IDENTIFYING THE EFFECTS OF LEAN CONSTRUCTION PRINCIPLES ON VARIABILITY OF PROJECT DURATION

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HACI HÜSEYİN EROL

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submitted by **HACI HÜSEYİN EROL** in partial fulfillment of the requirements for the degree of **Master of Science in Civil Engineering Department, Middle East Technical University** by,

Prof. Dr. Canan Özgen ____________________
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Ahmet Cevdet Yalçıner ____________________
Head of Department, **Civil Engineering**

Prof. Dr. İrem Dikmen Toker ____________________
Supervisor, **Civil Engineering Dept., METU**

Prof. Dr. M. Talat Birgönül ____________________
Co-Supervisor, **Civil Engineering Dept., METU**

Examining Committee Members:

Assoc. Prof. Dr. Rıfat Sönmez ____________________
Civil Engineering Dept., METU

Prof. Dr. İrem Dikmen Toker ____________________
Civil Engineering Dept., METU

Prof. Dr. M. Talat Birgönül ____________________
Civil Engineering Dept., METU

Asst. Prof. Dr. Aslı Akçamete ____________________
Civil Engineering Dept., METU

Gülşah Dağkıran, M. Sc. ____________________
GAMA Holding

Date: 20.06.2014

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name : Hacı Hüseyin Erol

Signature :

ABSTRACT

IDENTIFYING THE EFFECTS OF LEAN CONSTRUCTION PRINCIPLES ON VARIABILITY OF PROJECT DURATION

Erol, Hacı Hüseyin

M.Sc., Department of Civil Engineering

Supervisor: Prof. Dr. İrem Dikmen Toker

Co-Supervisor: Prof. Dr. M. Talat Birgönül

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Performance of the construction projects have been criticized for many years due to their low productivity rates and cost overruns as well as significant delays. Increasing number of dissatisfied customers compel practitioners to reform conventional practices of construction management. Lean construction emerges as a result of change efforts in the industry. Lean construction promises a much better project performance by eliminating the waste and improving value to customer. Although many practical application techniques of lean construction are developed, researches showing tangible benefits of them are scarce. For this purpose, this study aims to quantitatively evaluate the effects of lean construction principles on project duration and its variation. In this respect, starting from lean production subject, lean construction concept is reviewed in detail and a research methodology is developed. The methodology is based on comparing the lean and non-lean scenarios of a case study by means of Monte Carlo simulation model. Data used in the model is generated with a questionnaire responded by three experts. Research findings demonstrate that lean construction principles improve the performance both by reducing total duration of the project and its variation. The findings of this thesis cannot be generalized and this improvement may not be true for all types of construction projects. However, case study findings reveal that applying lean principles may have a potential to overcome delays and decrease unpredictability of construction project durations.

Keywords: Lean construction, lean construction principles, Monte Carlo simulation, construction industry, lean production

ÖZ

YALIN İNŞAAT PRENSİPLERİNİN PROJE SÜRESİNİN DEĞİŞKENLİĞİ ÜZERİNDEKİ ETKİLERİNİN SAPTANMASI

Erol, Hacı Hüseyin

Yüksek Lisans, İnşaat Mühendisliği Bölümü

Tez Yöneticisi: Prof. Dr. İrem Dikmen Toker

Ortak Tez Yöneticisi: Prof. Dr. M. Talat Birgönül

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İnşaat projelerinin performansı, düşük verimlilik oranları ve bütçe aşımlarının yanı sıra ciddi gecikmeler nedeniyle de uzun yıllardan beri eleştirilmektedir. Sayıları artmakta olan memnuniyetsiz müşteriler, proje uygulayıcılarını geleneksel yapım yönetimi yöntemlerini yeniden düzenlemeye zorlamaktadırlar. Yalın inşaat, inşaat endüstrisindeki değişim çabalarının bir sonucu olarak ortaya çıkmıştır. Yalın inşaat, fireyi yok ederek ve müşteriye yönelik değeri arttırarak daha iyi bir proje performansı vaat etmektedir. Her ne kadar, yalın inşaatın birçok pratik uygulama yöntemi geliştirilmiş olsa da, bu yöntemlerin somut faydalarını gösteren araştırmalar kısıtlıdır. Bu amaçla bu çalışma; yalın inşaat prensiplerinin proje süresine ve sürenin değişkenliğine olan etkilerini nicel olarak değerlendirmeyi hedeflemektedir. Bu bağlamda; yalın üretim konusundan başlanarak, yalın inşaat kavramı detaylı bir şekilde gözden geçirilmiş ve bir araştırma yöntemi geliştirilmiştir. Bu yöntem; örnek bir vakanın, yalın ve yalın olmayan senaryolarını Monte Carlo benzetimi yapan bir modelle karşılaştırmaya dayalıdır. Modelde kullanılan veri üç adet uzman tarafından cevaplanan bir anket aracılığıyla oluşturulmuştur. Araştırma bulguları yalın inşaat yöntemlerinin proje performansını; hem toplam süreyi, hem de toplam sürenin değişkenliğini azaltması yönünden geliştirdiğini ortaya koymaktadır. Bu tezin bulguları genelleştirilemeyebilir ve bahsi geçen geliştirmeler her tür inşaat projesi için geçerli olmayabilir. Ancak vaka çalışması bulguları; yalın prensipleri uygulamanın, süre aşımlarının önüne geçmek ve inşaat projelerinin tahmin edilemezliğini azaltmak için bir potansiyele sahip olabileceğini göstermektedir.

Anahtar Kelimeler: Yalın inşaat, yalın inşaat yöntemleri, Monte Carlo benzetimi, inşaat endüstrisi, yalın üretim

Dedicated to my lovely family and dear Bilgenur...

