedures may reduce the degrees of freedom of workers and define a space of safe performance where accidents will not happen. Standardization can directly impact several safety management practices. Starting with management commitment (S1), the fact that upper level management standardizes safety related procedures communicates the importance of working safely to all workers and improves project safety culture. Similarly, procedures can emphasize the importance of proper safety training (S4), the incorporation of safety plans (S3), expected safety outcomes for the workers (S5), and subcontractor procurement based on safety records (S7). Another very important aspect of safety management that can be standardized is accident investigation (S8), which may also include things such as near misses.

5.1.3.5 Continuous Improvement (T11)

Continuous improvement refers to the process of making incremental improvements, no matter how small, and achieving the lean goal of eliminating all waste and increasing value. Applying such strategy for many of the safety management practices with the goal of achieving better results every time can significantly improve the effectiveness of many of these safety efforts. It can be reasoned that in order for continuous improvement to be implemented within a company in the first place, it must be expressed from upper management (S1), hence the relation between continuous improvement and upper management commitment. Associated tools that implement continuous improvement, in addition to many of the other lean production tools, such as 5S and visual management, foster a culture of continual improvement, which is essential for the successful implementation of lean. Visual management is one of the most common continuous improvement strategies. It can be extended for safety purposes using things such as safety signs and boards displaying current accident rates allowing all workers to identify issues, thus providing an opportunity to be trained (S4), the boundaries for safe performance and compare the expected safety performance. 5S, which strongly involves all workers (S5) creates and maintains a clean, orderly, and safe work environment. As Nahmens and Ikuma (2009) discuss, the conscious effort towards continuous improvement, evaluating and recognizing improvements (S6), will drive the improvement of safety performance and planning for safety (S3) without the explicit integration of specific safety programs.

5.1.4 Empirical Evidence

From the evidence found, several of these studies also reported empirical evidence on the impact that some of the lean practices had on safety performance. As reiterated in the literature review, this strongly supports the hypothesis of how the implementation of lean practices results in safer environments, and thus improves safety performance. For the purpose of this study, however, the empirical evidence cannot support specific interactions for which evidence has been found to determine the cause of that interaction. The following table summarizes the studies from which the evidence supporting the interactions identified in the research synthesis has been collected. For each study, the number of interactions discussed is listed and whether or not empirical data was provided, related to safety performance.

Table V.2 - Summary of Studies with Supporting Interaction Evidence

Study	# of Interactions Supported	Empirical Data Provided (Y/N)
Thomassen et al. 2003	2	Yes
Saurin et al. 2004b	15	Yes
Sacks et al. 2005	5	No
Mitropoulos et al. 2005	2	No
Saurin et al. 2006	12	No
EPA 2007	1	No
Mitropoulos et al. 2007	1	No
Hallowell et al. 2009	1	No
Nahmens & Ikuma 2009	2	Yes
Rozenfeld et al. 2010	3	No
Leino et al. 2010	11	Yes

Of those studies on which empirical data was provided, three of the studies focused exclusively on the implementation of the last planner system. Thomassen et al. (2003) reported on the implementation of LPS by MT Højgaard, a large Danish contractor, and reported that projects implementing LPS resulted on a 45% lower incident rate than those projects that did not implement it. The LPS model implemented in Thomassen et al. (2003) includes all of the six main elements that were analyzed in the interaction matrix (T1-T6). Although no particular element in this study is said to be the main cause of improved safety performance, it suggests that LPS as a whole allows workers to have a more direct input on planning, which may have an impact on the building process, consequently improving the working environment.

Saurin et al (2004b) integrated safety management into a production planning and control system similar to LPS, in which the six elements (T1-T6) were used. Evidence for several of the interactions identified are from this study, the details are provided in Appendix F. Empirical data was related to the use of the percentage of safe work (PSW) complete measurement, something similar to the PPC measurement, which is used to measure the reliability of safety planning. It was indicated that after 50% of the project completion, both safety and production planning (PSW and PPC) increased showing that planning became more reliable and its variability was reduced. This suggests the extension of several elements of LPS, such as PPC measurement, that can greatly influence safety management and safety outcomes as well.

A more recent study on the impact that LPS has had on a company's safety performance is Leino et al. (2010). This study reports the impact that the implementation of LPS has had on Skanska, a Finnish construction company, over the past 5 years (2005–2009) in terms of safety performance. The company reports having built upon the integrated model of safety and production management suggested by Saurin et al. (2004b), and applying the model on over 180 projects. The paper discusses the implementation of three specific elements of LPS analyzed in the interaction matrix (T1, T2, and T4). The integration of safety into those three elements, along with the improvement of other safety management tools, such as improving the company's safety culture, resulted on drastically reducing their accident rate from 57 to 9 lost time accidents per million work hours in five years. These three studies (Thomassen et al. 2003, Saurin et al 2004b, and Leino et al. 2010) show how the implementation of several, if not all, of the last planner system elements (T1-T6) identified and analyzed here result in improved safety performance and more reliable safety planning.

5.1.5 Summary of the Data Analysis

The analysis of the interaction matrix has identified several interactions. From the 88 possible interactions that were defined with the developed interaction matrix, evidence specifically related to 37 interactions (~ 42%) was identified. These interactions emphasize how extending lean construction efforts to some of the most common safety management practices that may already be in use would not require much effort. The data analysis was developed adapting the morphological analysis approach and developing a logical argumentation to evaluate each interaction found in the research synthesis. Although empirical evidence was found in some of the studies that were analyzed during the research synthesis, the evidence cannot support specific interactions for which evidence has been found to determine the cause of that interaction. However, quite significant logical arguments have been identified to explain the direct or indirect cause of how lean construction interacts with safety management.

5.2 Research Validation

Following the morphological analysis of the interaction matrix, the research was then validated with an expert panel in order to further elaborate on the main results found during the analysis. The aim of the validation interviews was to validate the results obtained from the research synthesis with the participants' experience and knowledge implementing lean construction and safety management, in order to formulate conclusions and determine the accuracy and reliability of the results. In addition to this, the input on the interactions with no existing evidence was also requested. The protocol for conducting the interview and the validation process are discussed in this section, along with a summary of the validation results.

5.2.1 Structured Interviews

To ensure the validity of this research, it is vital to check the validity and reliability of both the findings and the research approach, given that the qualitative validity of the findings is what assesses the accuracy of the findings. Through the implementation of structured interviews with an expert panel, a consensus on the evidence collected for the specific interactions identified in the research synthesis was the main objective. This helped to identify other interactions that lack the evidence and to determine how reliable the inferences from the research synthesis can be, based on the feedback received from the expert panel. Also, it is important to note that the newly found interactions from the interviews are the basis for future studies, rather than to be considered a contribution by of this study. The interviews were one-on-one interactive interviews via teleconference, if physical interviews were not possible. If the interview was in person, notes were taken as the participant provided the feedback, and if it was via teleconference, the teleconference was recorded and reviewed afterwards.

5.2.2 Expert Panel

Six validation interviews were conducted with a selected expert panel consisting of different academic and professional backgrounds, all of whom were familiar with all the main concepts that were required in order to provide adequate feedback. This assessment of familiarity with the topic was done through a brief discussion before conducting the interview on the background of the research. The purpose of this brief discussion on the validation and the interaction matrix to be validated was to verify that each participant felt comfortable and understood the procedures. After performing this assessment of familiarity with the topic, as a minimum requirement, however, they were required to have at least one advanced academic degree, such as a BS, and a minimum of 5 years of working experience in the field.

Table V.3 - Expert Panel Expertise

Experience	Interview:	1	2	3	4	5	6	Total
Academic Background:	BS	X	X	X	X	X	X	6
	MS				X	X	X	3
	PhD				X	X		2
Academia Experience:	Faculty Member (yrs.)				17	2	10	29
	Publications				12	4	40	56
	Conference Presentations		1	2	20	10		33
Professional Experience:	Upper Management (yrs.)	15	8	12	7		3	45
	Project Engineer (yrs.)	3	2	4	4	2	4	19
	Laborer (yrs.)	2					3	5
	Consulting (yrs.)					3	15	18
Professional Registrations:	P.E.	X					X	2
	LEED AP	X	X					2
	OSHA 30 hr.	X	X					2

The expert panel consisted of three participants in upper management positions within a construction firm, two participants from the academia, and one consultant. Participants were asked about their academic background by asking if they held any advanced degrees, such as a BS, MS, and PhD. They were asked about their experience in the academia, if applicable, by specifying their experience as a faculty member at an accredited university, and if they had any publications (conference papers, peer-reviewed, and/or book chapters). Their professional experience in the construction industry was also asked for, and also if they held any professional registrations or certifications, such as a Professional Engineer certification (PE) or LEED AP certification, among others. There has not been any sort of lean construction certification yet (leanconstructioncertification.com 2010), which would have been helpful in determining the extent of each participant's knowledge and credentials regarding their ability to practice lean construction. In terms of safety, however, they were asked if they had a Certified Safety Professional (CSP) certificate or had had any OSHA training courses.

5.2.3 Validation Process

The validation of the research was a means to further validate and determine the accuracy of the results found during the research synthesis, primarily in regards to the interactions with supporting evidence. With the logical argumentation established for the analysis of the interaction matrix, a unidimensional scaling method was developed to measure, based on the expert panel's judgment, just how direct of a relation the interactions identified between the lean construction tools and safety management practices were. A unidimensional scaling method was determined to be most appropriate given that measuring how direct a relation is, is one-dimensional in nature. In other words, the input from the expert panel helped to determine how accurate the arguments given to the interactions from the research synthesis were. A 1 to 5 rating scale was implemented to allow each participant in the expert panel to judge how favorable each interaction was with respect to the following criteria:

5 – Direct: it is a *near or immediate dependency* of the safety management practice with respect to the lean construction tool.

4 – Somewhat Direct

3 – Neutral: a *dependency is present*, yet it could be a near or distant dependency.

2 – Somewhat Indirect

1 – Indirect: it is a *distant or future dependency* of the safety management practice with respect the lean construction tool.

In this manner, the participants evaluated the interactions identified with supporting evidence from the research synthesis. The option of leaving the cell blank, assigning it a 0 (null), was also an option if they in fact could not visualize a relation at all. As the interaction matrix was being completed, they were also asked to provide feedback as to why they thought each interaction had the scale that they had given it. If a particular rating contradicted the argument assigned to an interaction from the evidence or deviated from being within the assigned relation, they were asked to further elaborate on their rating. In order to determine when their ratings deviated or contradicted the arguments assigned in the research synthesis, the following rule was implemented: for a direct relation a rating should be > 3, and for an indirect relation, a rating should be < 3. Once they had completed the ratings for the interactions with evidence, they were asked to rate and provide feedback for the interactions without evidence.

5.2.4 Validation Results

From the ratings that were given by the expert panel during the validation interviews, Table 5.4 and Table 5.5 display the main results. Only the ratings for the interactions with evidence have been included. Given the small number of interviews conducted, to make use of the data collected from the validation, the median of the ratings has been taken to represent the results instead of the mean, because the median is less likely to be influenced by outliers or biased opinions. For the same reason, the absolute deviation has been used to represent a measure of consensus because it measures the variability in response to the median rather than the mean (Hallowell and Gambatese 2010). The following section will discuss the input received from the expert panel in regards to the interactions with the evidence. In addition to the interactions with evidence that were rated, several other interactions with no evidence have also been discussed following the discussion of the interactions with the evidence. For the complete results of the validation, see Appendix G.

Table V.4 - Median of the Interaction Ratings from the Validation Results

	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**T11**
S1	1.5	3.0		1.0					1.0	5.0	4.0
S2	5.0	2.5		4.5			4.0		4.0		
S3	5.0	4.5	4.0	4.0			5.0		4.0	4.0	3.0
S4								3.0		4.0	3.0
S5				5.0	5.0	4.0		4.0		2.0	4.0
S6					4.0	4.0					3.0
S7	4.0	3.5		4.0						1.0	
S8						5.0				4.0	
(5) Direct - (3) Neutral - (1) Indirect											

Table V.5 - Absolute Deviation of the Interaction Ratings from the Validation Results

	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	T11
S1	1.0	0.4		1.0					1.0	0.7	0.6
S2	0.3	0.8		0.8			0.8		1.1		
S3	0.0	0.8	0.7	0.7			0.5		1.4	1.0	0.9
S4								0.6		0.5	0.9
S5				0.3	0.9	0.6		0.6		0.3	0.5
S6					1.4	1.1					0.7
S7	0.3	0.8		0.7						0.7	
S8						0.7				0.9	

The validation with the expert panel provided additional comments and information for the interactions with existing evidence. In general, it was easier for the participants to discuss the impact and interactions related to the elements of LPS than it was to discuss the lean production tools. The discussion of the validation results uses the same order implemented in the data analysis (T1-T11) in order to keep a consistent discussion format. The comments related to specific interactions are from the validation interviews and how the expert panel describes certain aspects of either the tools or practices.

5.2.4.1 Lookahead Process - Intermediate Planning (T1)

The ratings show that there was a somewhat indirect rating given to the interaction between the lookahead process and management commitment (S1), and the consensus on it lies below 3.0, which can still be considered in agreement with the evidence for indirect relations (< 3) according to the rule implemented. One thing to notice is the fact that the interaction of the lookahead process with safety staffing and planning (S2 and S3) both have a median of 5.0, and the absolute deviation of the interaction with safety planning (S3) in particular is 0. Although it is quite a small sample size, being such a strong consensus on that interaction (T1/S3) demonstrates its importance. During the discussion of this interaction, one of the participants commented how “planning for safety should be included in production planning, and safety should be integrated in the lookahead and the last planner too, because there is not really a differentiation from planning for safety with other aspects of the project.” Some of the comments on these particular interactions discussed how by planning to “lookahead” at the work that is coming, planning in itself benefits safety. For subcontractor management (S7), there is a somewhat direct relation, with a relatively strong consensus as well. Typically the subcontractors have a more direct involvement at this planning stage, which allows them to have a longer perspective on the work coming up and consequently, helps them plan better. One of the main goals of the lookahead planning process is to coordinate and plan with the subcontractors, so that they may plan better. It should be expected that this in turn would provide more predictable work for them.

5.2.4.2 Constraint Analysis (T2)

In theory, as one of the participants commented, LPS is meant to have as little management intervention as possible, and the results indicate that the interaction with management commitment (S1) is neutral. Typically, management would not go past the constraint analysis, but a posteriori, management might get involved, such as when decisions need to be made regarding the removal of constraints. In this case management may get more involved in the constraint removal. The results from the validation indicate that this interaction is neutral, meaning that it may be indirect or it may be direct depending on the circumstances. From the research synthesis, however, this interaction (T2/S1) was determined to be an indirect relation; the consensus for this is also more spread out (0.8), which indicates that it may lean to be somewhat indirect or direct. As one of the participants pointed out, the extent of the constraint analysis may also include the removal, which can be a reason for the decision on how direct of a relation this can be. Based on the ratings, for the interactions with planning and staffing for safety (S2, S3), the expert panel indicated that the relation with staffing for safety is somewhat indirect and the interaction with planning can be more direct. For the subcontractor management (S7), the ratings indicate that it is also somewhat of a direct relation.

5.2.4.3 Backlog of Ready-Work (T3)

The results indicate that the interaction of the backlog of ready work with safety planning (S3) is somewhat direct (4.0). The consensus on this particular interaction also lies within the direct region of the rating scale (> 3). The comments received for this interaction were related to including safety as part of the prerequisites needed to define a task as "ready work," or workable.

5.2.4.4 Last Planner Process - Weekly Planning (T4)

Some of the participants expressed that at this planning level, staffing and planning for safety (S2 and S3) could benefit the most. The reason for this was that "typically it is during these weekly meetings that they define how many people will be working for a specific task, where, and when, which is ideal for planning for safety." The ratings indicate that these interactions are somewhat direct, with a consensus lying mainly on the direct region of the rating scale. The predictability of tasks is typically increased by providing more details about the assigned tasks, which helps for planning and forecasting risks. Also, ideally this works well for staffing for safety because all the workers are aware of who is going where at all times. "The definition of the last planner process in itself describes what staffing for safety does," one of the participants commented. In regards to the involvement of the workers (S5), there is a strong consensus on the interaction of the last planner process with worker involvement being a direct relation. It is at this planning level that the workers input is really taken into account in regards to planning and this is where they can really speak up. "Prior to this planning level, worker involvement is not as strong," one of the participants commented. Therefore, this is where the workers' concerns for safety can come up. Another important interaction that was discussed was the interaction with subcontractor management (S7). Although, it is not a direct plan for the safety of the subcontractors at this planning level, it does have some influence on planning, which based on the results from the ratings, the expert panel indicates is somewhat of a direct relation. However, there was a common comment regarding this safety management practice

(S7), and it was that at this planning stage, the interaction with subcontractor management was not as direct as the relation of the lookahead process with subcontractor management is, where subcontractors might have more influence and participation than at this planning level.