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LIST OF ABBREVIATIONS

ADM	Activity Definition Model
AEC	Architecture, Engineering, Construction
BIM	Building Information Modelling
CAVT	Computer Advanced Visualization Tool
CFP	Continuous Flow Process
CPM	Critical Path Method
CUQ	Complex, Uncertain and Quick
DSM	Design Structure Matrix
GDP	Gross Domestic Product
GM	General Motors
IGLC	International Group for Lean Construction
IMVP	International Motor Vehicle Program
IT	Information Technology
JIT	Just-in-Time
LCI	Lean Construction Institute
LPDS	Lean Project Delivery System
LPS	Last Planner System
MIT	Massachusetts Institute of Technology
PERT	Program Evaluation and Review Technique
PMBOK	Project Management Body of Knowledge
PPC	Plan Percent Complete
SCM	Supply Chain Management
TFV	Transportation-Flow-Value
TPS	Toyota Production System

TQM	Total Quality Management
VDC	Virtual Design & Construction
WBS	Work Breakdown Structure
WIP	Work-in-Progress

CHAPTER 1

INTRODUCTION

The construction industry plays a crucial role in national development of the counties in terms of both its proportion in gross domestic product (GDP) and contribution to employment rate. In this sense, nature and dynamics of construction industry should be very well comprehended to pursue the innovations within the industry. One of the recent topics in construction domain is lean construction, which arises from car manufacturing industry and intends to minimize waste in the construction process while maximizing the value generated. Lean construction is expected to change conventional perception of construction management in the forthcoming years. Due to its huge potential to revolutionize the industry, lean construction should be carefully analyzed. For this reason, this study aims to explain lean construction theory exhaustively starting from lean production and to express its potential benefits by providing a case study that measures effects of lean construction principles on project duration by means of stochastic simulation.

Construction practitioners working on this field present lean construction as a differentiation strategy. There is an obvious need for a change in construction industry for many years. Conventional model of construction project management frequently fails in terms of performance, efficiency, and customer satisfaction. In many construction projects, planning and execution functions are separately operated by different groups of people. Planning is conducted through complicated critical path method (CPM) schedules, which are defined prior to start of the project. Execution function, on the other hand, is performed by strictly obeying these schedules, which are created by people who are not acquainted with site conditions. In addition to that, dynamic nature of the construction works are not considered. Although, there are some updates in the schedules, they do not exactly reflect continuous changes in construction works. Current practices focus on estimating the duration, cost, and relationships of the tasks; and ignores the rest by hopefully expecting estimations will be realized. However, most of the time, outcomes are not parallel with predictions, which results in unsuccessful projects. The success of a construction project can be evaluated in various ways. Estimating its schedule performance and budget performance are some quantitative metrics while health and safety, quality, and sustainability are qualitative metrics. Regardless of performance measurement type, current practice of construction management frequently suffers from missing the targets. This is the reason why there is a demand for changeover in present habits of construction project management. Lean construction serves for this purpose through its innovative and holistic approach.

Although the term “lean construction” has emerged in early 1990s, its involvement to construction literature goes back a long way. Fundamental principles of lean construction stem from manufacturing industry. The concept of lean thinking has dramatically improved the performance of production sector. The principles that inspired lean thinking were developed by engineers of Toyota Motor Company. Toyota Production System (TPS) constitutively aims to minimize all types of waste in the process. Its unique approach brought a great success to Toyota Motor Company, which drew attention of its Western competitors. In 1979, International Motor Vehicle Program (IMVP) started at Massachusetts Institute of Technology (MIT) in order to discuss challenges that global automobile manufacturers encountered. The term “lean” initially used in the publications of IMVP and principles of lean thinking were founded with inspiration of TPS.

The innovation in automotive industry rapidly affected production sector. However, practice of lean thinking to construction industry could not be as easy as applying it to manufacturing. Dynamics of construction industry is considerably different from manufacturing industry due to its size, complexness, and non-repetitive structure.

Therefore, there must be an endeavor in order to adjust lean principles to construction. Arrival of term “lean construction” is a result of the effort made by construction practitioners. Since researchers developed lean principles that are applicable to construction, interest to lean construction principles has been increasing persistently. In this regard, some non-profit corporations were founded to research, practice, and spread lean construction principles. International Group for Lean Construction (IGLC), founded in 1993, and Lean Construction Institute (LCI), founded in 1997, are two of the most known organizations that serve for these purposes. Studies of these organizations and academicians working on this field have established the foundations of lean construction and made it one of the most popular topics in construction management sphere.

Lean construction can not only be regarded as an attempt to convert current practice but also should be considered as a strategy for construction companies to differentiate themselves. Tendency of constructing leaner facilities is increasing day by day. Especially real case examples showing quantifiable benefits of lean construction increase notice of contractors to adopt lean principles as a competitive advantage provider. In terms of competitiveness in construction industry, the earlier internalization of lean principles will enable construction companies to be ready for new construction era because eventually lean construction will be dominant in construction project management.

In the light of this information, this study initially aims to introduce concept of lean construction starting from lean production that pioneered to constitution of lean construction philosophy. Another object of the study is measuring the effects of lean construction principles in a quantitative manner. Results of the study are expected to attract interest of Turkish contractors and to encourage them to increase limited applications of lean construction in Turkey. Finally, this research aims to form a basis for feature researches that try to quantify the impacts of lean construction principles.

The following organization is adopted within this thesis. Chapter 2 presents literature review on lean production. In this chapter, historical development and general principles of TPS, comparison of TPS with other production techniques, adaptation of TPS to the West, benefits of lean production, and concept of lean thinking are discussed. Chapter 3 continues with literature review on lean construction. It includes current situation and change efforts of the construction industry, arrival of lean construction philosophy, basic principles, methods developed for lean construction applications, and procedure for measuring the effects of lean construction principles. Chapter 4 introduces the research methodology and questionnaire, which are utilized to identify the effects of lean construction principles on variability of project duration through a case study. In this respect, steps of the methodology and parts of the questionnaire, including information regarding the case study project and participants of the questionnaire, are explained. Chapter 5 presents the research findings and discusses results of the questionnaire in an elaborative expression. Finally, Chapter 6 concludes the study by highlighting the major findings, discussing the limitations, and making suggestions for future researches and applications.

CHAPTER 2

LEAN PRODUCTION

Lean production marked a new epoch in the manufacturing industry. Its unique approach to process management has dominated to manufacturing industry for three decades. It suppressed principles of Taylorism, Fordism, and Post-Fordism that dominated era of 1910s-1920s, 1930s-1960s, and 1970s-1980s respectively. Although Total Quality Management (TQM) inspired lean production in terms of objectives like elimination of anything that does not add value to customer, arranging the production as a continuous flow, generating a reliable flow between distributing information and decision making, and pursuing perfection (Aziz and Hafez, 2013), lean production has taken its core principles from the production principles of a car manufacturer: Toyota.

TPS defines the principles of lean thinking and lean production as: Stopping the line, pulling product forward, one-piece flow, synchronize and align, and transparency. Many of these principles have been invented and used by Toyota for many years and they lead Toyota to become one of the biggest car manufacturers in the world. Therefore, TPS comprises an important part of this chapter.