5.2.4.5 PPC Measurement (T5)

Given the importance of the PPC in the last planner, and how is used to control and improve workflow performance, there was a variety of notable comments from the expert panel on how the PPC interacts with several of the safety management practices. For the interaction that was supported by evidence from the research synthesis, the relation of the worker involvement (S5) and PPC measurement was rated as a direct relation, whereas it was rated as an indirect in the research synthesis. For the evaluation and recognition of workers (S6), from the ratings, the relation is somewhat of a direct relation. From the evidence, however, the relation was given an indirect argument. As one of the participants commented, “if a team with a higher or improved PPC measurement is also improving its safety performance, then they may be recognized for such improvements too.”

5.2.4.6 Root Cause Analysis (T6)

The ratings indicate that the relation of the root cause analysis with worker involvement (S5) and evaluation and recognition (S6) is somewhat direct. During a root cause analysis, the feedback received from the workers is considered the most valuable resource. Also, if a crew or an individual is found to be doing something proactive in regards to safety, for example, behavior that prevents accidents, then they might be recognized during the root cause analysis. All of the participants basically felt that the root cause analysis is the same thing as an accident investigation (S8), which is no surprise that this is one of the few ratings with a strong 5.0, indicating that it is a direct relation. As one of the participants discusses, in theory, just about any of the safety management practices might be either directly or indirectly related because through the discussion of the root causes, any of the practices might come up as the root cause and what needs to be improved or directly addressed. In this same topic, the definition of the root cause itself can impact the benefit of doing the root causes in the first place because it depends on how they are being addressed, if it is the typical person approach for safety management, or the system approach. For example, there was a lack of safety personnel in a specific phase of the project which led to an accident, therefore planning and staffing for safety need to be improved. In a way, this is the most related element of LPS to continuous improvement; through the feedback received from the workers, detection of root causes, and the future plans developed to prevent or improve a specific process, the solving of such complications is the prior target of continuous improvement.

5.2.4.7 Just-In-Time (T7)

During the research synthesis, the evidence found focused exclusively on the implementation of JIT for the scheduling and forecasting of risk. However, during the validations with the expert panel, the application of JIT delivery focused more on the impact on constraints related to the actual space of the worksite. For example, not having JIT delivery might lead to congestion which impedes proper working conditions, thus optimal inventory buffering would reduce congestion. Given this, the expert panel commented on the interaction with planning for safety (S3) discussing how using a JIT logistic, the sequence of events can be better planned to predict and reduce possible constraints. The ratings indicate that this relation is somewhat direct. Furthermore, this also helps to keep the site clear of material and equipment to the greatest degree, making housekeeping better, which affects staffing for safety when making sure that these housekeeping items are taken care of.

5.2.4.8 Autonomation (T8)

The concept of autonomation, which basically relies on the idea of detecting “defects,” stopping the line, and seeing what the cause of the defect is, can be extended for safety issues. “If a hazard, accident or near miss is detected, the work would be stopped and they would need to find out why it happened, similar to a root cause analysis, in order to make preventive plans for the future.” This concept, in a similar manner to the root cause analysis, triggers learning opportunities (S4). The ratings indicate that the relation of autonomation with safety education is neutral. Worker involvement (S5), based on the ratings, is considered to be somewhat of a direct relation with autonomation.

5.2.4.9 Production Leveling (T9)

The results from ratings indicate that management commitment is indirectly related to production leveling, which is what was assigned during the research synthesis. The participants did see a somewhat more direct relation of production leveling with staffing and planning for safety (S2, S3), as the ratings indicate. The consensuses in regards to these interactions with production leveling have some of the highest spread. The spread on the consensus for the interaction of production leveling with safety planning is 1.4, which makes highly variable in comparison to the rest.

5.2.4.10 Standardization (T10)

The commitment of upper management (S1) was given a 5.0, indicating that it is a direct relation with standardization, based on the ratings. The panel commented that in order for standardization to be effective in the first place, the commitment from the upper management to standardize any safety related procedure must be present. In other words, standardization is directly related to management commitment because management has to get involved in order for this tool to be implemented successfully. The ratings indicate that standardization has somewhat of a direct relation with planning for safety (S3) and safety education (S4). The interaction with worker involvement (S5) and subcontractor management (S7) is indirect, from the ratings. And accident investigation (S8), is somewhat direct, based on the ratings, however, many of the participants indicated how strongly they felt that standardization can definitely have a strong impact on accident investigation. One of the common examples that they discussed, was standardizing the reporting of near misses, which can have a great impact not only on accident investigation directly, but on many other aspects of safety management.

5.2.4.11 Continuous Improvement (T11)

As the ratings indicate, the interactions for which evidence was provided in the research synthesis, all have a neutral or somewhat of a direct relation. Continuous improvement is the effort to make incremental improvements every time for any sort of practice, thus it could be related to any of the safety management practices. However, for the interactions with evidence related to continuous improvement specifically, the panel also made a similar comment to the one related to standardization in regards to management commitment (S1). Management has to commit and make continuous improvement a priority in order for it to be effective when implementing it. As for the rest of the interactions with continuous improvement (S3-S6), which are for the most part neutral, based on the ratings, the effect that continuous improvement has on each practice can be direct or indirect depending on how it's implemented and to what extent.

5.2.5 Additional Validation Findings

Besides the interactions with evidence, the expert panel was also asked, if and where they could, to rate and provide feedback for the interactions with no evidence. As a rule of thumb, interactions with no evidence with at least 3 or more ratings and comments from the expert panel have been included. Some of the details are discussed. Table 5.6 shows the measure of the results with 3 or more ratings that have no evidence. There are a total of 23 additional interactions that have been included in this table.

Table V.6 - Median of the Interaction Ratings for Other Interactions

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
S1						3.0		4.0			
S2			3.0								3.0
S3					2.5	3.5					
S4	3.0	1.0			1.0	4.0					
S5	5.0	1.0	3.0				2.0		2.0		
S6											
S7			3.0		3.0	4.0	1.0		2.0		3.0
S8		3.0									4.0
(5) Direct - (3) Neutral - (1) Indirect											

5.2.5.1 Management Commitment (S1)

As mentioned, for the interaction with management commitment for most of the last planner elements, in theory LPS is meant to have as little management intervention as possible. During root cause analyses, however, when important issues are brought up, management can intervene and either provide the necessary tools to address the issues, which may be related to safety, or simply approve of necessary actions to address the root causes. This is where there is strong evidence of the management commitment to safety too because simply emphasizing the importance of doing such things to address the root causes for non-conformance with the plans shows the commitment from the top. Without the management commitment allowing the workers to implement the rule of autonomation, or explicitly considering the option, the impact of autonomation wouldn't be as effective. "It takes a lot of courage for management to allow the workers to that," one of the participants commented.

5.2.5.2 Staffing for Safety (S2)

With a strong backlog of ready work (T3), it becomes easier to staff professionals regardless of it being safety related or other personnel. One of the discussions commented on how the PPC measurements could be used for staffing for safety, indirectly, by using the PPC as a signal for hazards. For example, if the PPC starts to drop, it not only indicates that there are problems in production, but it also says that there is more variability, predictability drops, and it might be a warning for an increase in hazards throughout the site.

5.2.5.3 Safety Education (S4)

For the interaction of the lookahead process with safety education (T1/S4), the lookahead helps to identify new types of work that are coming in the future so that safety education, such as workshops, may be tailored to the expected plans to address special circumstances. Similarly, the interaction of the constraint analysis with safety education (T2/S4), as one of the participants commented, could be that in order to handle and implement a constraint analysis and to better tackle and eventually release the constraints, workers and the staff implementing the last planner need to be educated on how to tackle the safety related issues during the constraint analysis.

Another important interaction with this practice is the root cause analysis, which was where the expert panel felt the most strongly about. "If there is a specific element that directly affects safety education, it is the root cause analysis," one of the participants commented. If an accident has occurred, they have to analyze why it has happened and what led to the accident itself, there's definitely a great opportunity for learning here for the workers and management. There is specifically a direct relation here because it is often where we find the root cause of accidents and therefore look for solutions to prevent it. This is where the reason to increase safety education often comes up as well. Allowing the workers to stop the line, autonomation also implies that training on the proper way to stop the line, or detecting hazards, must be provided for the implementation of the tools to be effective.