Due to its significant contribution development of lean production principles, TPS is described thoroughly in following sections after explaining the evolution of Toyota. This chapter also includes conventional production concepts of Taylorism and Fordism along with their comparison with Toyota’s way of production. In addition to this, transition of TPS from Japan to the West and role of IMVP are introduced in the upcoming section. Moreover, the differences between mass production and lean production is emphasized. The chapter continues with a literature survey that demonstrates the potential benefits of lean production and, finally, it is concluded with lean thinking concept.

2.1 The Evolution of Toyota

Development of TPS reaches a long time ago when the foundations of the Toyota Motor Company was established in 1918 by Sakichi Toyoda who has started spinning and weaving business based on his automatic loom. Selling of this facility in 1929 enabled his dream of manufacturing automobiles to be realized. By the funds coming from the sale and by help of newly released Japanese automotive manufacturing law in 1930, Sakichi's son Kiichiro has formed Toyota Motor Company. At that time, Japanese market was possessed by affiliated companies of Ford and General Motors (GM). World War II and economic difficulties, which were followed by industrial disputes caused resignation of Kiichiro who replaced by his cousin Eiji Toyoda. However, the individual that contribute substantially to development of TPS was Taiichi Ohno who joined the automotive business in 1943. He analyzed Western production system and determined two logical errors of them. First observation of Taiichi Ohno was that producing component in large batches causes large inventories and this leads increasing capital expenditure, space usage, and defected products. Secondly, he saw that Western production system was insufficient to listen choice of the customer for product diversification. After 1948, Ohno concentrated on small-lot production system. His main focus was to decrease the cost of production while eliminating waste. This concept has created the basic principles of TPS and he improved it further by determining two pillars of the system: "Jidoka", autonomous machine concept, and "Just-in-Time" (JIT) production. TPS is improved further by Shigeo Shingo who was hired as consultant in 1955. The efforts and harmony of Ohno and Shingo give Toyota the ability of producing variety of automobiles in low volumes with a cost advantage over its competitors. In year 1955, Toyota builds 23,000 cars per year while Ford builds more than 8,000 vehicles per day. However, in 2003, Toyota became second largest car manufacturer in the World as they passed Ford. After three years, in 2006, Toyota took number one place by overtaking GM. As a result, TPS changed conventional perception of production, which is based on mass production. (Holweg, 2007).

Details of their production system is explained in the following section.

2.2 Toyota Production System

There is no doubt that the contribution of Western practitioners to lean production philosophy is incontrovertible. They enhance lean production further by adding many comments and tools to original form of TPS. Nonetheless, lean production can be regarded as a translation of TPS from Japanese to English since many element of it are adopted from TPS. Therefore, in order to understand lean production and lean thinking profoundly, fundamentals of TPS must be researched punctiliously. Ohno (1988), Shingo (1989), Monden (1998), and Liker (2004) are the most known publications that explains the key principles of TPS.

TPS is not only a procedure for manufacturing but also a monolith set of management principles. Liker (2004) addresses 14 management principles of Toyota as follows:

1. Management decision should be performed on a long-term consideration, even if short-term financial targets are missed.
2. In order to make problems clear, a continuous process flow should be created.
3. In order to avoid overproduction, pull systems driven by the customer must be used.
4. Workload should be fixed (“Heijunka”).
5. A work environment should be promoted for stopping the works and fixing the issues in case of a problem, which enable to get quality right the first time.
6. Continuous improvement and empowerment of employees should be developed by means of standardized tasks.

7. Visual control should be utilized to prevent hiding of problems.
8. Only properly tested technology that serves for people and processes should be used.
9. Leaders who thoroughly understand the work and philosophy and can teach it to others should be grown.
10. Extraordinary people should be grown to follow company's philosophy.
11. Network of partners and suppliers should be interested in order to challenge and help them to enhance themselves.
12. The problems should be completely controlled and checked in-situ by directors ("Genchi Genbutsu").
13. When making decisions, all alternatives should be carefully considered by participation of all members, but implementation of them should be quick ("Nemawashi").
14. A learning organization should be developed by relentless reflection and continuous improvement ("Hansei" and "Kaizen").

TPS has been illustrated by a house in various sources (Liker, 2004; Lean Enterprise Institute, 2008; "Art of Lean"). These publications inspired the interpretation and development of TPS within this study. Liker and Lamb (2000), explain the role of house metaphor by emphasizing on holistic structure of house. If a house does not have a solid foundation, strong columns and a good roof, it will collapse. Therefore, the elements of structure must be well-supported and consistent with each other. TPS has such a power and consistency so that it can be represented with house example. Figure 2.1 shows TPS components, which will be explained in detail in following sections.