5.2.5.4 Subcontractor Management (S7)

"The implications of LPS are the way in which backlogs of ready work are prepared, which result in fewer ad hoc events during the execution of the work." That was one of the comments from the participants indicating how the last planner overall can impact subcontractor management. Another constant comment that was discussed with the expert panel was the interaction of the backlog on subcontractor management. If a good backlog of ready work is provided, it can be assumed that it would allow subcontractors to get ready and prepare for safety as well as their tasks.

5.2.5.5 Backlog of Ready Work (T3)

Given the fine granularity of LPS that was provided for the analysis in this investigation, defining where the backlog really is implemented raised the issue of its definition and use. For example, the backlog of ready-work might be carried over to the last planner process where the workers involvement highly influences the planning process. However, as it has been implemented in this matrix, when the backlog lies in the same planning level as with the lookahead, it is the superintendent's responsibility to define the backlog, and thus the worker's involvement does not come up in this manner. This raises the issue of definition of the elements of the last planner, for example, to what extent does the backlog gets implemented and who participates in it?

5.2.6 Summary of Research Validation

The results have been useful in identifying significant differences between the proposed relations from the analysis and the feedback from the expert panel. In addition to the comments on the interactions with evidence, significant feedback on other interactions was provided. However, given the small number of interviews that were conducted (6), measuring a consensus on the interactions and the rating scale has little, if any, statistical significance and has many threats to the validity of the results. Additionally, the ratings provided by the expert panel raised several issues that were further elaborated upon by the participants and which have been summarized in this section.

5.3 Chapter Summary

This chapter has covered the main contributions of this research work and how it has been carried out to arrive at the results presented. A detailed discussion of the development of the interaction matrix that was used to analyze the interface between lean construction and safety management, by focusing on the means to achieve lean construction, has been presented. The data analysis adapted the morphological approach, given the characteristics of this research problem, which helped to systematically analyze and identify the interactions with specific evidence. Following the analysis, the results from the research synthesis were validated with an expert panel, for which six validation interviews were conducted. The interviews provided significant feedback on the interactions identified during the analysis, as well as other interactions with no evidence.

VI. SUMMARY AND CONCLUSIONS

The research work that has been carried out for the completion of this thesis is reviewed in this chapter. Important steps that have been an essential part of the development of this research are also revisited. Finally, a discussion of the findings, the contribution of this thesis to the base of knowledge, its limitations and recommendations for future research are discussed.

6.1 Research Summary

A literature review on the existing body of knowledge pertaining to the topics of interest has been carried out and presented in Chapter II. Following this in-depth literature review, a point of departure was established to depart with the proposed research for this thesis. This thesis tried to develop a framework that reiterates the interactions between aspects of lean construction and safety management, which enables the in-depth conceptual discussion on this interface. The results from this thesis provide evidence to promote and demonstrate the value of lean construction in construction safety, yet another aspect of significant importance to construction projects. Safety managers, lean construction practitioners, and contractors in general can benefit from the results obtained by this study by serving as an aid to recognizing the potential synergies when planning for lean and safety strategies.

A research methodology approach known as a research synthesis was applied in this thesis. A map of the research process to complete the thesis was also provided, which was an adaptation of the CIFE 'Horseshoe' Research Method (Fischer 2006) used to map the research process. The analysis approach taken to do this thesis was inspired by two similar studies to this thesis, in which similarly, the principles of sustainable construction and lean construction were integrated (Martinez et al. 2009), and the interaction between lean construction and Building Information Modeling was analyzed (Sacks et al. 2010).

As part of the objectives of this thesis, the development of a framework, which became an interaction matrix, in which the interface between lean construction and safety management practices can be closely analyzed, was developed. This interaction matrix allowed for the analysis of detailed aspects of the interface between lean construction and safety management, which helps to further explain how the implementation of lean construction tools specifically result in safer environments. To provide an understanding as to how this interaction matrix was developed, the granularity of this research problem was made finer, so as to be able to establish a referential point for the development of this interaction matrix. That referential point was the definition of the three-dimensional matrix (see Figure 4.2), consisting of the three main variables that make up the research problem: the safety management practices, the lean construction tools and the lean construction principles. Given this, in order to provide more tangible information on how lean construction results on safer environments, the tools of lean construction, as opposed to the principles, which are the means to achieve lean construction were chosen to be analyzed closely with the most common safety management practices.

6.2 Discussion

The central question that this thesis began exploring was: How does the implementation of lean construction affect safety performance? The hypothesis developed to answer this was based on the idea that given the inherent characteristics of lean construction, such as the reduction of waste, the reduction of occupational hazards would also seem to be a natural occurring outcome of the implementation of lean construction. To narrow down the question, and to further elaborate upon this hypothetical assumption, this thesis addressed this question on specific tools and methods of lean construction that improve safety management efforts. The first sub question in which the central question was further narrowed down was: what specific tools and methods of lean construction improve safety management efforts?

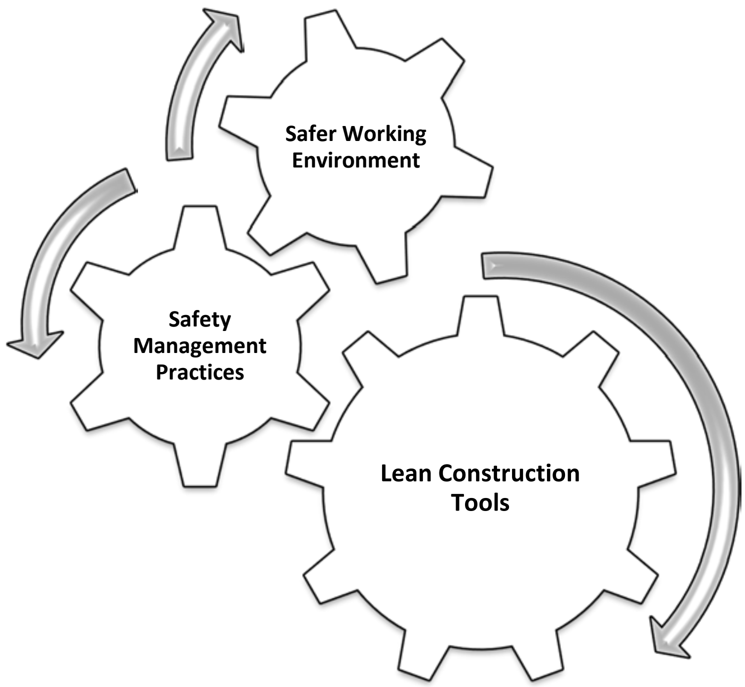


Figure VI.1 - The Impact of Lean Construction Tools on Safety Performance

If the hypothesis held to be true, then the inherent characteristics of lean construction naturally reduce occupational hazards improving safety performance. Given this, through the implementation of several specific lean construction tools, typical safety management practices shall benefit from this, providing a safer working environment and improving safety performance. The results demonstrate that several lean construction tools are related, directly or indirectly, to some of the most common safety management practices that are implemented in the industry. The last planner system, which has been one of the most successful tools developed thus far, shows that if applied correctly and implementing all of the elements that make up the system, many of the principles of lean construction are implemented successfully. Furthermore, as the results have shown, there are opportunities to include safety management into the system, and improve safety performance in the same way that the last planner system improves production performance. In fact, it almost seems unreasonable not to integrate or include safety with production planning, given its importance in today's industry. Along with cost, time, and quality, safety shall be treated as another one of the performance variables targeted by production management. The interactions that have been identified and validated with an expert panel can now be used to integrate current production management efforts. The interaction matrix, along with the explanations of the interactions, can be used to further investigate this specific issue, or help with the realization of the potential synergy that is obviously present between lean construction and safety management.

A second sub question into which the central question was further narrowed down was: what is the correlation, if any, between the implementation of lean construction practices and safety performance? With the developed interaction matrix, doing the research synthesis and adapting the morphological analysis approach to the interaction matrix, the interface between lean construction and safety management was systematically analyzed. For the analysis of the data collected, evidence for 37 interactions, from the 88 possible interactions, was identified. These interactions were then given a logical argument, based on a logical argumentation developed, to determine how direct the relation, between a specific lean construction tool and a safety management practice was. Following this, a validation with an expert panel was conducted to verify the accuracy of the results, where a rating scale for the interactions was also used. To make use of the data collected from the validation, the median of the ratings was taken to represent the results. Table 6.1 below shows the median for all the interactions for which evidence was collected during the analysis. For each interaction (cell) in the interaction matrix, the proposed relation (direct or indirect) from the collected evidence (E) in the research synthesis is provided followed by the median values from the validation (V), to compare the main results (i.e. D – 4).

Table VI.1 - Comparison of Arguments from Evidence and Validation

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
	E - V	E - V	E - V	E - V	E - V	E - V	E - V	E - V	E - V	E - V	E - V
S1	I - 1.5	I - 3		I - 1					I - 1	D - 5	D - 4
S2	D - 5	D-2.5		D-4.5			D - 4		D - 4		
S3	D - 5	D-4.5	D - 4	D - 4			D - 5		D - 4	D - 4	I - 3
S4								I - 3		D - 4	I - 3
S5				D- 5	D - 5	I - 4		D - 4		I - 2	I - 4
S6					I - 4	I - 4					I - 3
S7	D - 4	D-3.5		D - 4						I - 1	
S8						D - 5				D - 4	

* Rating Scale: (5) - Direct, (4) - Somewhat Direct, (3) - Neutral, (2) - Somewhat Indirect, (1) - Indirect

The analysis of this interaction matrix has focused exclusively on how lean construction tools impact safety management practices, which in turn results in safer working environments for construction projects improving safety performance. Several safety management practices are more directly related to lean construction tools than others. For example, planning for safety seems to be either somewhat or for the most part directly related to the lean construction tools identified. As the results from the analysis show, this is mainly due to the fact that a big part of implementing lean is planning itself, which naturally tackles safety planning.

One of the major contributions of this thesis is the development of the interaction matrix and the data collection process that has been set up to improve the amount of in-depth discussions on the interface between lean construction and safety management. This will allow researchers and professionals to reference this work in order to further build upon it, or simply use it as a guide to realize the existing synergy between lean construction and safety management.

6.3 Limitations

There are several limitations that need to be noted in regards to the development of this thesis. The first limitation to note is the scope of the project, which has had to be narrowed down given the time constraint. When the three dimensional matrix (the morphological box) was defined after the data collection, it was decided to focus exclusively on one aspect of the morphological problem field (the lean construction tools - safety management practices matrix) as opposed to trying to examine the whole problem. This would need a similar analysis of the interaction between lean construction principles and safety management practices, and another analysis of the integration of the lean construction tools and principles (Table 4.2).

Initially, the proposed research methodology implemented to investigate the research problem in this thesis was a research approach known as a meta-analysis. A meta-analysis is a method that similarly to a research analysis, statistically combines *quantitative* results of similar studies that address similar or related hypothesis. A significantly large body of literature surrounding the proposed topic needs to be present. For the topic being addressed here, however, the body of literature is relatively small and the amount of empirical studies regarding the topic is even smaller. For that same reason, it was decided to try and focus on the qualitative aspects of the data, given that more qualitative data exists on the topic.

The implications of deciding to conduct structured interviews with different participants, and given that lean construction in itself is still a growing area that does not necessarily have standardized outcomes or definitions yet, is that many of these participants could have interpreted the concepts differently than others. The participants have different experience implementing lean construction; for example, whereas some of them have a formalized last planner system, others simply follow the recommendations without explicitly following lean construction, or the last planner. The consequence of this is that they will have different perspectives on the interactions of certain tools with the safety management practices, depending on their experience implementing the system. In order to analyze the last planner, it had to be broken into its main elements. However, given that certain elements might not be in a specific sequence or level of planning as the last planner system model developed for this thesis, the participants might have interpreted this differently as well. One constant topic that kept coming up was the 'gray' areas of where certain tools belong, what they do, and how they are implemented.

6.4 Recommendations

Future research needs to address the morphological box, the three-dimensional problem that has been developed in this thesis from the data collection, to further elaborate upon the hypothesis in this thesis. Addressing the hypothesis and research question extending the morphological box as a whole would definitely provide a broader perspective into how lean principles are realized through certain tools or practices, and how this tools impact safety management, which results in safer environments.

Many of the participants expressed how there really isn't a clear definition of what the last planner is. For example, the mentioned 'gray' areas in the last section are a consequence of there not being a clear definition, yet, of the last planner system as a whole. This also refers to specific elements, such as the constraint analysis and the backlog of ready work.

Last, as a recommendation for future research, similarly to what has been done in this thesis, if some sort of weighting was to be added to either the lean construction aspects of the analysis or the safety management practices, then the results could be cumulative. For example, if planning for safety was more effective than safety education in terms of improving safety performance, then using the results from the analysis and the validation, the practices could be further evaluated comparing the cumulative results.

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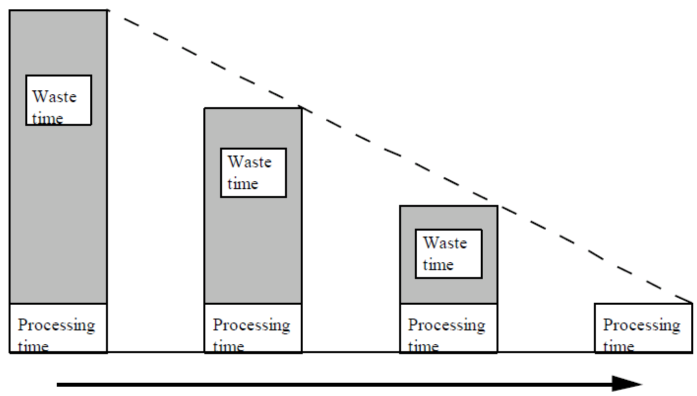
APPENDICES

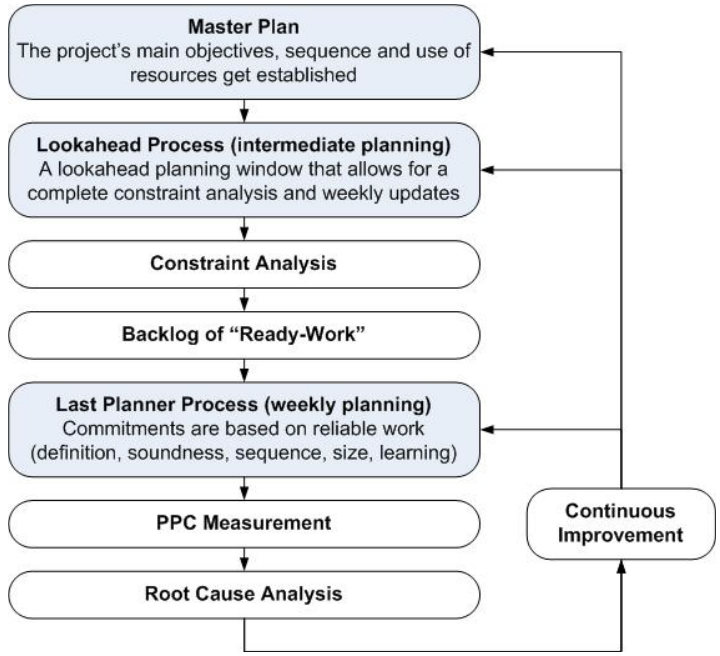
Appendix A: Principles of Lean Construction