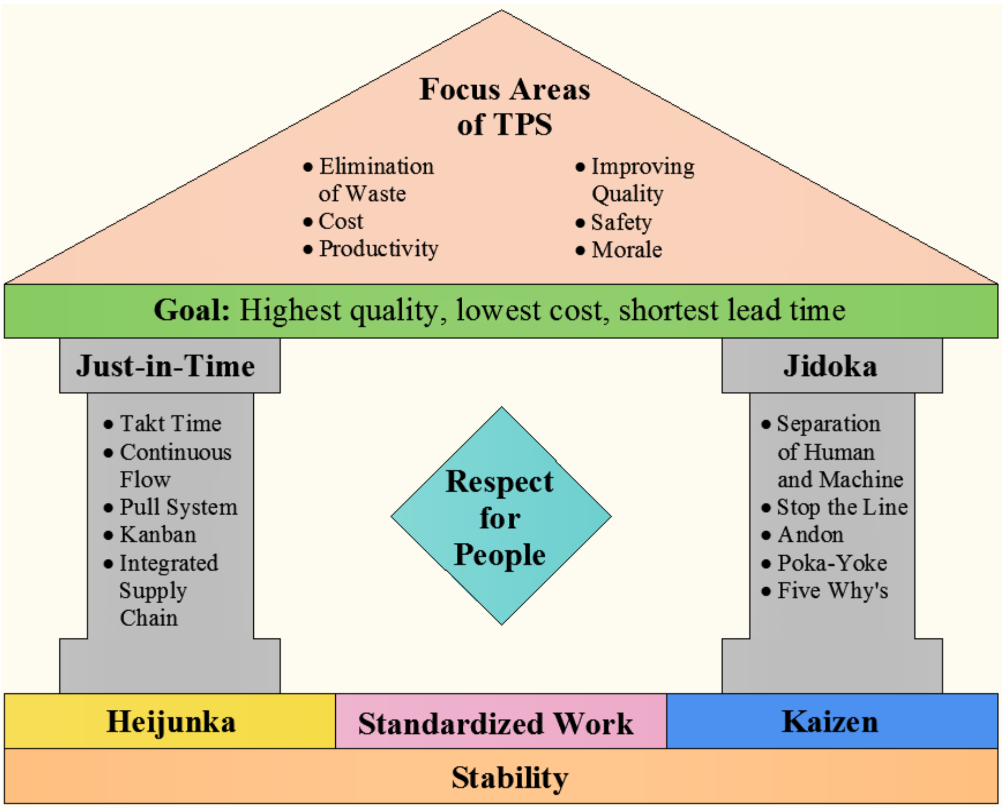

Figure 2.1: Toyota Production System House

2.2.1 Focus areas of Toyota Production System

Elimination of waste, cost reduction, increasing productivity, improving quality, ensuring safety, and promoting morale values constitute the most important focus areas of TPS, which are explained in following subsections.

2.2.1.1 Elimination of waste

The main focus of TPS is systematical elimination of all types of waste. In order to eliminate the waste, a clear description of it must be propounded. In this respect, Ohno (1988) identified seven types of "muda", Japanese term of waste, in production process. These wastes are illustrated in Figure 2.2 and explained further below;

Figure 2.2: The Seven Wastes (Liker and Lamb, 2000)

1. **Waste of overproduction:** This is a typical waste type of mass production. Producing products that are not required leads to excess inventory, overstaffing, and cost of transportation and storage.
2. **Waste of waiting (time on hand):** Workers often have no work because of stockouts, lot processing delay, equipment downtime, and capacity bottlenecks (Liker, 2004). Such cases causes an important loss of time, which is termed as waste of waiting.
3. **Waste of transportation:** Carrying materials, parts, or finished goods over long distances during the process generates inefficient usage of transportation.
4. **Waste of over-processing or incorrect process:** Mistakes in product design lead incorrect process, and fixing it requires over-processing that is a typical source of a waste.
5. **Waste of stock on hand (inventory):** Liker (2004) indicates that "*Excess raw material, WIP* (work-in-progress)*, or finished goods causing longer lead times, obsolescence, damaged goods, transportation and storage costs, and delay.*"
6. **Waste of unnecessary movement:** The time that a worker does not produce value, even walking, is accepted as a source of waste.

7. **Waste of making defective product:** Products errors is a waste type that require replacement, time, and effort.

2.2.1.2 Cost reduction

TPS continuously seeks a way to reduce sales prices by decreasing the cost of raw materials, labor, and other expenses. Traditional cost reduction methods, on the other hand, focus only on sales price that neither contribute profitability nor customer satisfaction. This approach of TPS towards cost reduction is described in Figure 2.3.

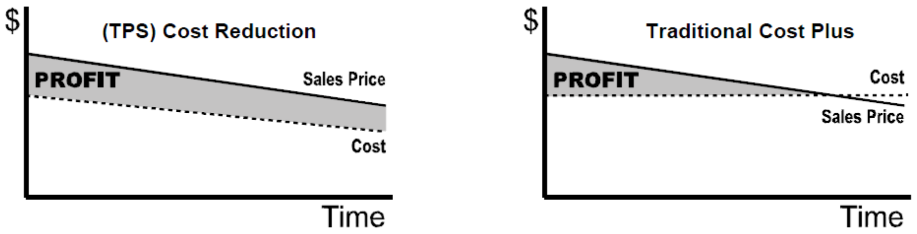

Figure 2.3: Cost Reduction of TPS (“Art of Lean”)

2.2.1.3 Increasing productivity

The best way of increasing productivity is increasing true efficiency, which concentrates on producing in sellable quantities with the fewest labor-hours possible in the best time. TPS adopts this principle of improving efficiency instead of just trying to increase production quantity with current resources (“Art of Lean”).

2.2.1.4 Improving quality

Improving quality is a vital focus area for TPS because it ensures ultimate goal of the system: increase value offered to customer. For this reason, TPS is consistently putting efforts to achieve this objective. All elements of TPS shown in Figure 2.1 primarily pursue aim of improving quality. Commitment plans, identifying errors, and training of employees are some methods for improving quality.

2.2.1.5 Ensuring safety

Safety problems usually arises when working area is huge and unorganized, tasks are difficult to perform, and individual is doing something out of the ordinary ("Art of Lean"). TPS has principles that helps to disappear of risk factors. For example, as compared to mass production, TPS prefers smaller lot size that offers small and organized working area and prevents safety problems in the field. For this reason, TPS places a great importance to standardized work to ensure safety.

2.2.1.6 Promoting morale values

Values like respect, trust, pride, integrity, dignity, and cooperation forms basic principles of human relationships in TPS. Utilizing knowledge, experience, and creativity of all employees is the mission of leader, which enables the continuous improvement ("Art of Lean").

2.2.2 Just-in-Time

"*JIT philosophy advocates: producing and/or delivering only the necessary parts, within the necessary time in the necessary quantity using the minimum necessary resources."* ("Art of Lean"). JIT systematically aims to minimize all inventory and WIP. Takt time, continuous flow, pull system, "Kanban", and integrated supply chain are some elements of JIT, which are explained in following subsections.

2.2.2.1 Takt time

“*Takt time is the time in which a unit must be produced in order to match the rate of customer demand.*” (Liker and Lamb, 2000). Takt time is calculated by both using customer requirements for a period of time and time available for manufacturing for the same period of time as shown in the Equation (1):

$$\text{Takt Time} = \frac{\text{Time Available}}{\text{Customer Requirements}} \tag{1}$$

Takt time calculation can be exemplified with following numbers. An assembly area that can take 5,000 units of product A and 15,000 units of product B in a month constitutes total of 20,000 units for customer requirements. It is assumed that the work is scheduled for two eight hours shifts from which 15 minutes of morning break, 60 minutes of lunch break, and 15 minutes of afternoon break are subtracted. If there is a 20 work days in a month, daily customer requirement equals 1,000 units per two shifts and 500 units per one shift. Moreover, total daily time available for a shift is calculated by subtracting breaks from total of 480 minutes, which is equal to 390 minutes or 23,400 seconds. As a result, Takt time is calculated as 46.8 seconds by dividing total daily time of 23,400 seconds to daily customer requirement of 500 units according to Equation 1. This result implies that completion of a unit should take 46.8 seconds. JIT aims to maintain this number because decrease of it will lead overproduction problem, whereas increase of this number will result in capacity bottleneck problem. Takt time can be used as a measurement that ensures JIT by alerting workers whenever they are getting ahead or behind (Liker and Lamb, 2000).

2.2.2.2 Continuous flow

“*Eliminating the congestion of parts within a process or between processes and achieving sequential flow production is called continuous flow processing.*” (“Art of Lean”). Continuous flow has following set of advantages (“Art of Lean”):

- It can easily shift production among different types.
- It causes fewer defects.
- It decreases WIP.
- It improves the efficiency of labor.
- It provides shorter lead times.
- It decreases required floor space.

Figure 2.4 illustrates the contribution of continuous flow to JIT principle. Continuous flow processing improves production in terms of WIP and lead time.

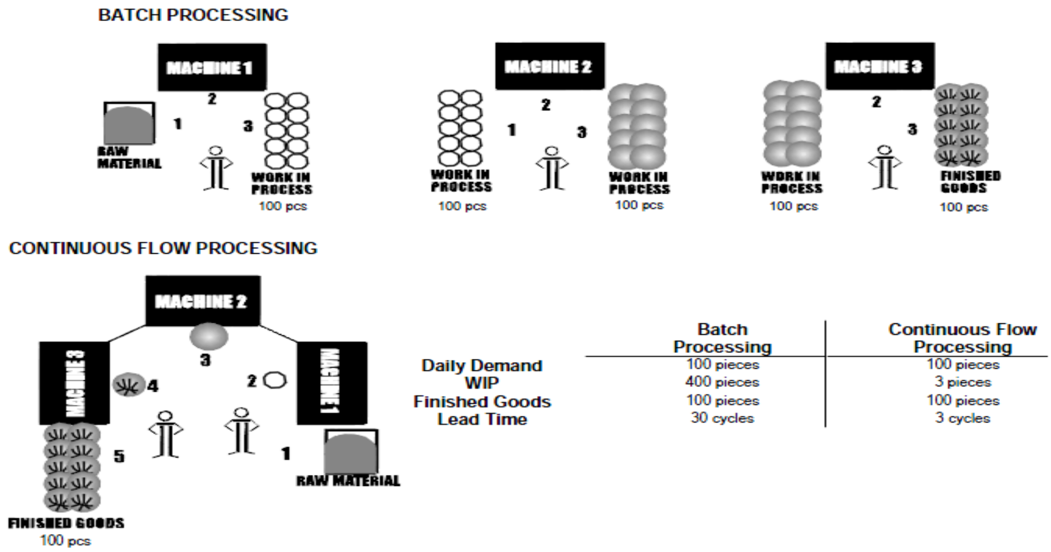

Figure 2.4: Continuous Flow Processing vs. Batch Processing ("Art of Lean")

2.2.2.3 Pull system

TPS differentiates itself through its relationship with the market. In traditional push system, production is pushed to downstream according to previously determined plans. However, in lean production, production flow is pulled by downstream with respect to demands of the market (Forza, 1996). Pull system both helps to avoid overproduction and ensures continuity of JIT. Liker (2004) explains principles of pull system as follows:

- Customers should be allowed to decide which product they want, when they want it, and the amount they want.
- WIP and warehousing of inventory must be minimized to small amount of products that customer actually prefers.
- Customer demands must be satisfied by flexible shifts instead of abiding by computer schedules.

2.2.2.4 Kanban

"*Kanban is a Japanese word that means 'visual record' and refers to a manufacturing control system developed and used in Japan.*" (Halevi, 2001). It is a simple and effective signal system that conveys instructions to withdraw parts or produce a given product. The signals of "Kanban" can be cards, colored balls, lights, and electronic systems. By means of these signals, communication between processes is procured. There are many functions of "Kanban", which are defined by Ohno (1988) as follows:

- It provides acquisition or transformation of knowledge.
- It informs people about production.
- It prevents waste of overproduction and transportation.
- It serves as a work order added to products.
- It prevents waste of making defective products by identifying process.
- It finds out the problems and carries on inventory control.

"Kanban" brings great advantage to producers by providing improvement in both work flow and equipment. According to Sugimori et al. (1977), having employed "Kanban" system reduces cost of processing information, provides rapid and precise acquisition of facts, and limits surplus capacity of preceding shops. General rules of "Kanban" are summarized by Halevi (2001) as follows:

> *1. The earlier process produces items in the quantity and sequence indicated by the Kanban.*
>
> *2. The later process picks up the number of items indicated by the Kanban at the earlier process.*
>
> *3. No items are made or transported without a Kanban.*
>
> *4. Always attach a Kanban to the goods.*
>
> *5. Defective products are not sent to the subsequent process. The result is 100% defect-free goods. This method identifies the process making the defectives.*
>
> *6. Reducing the number of Kanban increase their sensitivity. This reveals existing problems and maintains inventory control.*

2.2.2.5 Integrated supply chain

Integrated supply chain in JIT philosophy aims to improve supplier relationships by continuously supporting and forcing suppliers to improve themselves. Patterson et al. (2003) explain benefits of supply chain integration based on study of Levary (2000) as follows:

1. It minimizes bullwhip effect.
2. It maximizes the efficiency of conducting activities along the supply chain.
3. It minimizes inventories along the supply chain.
4. It minimizes cycle times along the supply chain.
5. It achieves an acceptable level of quality along the supply chain.

2.2.3 Jidoka

“Jidoka” or autonomous machine concept is one of the fundamental components of TPS. Whenever an abnormal or defective condition arises in production process, “Jidoka” stops to machines and workers stop the production line. The reasons why

"Jidoka" is so important for TPS are that it both prevents making too much when required amount is produced and enables the control of abnormality (Sugimori et al., 1977).

2.2.3.1 Separation of human and machine

If a machine used in the process that has ability of detect a problem and alert the operator, there will be no more need for a worker who controls the machine and waits for it to cycle. Separation of human and machine leads operator to do more value-added works (Liker and Lamb, 2000). Person machine separation is illustrated in Figure 2.5.