Principle	Description	Key
Reduce Waste	This is the most essential principle in lean production. Eliminating or reducing the share of non value-adding activities within a production process will efficiently increase productivity. Waste exists because of the structure of the production system, the way production is controlled, or the inherent nature of production such as defects, machine breakdowns and accidents.	**P1**
Reduce Cycle Time	Cycle time (also referred to as lead time) can be progressively reduced through the elimination of all non-value-adding activities and variability within a production process. Cycle time is referred to as the time required for a particular piece of material to traverse flow, which is processing time, inspection time, waiting time, and moving time. 	**P2**
Reduce Variability	Given that production processes are variable, variability in production increases cycle time, therefore it adds non-value-adding activities to a production process and thus it needs to be avoided. Schonberger (1986) states that "variability is the universal enemy of production." Variability is the main source of uncertainty and its reduction increases reliability as well. There are two types of variability in flows of production: Process Variability consists of natural variability, such as minor fluctuations due to differences in operators, machines and material. Flow Variability refers to the variability of the arrival of jobs to a single workstation.	**P3**
Simplify	The very complexity of a product or process increases the costs beyond the sum of the costs of individual parts or steps, thus production must be simplified by eliminating waste from the production process and reconfiguring value-adding parts or steps. Simplification can be understood as the reduction of the number of components in a product or reduction of the number of steps and linkages in a material or information flow.	**P4**
Increase Flexibility	The focus on the flow of production can result on improved efficiency and customer satisfaction through the use of more flexible processes. Increasing flexibility rests on the simultaneous implementation of the other flow principles, such as waste (or cycle time) reduction and increased transparency.	**P5**
Increase Transparency	In order to make a production process transparent and observable for the facilitation of control and improvement, Stalk and Hout (1990) hold that it is of extreme importance "to make the main flow of operations from start to	**P6**

	finish visible and comprehensible to all employees involved" so that mistakes can be located and solved quickly. Increased transparency can be achieved through the implementation of organizational and physical measurements, and public display of information.	
Focus Control	Focus control on the complete process. Segmented flow leads to suboptimization and should be avoided, therefore instead of controlling individual activities, control should be focused on the entire production process for optimal flow.	**P7**
Build Continuous Improvement	Build continuous improvement into the entire process. The attempt to improve work productivity and eliminate waste must be carried out continuously. Every participant in the production process must be given the opportunity to contribute in this effort. Solving production complications must be the prior target of the continuous improvement.	**P8**
Balance Improvements	Balance flow improvement with conversion improvement. Flow improvement and conversion improvement are interconnected; therefore, their individual improvements should be analyzed to create balance within the process.	**P9**
Benchmarking	Benchmarking is a useful stimulus to achieve breakthrough improvement through radical reconfiguration of processes. It is an important continuous improvement tool that enables companies to enhance their performance by identifying, adapting, and implementing the best practice identified in a participating group of companies.	**P10**
Meet Customer Requirements	Increase output value through systematic consideration of customer requirements. Value is generated through fulfilling customer requirements. The customer is defined to be the next activities, as well as the owner, thus a practical approach to this is to define the customer at each stage and analyze their requirements in order to meet them. This allows to increase the output value through systematic consideration of customer requirements	**P11**

Sources: Koskela 1992.

Appendix B: Elements of the Last Planner System



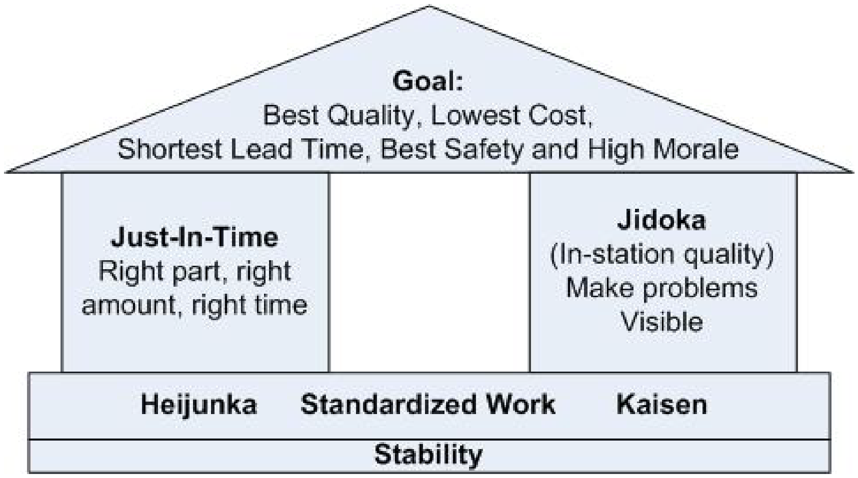
Sequence of LPS Implementation (adapted from Leal 2010)

Element	Description	Key
Lookahead Process	The lookahead process is the second level of planning, the intermediate plan, that expresses what CAN be done after the master plan defines what SHOULD be done (see Figure 2.7). The number of weeks (a sliding window) over which a lookahead process extends is decided based on project characteristics, the reliability of the planning system, and the lead times for acquiring information, materials, labor, and equipment (Ballard 2000). A typical lookahead planning window is anywhere from 3 to 12 weeks. The functions of the lookahead process, which helps to control the work flow, are: • Shape work flow sequence and rate • Match work flow and capacity • Decompose master schedule activities into work packages and operations • Develop detailed methods for execution (*constraint analysis*) • Maintain *backlog of ready-work* • Update and revise higher level schedules as needed	**T1**
Constraint Analysis	As part of the lookahead planning process, one of the most important tools implemented in the lookahead process is a constraint analysis, which consists on determining what must be done for each assignment in order to make it ready to be executed. This allows for the identification of constraints, or restrictions that need to be removed.	**T2**
Backlog of "Ready-Work"	Once all constraints have been removed for each assignment, the activities are then put into the workable backlog from which the last planners can establish the weekly plan (the next level of planning). "The objective is to maintain a backlog of sound work, ready to be performed	**T3**

	with assurance that everything in workable backlog is indeed workable" (Ballard 2000).	
Last Planner Process	The last planner process is the third and last level of planning closest to the week in question, after the lookahead process (see Figure 2.7). This is the planning level where the last planners establish weekly commitments to production (what WILL be done) based on the workable backlogs produced in the lookahead process. The work plans are based on assigning reliable work, and may only be assigned if the following five characteristics apply (Ballard 2000): • Definition: is the scope clear? • Soundness: are all assignments sound (see seven preconditions for soundness in the literature review)? • Sequence: is the work planned in the right sequence? • Size: are assignments planned accordingly? Do they meet the capability of the resources available (manpower, equipment, material, etc)? • Learning: are assignments not complete tracked and analyzed (Root Cause Analysis)?	**T4**
PPC Measurement	One of the most valuable and fundamental tools that the LPS implements is the measurement of plan reliability through the PPC. The Percent Plan Complete (PPC) consists on systematically comparing the plans committed to the plans executed. This measures the extent to which the front line supervisor's commitment (WILL) was realized and becomes the reliability performance indicator.	**T5**
Root Cause Analysis	Following the PPC measurement and having determined the nonconformance of assignments, the root causes for nonconformance with the plan are tracked and analyzed in order to develop a future plan and prevent it from happening in the future, so that improvements can be made in the future.	**T6**

Sources: Ballard 2000 and GEPUC 2010.

Appendix C: Lean Production Tools



TPS House (Liker 2004)

Tool	Description	Key
Just-In-Time	Just-In-Time (JIT) consists on producing and delivering products in small quantities, with short lead times, to meet specific customer needs; in other words, JIT allows for "the delivery of the right items at the right time in the right amount." It is aimed at reducing inventory, or 'buffers,' and achieving an ideal one-piece flow system, that is transforming from a "push" to a "pull" system. This in turn makes problems, like quality defects, become immediately visible and thus reinforcing Autonomation.	**T7**
Autonomation	Autonomation (Jidoka), or "automation with a human touch," consists on never letting a defect pass into the next station allowing machines or workers to stop production whenever something unusual is detected, such as a defective product, which may disrupt the production process.	**T8**
Production Leveling	Production leveling (Heijunka) levels out the volume and mix of items produced so there is little variation in production, thus controlling the type of waste associated with inconsistencies in production (mura).	**T9**
Standardization	Standardization refers to using stable, repeatable methods everywhere to maintain the predictability, regular timing, and regular output of processes, thus controlling the overburdening of people or equipment (muri).	**T10**
Continuous Improvement	Continuous improvement (Kaisen) is the process of making incremental improvements, no matter how small, and achieving the lean goal of eliminating all waste (that adds cost without adding to value) and increasing value. It is a continuous internal, incremental, and iterative process.	**T11**

Sources: Liker (2004) and Womack et al. (1990; 1996)

Appendix D: Safety Management Practices

Practice	Description	Key
Management Commitment	The importance of working safely is emphasized when management makes its commitment to safety known to personnel in the field. The key is that top managers must be actively involved in worker safety at the project level to exert a strong influence on establishing the project safety culture. Examples of management commitment strategies are: • The inclusion of safety in the mission statement • Allocating adequate funding for safety-related activities • Upper level participation in safety-related activities (inspections, training, meetings, accident investigations, etc)	**S1**
Staffing for Safety	Staffing for safety implies that the right people, methods, and resources are used to ensure safety on a construction project. The appropriate staff ensures that safety needs are being satisfied. Examples of staffing for safety strategies are: • Employment of a safety and health professional (either from experience or with a formal education) whose primary responsibility is to perform and direct the implementation of safety and health program elements within a company • Full-time presence of safety personnel on project sites • First-aid facilities and medical personnel • Providing personal protective equipment for workers	**S2**
Planning for Safety: Pre-Project and Pre-Task	In order for safety programs to be effective they must be relevant to the jobsite. Pre-project planning (longer-term) establishes and communicates project-specific safety goals, plans, and policies before the construction phase of the project. Pre-task planning (shorter-term), such as JHA's, ensures that tasks are performed with safety integrated into the daily work routine. Examples of planning strategies are: • Including safety as part of constructability reviews • Job hazard analyses (JHA's) • Documented safety plans • General safety and health plan • Project-specific programs • Emergency response planning	**S3**
Safety Education: Orientation and Specialized Training	Knowledge about performing tasks safely is vital to worker safety. There are a variety of ways that this knowledge can be instilled, but training is perhaps the most effective means. Training covers a wide variety of topics, each of which may directly influence safety performance when performing a given task. Examples of safety education strategies are: • Orientation training for all new hires • Additional monthly safety training beyond orientation • Toolbox meetings covering safety rules, hazards, corrective actions, accident prevention, review of recorded injuries and near misses among other topics.	**S4**
Worker	This is essentially based on the view that workers are not just a valuable resource to be protected but also a resource that can contribute to achieving	**S5**

Involvement	the goal of zero accidents. Workers perception about safety is extremely valuable in evaluating different aspects of a safety program. Examples of worker involvement strategies are: • Behavior-based safety programs, which basically assigns safety observers to implement safety • Worker safety perception surveys helps to evaluate the safety climate of a project and take corrective actions • Safety committees consisting of a diverse group including supervisors, laborers, representatives of key subcontractors, and owner representatives	
Evaluation and Recognition	In order to encourage safety performance, reinforcing such behavior is a key element. If workers are evaluated and/or recognized for safe behavior, then workers will seek to repeat that performance. Examples of evaluation and recognition strategies are: • Incentive programs focusing on addressing injury occurrences (negative results) and safe work behavior (positive results). • Including participation and safe work behavior as part of worker's evaluation.	**S6**
Subcontractor Management	If a safety program is to be effective, it must involve the subcontractors. They should be included in the orientation training, the drug testing and the safety planning among other activities. All parties must comply with the same safety guidelines including employees of the subcontractors. Examples of subcontractor management strategies are: • Offering orientation training for subcontractor employees • Including subcontractors on project safety meetings • Incorporation of safety performance records as part of the procurement process of subcontractors (e.g., prequalification and required compliance)	**S7**
Accident Investigation	Accident/incident investigations are important for identifying the root causes of injuries in order to devise effective preventative measures. Many companies may include near misses as well indicating proactive measures. Examples of accident/incident investigation: • Investigation of all types of accidents (OSHA recordable, lost work days, etc) • Regular worksite inspections • Reporting of near misses	**S8**

Sources: CII 1993, Hinze 2002, Razuri et al. 2007, Hallowell and Hinze (In Press).

Appendix E: Index of Interactions

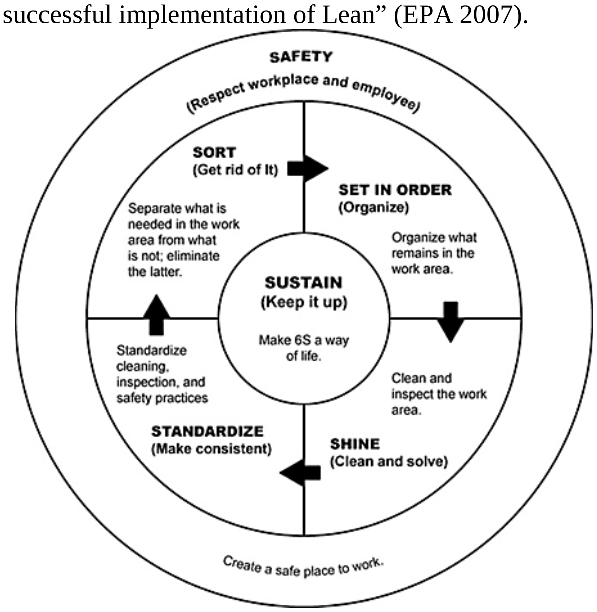
Lean Construction Tools / Safety Management Practices		Last Planner System						Lean Production Tools				
		Lookahead Process	Constraint Analysis	Backlog of Ready-Work	Last Planner Process	PPC Measurement	Root Cause Analysis	JIT	Autonomation	Production Leveling	Standardization	Continuous Improvement
		T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**T11**
Management Commitment	**S1**	1	1		5					14	16	18
Staffing for Safety	**S2**	2	3		6			11		11		
Planning for Safety	**S3**	2	3	4	6			11		15	16	20
Safety Education	**S4**								12		17	18
Worker Involvement	**S5**				7	8	9		13		17	19
Evaluation and Recognition	**S6**					8	9					20
Subcontractor Management	**S7**	1	1		5						16	
Accident Investigation	**S8**						10				16	

Appendix F: Explanation of Interactions

Index	Interaction(s)	Explanation	Evidence
1	T1/S1 (I) T2/S1 (I) T1/S7 (D) T2/S7 (D)	Production managers, planning coordinators, safety specialists, and subcontractors' representatives can all participate in the lookahead meetings and constraint analyses in which safety constraints can also be systematically included. In addition to the participation of upper management in these meetings, this also allows subcontractor management to be actively involved in safety-related activities.	Saurin et al. 2004b, p. 162; Leino et al. 2010, p. 249;
2	T1/S2 (D) T1/S3 (D)	At the lookahead planning stage, project-specific safety objectives, plans and policies can be incorporated. This allows to proactively plan for safety and staff for safety accordingly.	Saurin et al. 2004b, p. 162
3	T2/S2 (D) T2/S3 (D)	Including safety constraints in the lookahead constraint analysis directly incorporates pre-task planning for safety given that it determines what safety constraints are needed to be freed in order to perform a task. In addition to this, this allows to predict risk levels so that safety management may tackle risky situations when needed and can allocate safety resources accordingly (safety personnel, PPE).	Saurin et al. 2004b, p. 162; Sacks et al. 2005, p. 518; Leino et al. 2010, p. 249
4	T3/S3 (I)	Backlogs of work packages ready to be executed (ready-work) assigned in the lookahead process can also be extended to safety planning by incorporating safety as part of the soundness requirements (see Appendix B). Also, checking for all of the *seven preconditions for soundness* affects safety to some extent, for it makes it easier to stay in a space of "non-chaos" consequently reducing hazards.	Thomassen et al. 2003, p. 9; Saurin et al. 2004b, p. 163
5	T4/S1 (I) T4/S7 (D)	At this planning level upper management and subcontractor management can similarly participate in the last planner planning meetings just as with the lookahead meetings (see explanation 1).	Saurin et al. 2004b, p. 162; Leino et al. 2010, p. 249;
6	T4/S2 (D) T4/S3 (D)	At this planning level, weekly and daily planning meetings can discuss safety measures to plan for safety and staff the for safety accordingly. The last planner planning meetings simply focus on shorter-term planning for safety, as opposed to the longer-term planning for safety that is incorporated in the lookahead planning meetings (see explanation 2).	Saurin et al. 2004, p. 162 Leino et al. 2010. P. 250
7	T4/S5 (D)	LPS also implements a fundamental strategy that allows for a system to be more maneuverable, that is, the bottom-up approach to planning which allows for the last planners (the foreman and other people working on site) to play a significant role in planning. It directly incorporates worker involvement.	Thomassen et al. 2003, p. 9 Leino et al. 2010, p. 250
8	T5/S5 (D) T5/S6 (I)	The concept of PPC measurement can be extended to measure safety performance in order to evaluate safety effectiveness in the same way. A similar measurement for safety, the percentage of safe work packages (PSW) indicates the percentage of work packages safely carried out. This helps to evaluate safety aspects of production as well as worker's safety performance.	Saurin et al. 2004b, p. 163
9	T6/S5 (I) T6/S6 (I)	Workers feedback on the root cause for accidents or near misses are valuable resources to evaluate hazards; the dissemination to the workers of successful analyses based on this feedback can provide successful prevention strategies. Investigating causes for successful performance rather than just	Saurin et al. 2006, p. 488