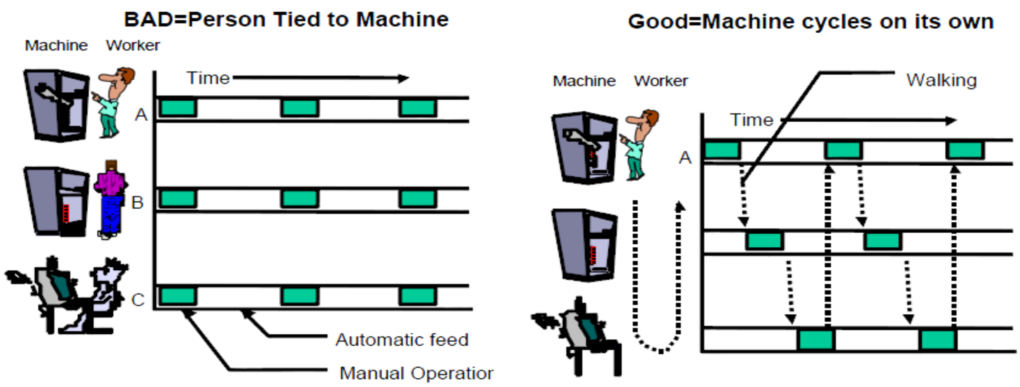

Figure 2.5: Person-Machine Separation (Liker and Lamb, 2000)

2.2.3.2 Stop the line

In TPS, every assembly line worker is empowered to stop the line if they see defects or problems. A production line may have been halted for several times. It can be argued that this causes productivity loss but, at the same time, problems are not hidden anymore. They are visualized and fixed directly with all resources. As a result, good quality, which is primary importance in TPS, is achieved for the first time (Li and Blumenfeld, 2005).

2.2.3.3 Andon

All components of "Jidoka" are complementary for each other. In this respect, "Andon" can be regarded as a supplementary concept for stop the line principle that is described in Section 2.2.3.2. "Andon" is a Japanese term used for visible control system of line stopping by means of an electrical light board or other signal devices. When a worker realizes an abnormality the line is stopped and people are warned through "Andon" as shown in Figure 2.6:

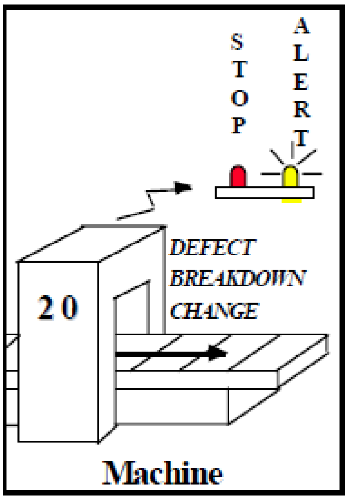

Figure 2.6: Andon System (Liker and Lamb, 2000)

"Andon" and stopping the line may have been avoided due to frequent stop of work. However, a research figured out that implementing "Andon" improves product quality in terms of production rate by decreasing the repair times (Li and Blumenfeld, 2005).

2.2.3.4 Poka-yoke

"Poka-yoke" is Japanese term of error proofing. It is the control system of TPS that achieves full inspection over the production. It can be both used as a control or as a warning. As control, it halts the process until the problem is solved. As warning, on the other hand, it flashes an exciter lamp to warn the worker about the problem. Shingo (1989) indicates that there are three types of “poka-yoke” method:

- Contact Method: It identifies defected products by inspecting the shape, size, and color of the product.
- Fixed Value Method: It warns the operator if given numbers of movements are not made.
- Motion Step Method: It determines whether predefined steps or motions of the process have been followed or not.

2.2.3.5 Five why’s

Five why’s is a “Jidoka” component, which try to solve root causes of the problems that result in stop of the machines. Liker (2004) explains five why’s as “*a method to pursue the deeper, systematic causes of a problem to find correspondingly deeper countermeasures*”. This process is exemplified by Scholtes (1998) with the situation provided in Figure 2.7. The problem is related to an oil leakage coming from a machine. Root cause of the problem is established by asking five times “Why” question while corresponding level of improvement is implemented. As a result, the main reason of the problem is determined. A simple leakage leads company to change the policy of purchasing.

Level of a problem	Corresponding level of improvement
There is a puddle of oil on the shop floor.	Clean up the oil.
Why?	
Because the machine is leaking oil.	
Why?	
Because the gasket is deteriorating.	Replace the gasket.
Why?	
Because we bought gaskets made of inferior material.	Buy better gaskets.
Why?	
Because we got a good deal on them.	
Why?	
Because the purchasing agent gets evaluated on the basis of savings over normal price tags.	Change the policy.

Figure 2.7: Five Why's Example (Scholtes, 1998)

2.2.4 Respect for people

TPS accept the employees as the heart of the system because the goals of highest quality, lowest cost, and shortest lead time can be achieved in the best way through participation of all employees. Competence of individuals or work teams can be increased by learning how to apply TPS rules. TPS determines areas where the production team members can participate in achieving company goals as: Developing work standards, forming a problem solving mechanism for daily performance, participating in the continuous improvement process, organizing an efficient teamwork ("Art of Lean").

2.2.5 Heijunka

"Heijunka" is Japanese term of production smoothing, which means leveling the volume and mix of items so that there is a little variation in production from day to day. A leveled schedule is essential in terms of keeping the system stable and allowing for minimum inventory. Elimination of waste does not fully guarantees lean production to be successful. Eliminating overburden to people and equipment and eliminating the unbalance in the production schedule is as important as waste elimination because achieving “Heijunka” is the starting point of eliminating unevenness (“mura”), which is fundamental to eliminate waste (“muda”) and overburden (“muri”). This is explained as relationships of three M(s) in TPS (Liker, 2004).

A downstream requirement of 100 units per day can be produced either by producing 1,000 units every 10 day or by producing daily lot size of 100 units. First choice create an average inventory of 500 units while second choice has average of 50 units. Figure 2.8 shows role of “Heijunka” in reducing lot size by using this example (“Art of Lean”).