		causes for non-conformance might also influence workers perspective on safety by recognizing such “causes for conformance.”	
10	T6/S8 (D)	When the root causes for nonconformance are tracked and analyzed, accidents and near misses might be part of those root causes and will be evaluated as well. Therefore, the analysis of root causes for nonconformance with *safety* can be easily conducted and incorporated with root cause analyses.	Saurin et al. 2004b, p. 162
11	T7/S2 (D) T7/S3 (D) T9/S2 (D)	The concept of Just-In-Time can be extended to safety management by “leveling risk” to forecast safety risks better. Using tools such as CHASTE (Rozenfeld et al. 2009) helps in forecasting safety risks better, thus allowing to plan for safety. Being able to forecast risks also helps in allocating safety management efforts when and where they are needed. From a lean perspective, this is basically transforming the traditional “push” approach for safety management into a more effective, and less wasteful “pull” approach.	Rozenfeld et al. 2010, p. 492; Sacks et al. 2005, p. 514
12	T8/S4 (I)	It is necessary to provide the adequate guidance and training for workers to make the right judgment when they feel they need to stop production in order to maintain a desired level of risk or risk averseness.	Saurin et al. 2006, pg. 490 Mitropoulos et al. 2005, p.823
13	T8/S5 (D)	The extension of autonomation to safety means that workers should be granted autonomy to stop production whenever they feel in danger and before an undesired outcome occurs. Workers stop work or ask for help when the worker notices a problem, such as a bad rule or no rule situation.	Saurin et al. 2006, pg. 489
14	T9/S1 (I)	Production practices (encouraged by the management) such as production leveling aims at matching skills to task demand, which reduces the chances of construction accidents while increasing productivity.	Mitropoulos et al. 2007
15	T9/S3 (D)	When leveling production, safety can be the most efficient by ensuring that production demands do not exceed capabilities, because while leveling production demands, the capability of the workers must be prioritized in order to reduce human errors created under pressure.	Hallowell et al. 2009, pg. 26
16	T10/S1 (D) T10/S3 (D) T10/S7 (I) T10/S8 (D)	The explicit concerns for safety from the owners and upper management, such as safety requirements and contractor selection policies can have a direct impact on safety performance by standardizing such expected safety outcomes. Standardizing safety by developing specific procedures for safety is often done establishing procedures for pre-task planning, accident investigations, and safety requirements for subcontractor procurement processes.	Saurin et al. 2006, pg. 486
17	T10/S4 (D) T10/S5 (I)	Standardization implies that all work be highly specified in terms of timing, content, sequence and outcome. These procedures often include safety hazards into their content, which requires workers to learn. This also implies that procedures may reduce the degrees of freedom of workers and define a space of safe performance where accidents will not happen. This has been shown through Rasmussen’s work behavior model (Rasmussen et al. 1994).	Saurin et al. 2006, pg. 486 Mitropoulos et al. 2005. Pg. 818
18	T11/S1 (D) T11/S4 (I)	Visual management is one of the most common continuous improvement strategies. It can be extended for safety purposes using things such as safety signs and boards displaying current	Saurin et al. 2006, pg. 490

<table>
<tr><td></td><td></td><td>accident rates allowing all workers to identify, thus providing an opportunity to be trained, the boundaries for safe performance and compare the expected safety performance. Implementing continuous improvement strategies shows the commitment of management to safety.</td><td></td></tr>
<tr><td>19</td><td>T11/S5 (I)</td><td>Integrating safety into tools such as 5S, another important CI tool, creates and maintains “a clean, orderly, and safe work environment, and it also fosters a culture of continual improvement and employee engagement that is essential for the successful implementation of Lean” (EPA 2007).



The six pillars of 6S (EPA 2007)</td><td>EPA 2007</td></tr>
<tr><td>20</td><td>T11/S3 (I)
T11/S6 (I)</td><td>The conscious effort towards continuous improvement and implementing related tools such as visual management and 5S, will drive the improvement of safety performance and planning for safety without the explicit integration of specific safety programs. Improvements which are recognized and evaluated.</td><td>Nahmens and Ikuma 2009, p.4</td></tr>
</table>

* (D) Direct Relation, (I) Indirect Relation, ( ) No Relation

Appendix G: Validation Results

Median

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
S1	1.5	3.0	4.0	1.0	2.0	3.0	3.0	4.0	1.0	5.0	4.0
S2	5.0	2.5	3.0	4.5	2.0	3.0	4.0	3.5	4.0	3.0	3.0
S3	5.0	4.5	4.0	4.0	2.5	3.5	5.0	4.0	4.0	4.0	3.0
S4	3.0	1.0	2.5	4.0	1.0	4.0	1.0	3.0	1.0	4.0	3.0
S5	5.0	1.0	3.0	5.0	5.0	4.0	2.0	4.0	2.0	2.0	4.0
S6	2.5	4.0	3.0	2.0	4.0	4.0	1.5	3.5	1.5	3.5	3.0
S7	4.0	3.5	3.0	4.0	3.0	4.0	1.0	3.0	2.0	1.0	3.0
S8	1.0	3.0	3.0	1.5	2.5	5.0	1.0	5.0	1.0	4.0	4.0

Absolute Deviation

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
S1	1.0	0.4	1.0	1.0	0.0	0.8	2.0	0.4	1.0	0.7	0.6
S2	0.3	0.8	1.0	0.8	1.6	1.1	0.8	0.5	1.1	0.0	1.1
S3	0.0	0.8	0.7	0.7	1.3	1.3	0.5	0.0	1.4	1.0	0.9
S4	1.1	1.3	0.5	1.3	0.0	1.3	0.0	0.6	0.0	0.5	0.9
S5	1.8	1.8	0.4	0.3	0.9	0.6	0.7	0.6	0.4	0.3	0.5
S6	1.5	0.0	0.0	1.6	1.4	1.1	0.5	0.5	0.5	0.5	0.7
S7	0.3	0.8	1.1	0.7	1.3	0.6	0.4	1.0	1.3	0.7	0.9
S8	0.0	1.1	0.0	0.5	1.5	0.7	0.0	0.0	0.0	0.9	1.1

Mean

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
S1	2.0	2.7	4.0	1.8	2.0	3.0	3.0	3.7	1.8	4.4	3.6
S2	4.8	2.8	3.0	4.2	2.7	3.3	4.0	3.5	3.8	3.0	3.3
S3	5.0	4.2	4.0	4.0	2.8	3.3	4.6	4.0	3.2	3.8	3.4
S4	2.7	2.0	2.5	3.0	1.0	3.6	1.0	3.2	1.0	4.4	3.4
S5	3.7	2.3	2.7	4.8	4.3	3.8	2.0	4.2	1.7	2.2	3.6
S6	2.5	4.0	3.0	2.7	2.8	3.7	1.5	3.5	1.5	3.5	3.6
S7	3.8	3.5	2.4	3.5	3.3	3.8	1.3	2.2	2.4	1.6	3.7
S8	1.0	2.7	3.0	1.5	2.5	4.5	1.0	5.0	1.0	3.6	3.7

Standard Deviation

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
S1	1.3	0.5	1.4	1.3	###	1.2	2.8	0.6	1.3	0.9	0.9
S2	0.4	1.0	1.6	1.0	2.1	1.5	1.0	0.7	1.6	0.0	1.5
S3	0.0	1.0	0.9	0.9	1.7	1.7	0.5	0.0	1.6	1.3	1.1
S4	1.5	1.7	0.7	1.7	0.0	1.7	###	0.8	###	0.5	1.1
S5	2.3	2.3	0.6	0.4	1.0	0.8	1.0	0.8	0.6	0.4	0.5
S6	2.1	###	###	2.1	1.6	1.4	0.7	0.7	0.7	0.7	0.9
S7	0.4	1.0	1.3	0.8	1.5	0.8	0.6	1.1	1.7	0.9	1.2
S8	0.0	1.5	###	0.7	2.1	0.8	###	####	###	1.1	1.5

Rating Count per Interaction

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
S1	6	6	2	5	1	5	2	3	5	5	5
S2	6	6	4	6	3	3	5	2	5	2	3
S3	6	6	6	6	4	4	5	2	5	5	5
S4	3	3	2	3	2	5	1	5	1	5	5
S5	3	3	3	6	6	6	3	5	3	5	5
S6	2	1	1	3	5	6	2	2	2	2	5
S7	6	6	5	6	4	5	3	5	5	5	3
S8	2	3	1	2	2	6	1	1	1	5	3