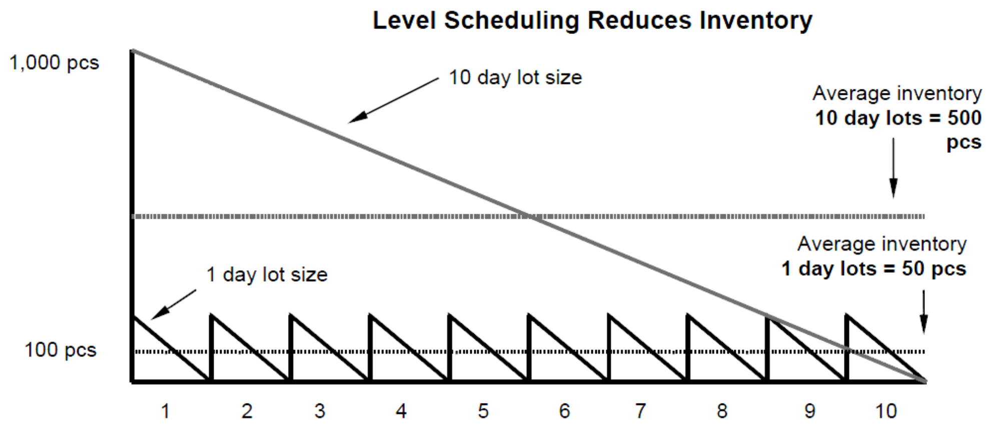

Figure 2.8: “Heijunka” and Inventory Size (“Art of Lean”)

Liker and Lamb (2000) explain reasons of implementing “Heijunka” as:

- It reduces risk of unsold products.
- It improves the quality.

- It requires less floor space usage.
- It enables to smooth demand on upstream processes.
- It makes better controlling and monitoring of production environment.

2.2.6 Standardized work

Standardized work is important for ensuring flow and pull. Using stable and repeatable methods maintain the predictability, regular timing, and regular output of the production process. In addition, standardized work is easier, cheaper, and faster to manage. (Liker, 2004).

Five S(s) rule of TPS shows the role of standardized work in elimination of waste. Five S(s) shown in Figure 2.9 are coming from Japanese words of "seiri", "seiton", "seiso", "seiketsu", and "shitsuke", which are translated English as sort, straighten, shine, standardize, and sustain respectively. Sort means organization of items, which suggests throwing unnecessary items while keeping necessary ones. Straighten indicates orderliness by keeping everything in its place. Shine term is used for cleaning process, which acts as a form of inspection that exposes abnormal and pre-failure conditions. Standardize is the term that is explained in this section. It monitors first three S(s). Sustain stands for maintaining and stabilizing the workplace (Liker and Lamb, 2000).

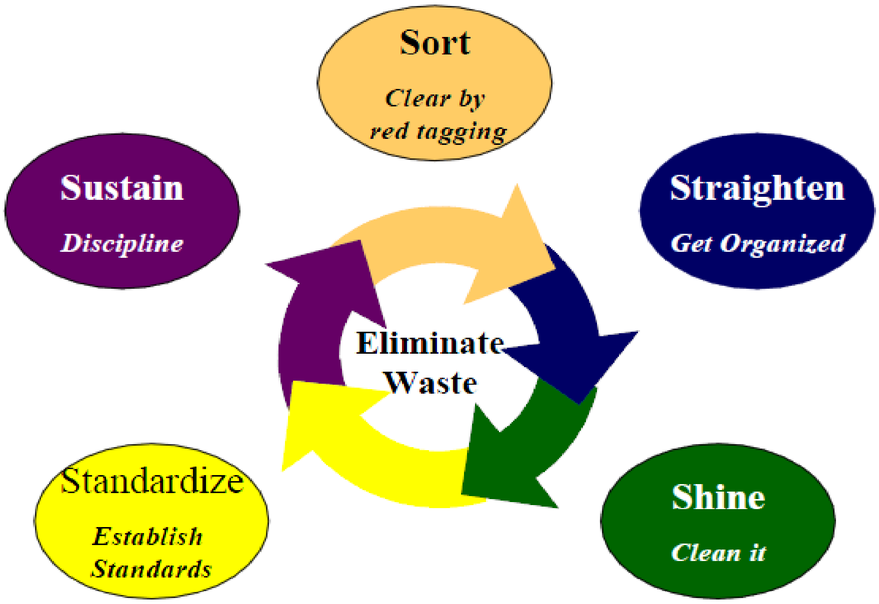

Figure 2.9: The Five S(s) (Liker and Lamb, 2000)

2.2.7 Kaizen

"Kaizen" is translated from Japanese as continuous improvement. Liker (2004), explains role of Kaizen in TPS as follows:

> *Kaizen teaches individuals skills for working effectively in small groups, solving problems, documenting and improving processes, collecting and analyzing data, and self-managing within a peer group. It pushes the decision making (or proposal making) down to the workers and requires open discussion and a group consensus before implementing any decisions. Kaizen is a total philosophy that strives for perfection and sustains TPS on a daily basis.*

"Kaizen" is a gradual improvement of quality to reach perfection. Although it does not require a great investment for implementation, it demands continuous efforts and commitment. Starting from this point, Radharamanan et al. (1996) explains characteristics of "Kaizen" based on Shingo (1985) as follows:

- Its effects are long term and lasting.
- It has continuous and incremental time structure.
- It focuses on collectiveness, team effort, and system focus.
- Its basic methods are maintenance and improvement.
- It encourages “know-how” and conventional updating.
- It demands less investment but greater effort to maintain.
- Its effort orientation is towards to persons.

Value-stream mapping is the most widely used tool to implement continuous improvement. A value stream map includes all necessary materials and information required in manufacturing process of a product and shows how they flow through production system. It simply transfers information about the value stream to a map that demonstrates either current or future situation of production process. Figure 2.10 shows an example value stream map.

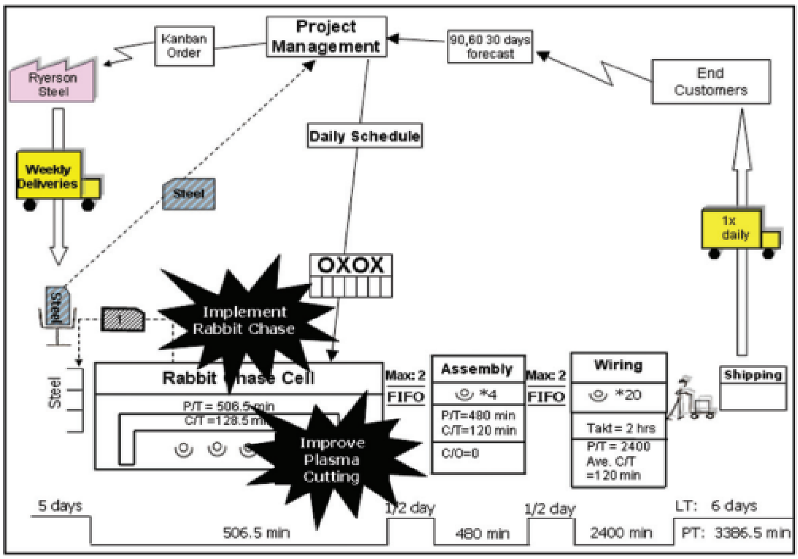

Figure 2.10: An Example Value Stream Map (Chen et al., 2010)

2.2.8 Stability

Organizational stability is the foundation of TPS. All TPS components discussed within this section not only serve for goals of highest quality, lowest cost, and shortest lead time but also secure organizational stability of the system. In addition to these components, equipment reliability is critical for TPS. Maintenance is very important to eliminate machinery and equipment problems. TPS internalize that the prevention of problems is more important than the ability of repair equipment. Changeover capacity of equipment is another important factor for flexibility, level production, and capital savings. The ability to quick and accurate changeover and set-up the equipment removes wastes of waiting, overproduction, and inventory. Furthermore, quality standards of equipment ensure a production in TPS norms. Finally, procurement strategy of equipment is based on meeting minimum requirements. Bells and whistles can be added anytime if there exists a requirement. Reliability and ease of maintenance are privileged concepts for the equipment purchase. Thanks to machinery and equipment reliability and other elements of TPS, organizational stability of the system is guaranteed ("Art of Lean").

2.3 Taylorism & Fordism versus Toyotism

TPS and principles that it brought have dominated manufacturing industry since 1980s by its path-breaking dynamics. Inability of previous approaches that were used widely in production processes, like Taylorism and Fordism, led emergence of lean production concept. In order to better conceive pioneering principles of lean production, conventional methods of production should be examined. In this regard, Taylorism, Fordism, and their differences with lean production are discussed within this section.

2.3.1 Taylorism

Taylorism, also called "scientific management", was a theory developed by Frederic Winslow Taylor, who aims to make efficiency better in terms of labor productivity. Taylor (1911) determined main principles of scientific management as follows:

- Work methods should be determined by scientific studies instead of rule of thumb methods.
- Each worker should be selected, trained, and developed based on scientific techniques. They should not be allowed to choose their own works or train themselves.
- Workers should be given detailed instructions and effective supervision during performance of the task.
- Work should be distributed equally between managers and workers. By this way, managers will be responsible for planning of the work by applying scientific management techniques and the workers will perform the task according to planned work.

Taylorism has gathered great attention throughout the years. Although it is criticized due to reasons like exploitation of workers, individualist approach, and mechanical nature, it has been used widely in manufacturing industry. According to Green (1986), the influence of Taylorism is increasing the ability of managing the work process by both controlling the planning and the execution of the work.

2.3.2 Fordism

Fordism is developed by Henry Ford, the founder of the Ford Motor Company. He has inspired from the principles of Taylorism and developed it further. Fordism is based on standardized mass production and aims to produce cheap products in high volumes. Principles of Fordism can be summarized as follows:

- There should be a transformation from craftwork to machine work in order to generate standardized products.
- The work should progress throughout the assembly lines, which enables low skilled workers to operate by perpetually doing same task.
- Salary of the workers should be high enough so that they can able to buy products that they produce.

2.3.3 Basic differences of Toyotism

The conventional Fordist and Taylorist production techniques strictly separates the planning and execution functions of a project and assign these functions to different groups of people. Functional specialization and detailed division of labor are accepted as the ideal way of increasing the efficiency for conventional production techniques. Braczyk (1996) determines the main characteristics of Fordist production model as standardization, structural organization, predetermination, and calculability. The new labor coordination method, lean production, on the other hand, adopts opposite principles. Braczyk (1996) explains this with following opposition terms:

> *Regulation versus deregulation; normal working hours versus flexible working hours; working time versus company time; instruction versus negotiation; mistrust versus trust; exploitation versus further training; hierarchy versus self-organization; segmentation versus cooperation; division of labor versus integration; solidarity versus self-interest.*

Another deep difference of lean production from conventional production techniques adopted by Taylorism and Fordism comes from its approach to workforce. Lean production do not recognize human resources as a resistance to supply of the work. On the contrary, labor force is accepted as a part of unified community and a greater collaboration is promoted (Forza, 1996). Furthermore, when compared with Fordism, the lean model requires less inventory, less field, less transportation, less time to install machineries, less labor, and less technology (Ohno, 1988). Therefore, lean model absolutely overweighs Taylorism and Fordism, both from the production point of view, since it become flexible and gains in quality; and from the human point of view, where worker involvement is enhanced (Forza, 1996).

2.4 International Motor Vehicle Program and Integration of TPS to the West

Toyota's success could not be underestimated by its Western competitors. First and second oil crises, occurred in 1973 and 1979 respectively, compel big three (Ford, GM, and Chrysler) to take action. Predicament of Western automobile manufacturers led to initiation of IMVP at MIT in 1979. IMVP has targeted to understand challenges that global automobile manufacturers suffer from, to analyze Japanese form of production, and to establish standards for car producers. As a result of studies of IMVP, many publications were released. It is argued that (Holweg, 2007) the term "lean" is first coined by Krafcik (1988) whose research is continued by the IMVP. The efforts of IMVP researchers have brought results with a very famous book "The Machine That Changed the World" (Womack et al., 1990) that explains "*how Japan's secret weapon in the global auto wars will revolutionize western industry*". With contributions of this book, success of TPS was dealt with from many aspect and it was translated to the West as "lean production".

2.5 Mass Production versus Lean Production

There are some characteristic differences between mass production and lean production. Womack et al. (1990) indicates that mass production do not require highly skilled workers for production. Design of products is made by unskilled or semi-skilled workers by operating machines that serves for single purpose. This approach ensures high volume of standardized products, but mass production adds many buffers to prevent setback. It requires excessive number of workers, space, and raw material to continue production. Although customer purchases products with low prices, they do not have many options to choose because customer preferences are underestimated in mass production. In addition to this, labor force working in mass production finds their job unexciting and demoralizing. Lean production, on the other hand, combines craft production and mass production. It uses multi-skilled workers in different stages of an organization in a flexible manner. By this way, it achieves to get products in a huge variety while satisfying the customers.

The most impressive difference between mass production and lean production is that mass production has ultimate goal of producing in high volumes with maximum level of inventories and narrow range of standardized product that can tolerate an acceptable number of defects whereas lean production pursuing perfection by permanently decreasing cost, targeting zero defects, zero inventories, and endless product diversification (Womack et al., 1990).

TPS and lean production prefer order-based production instead of large lot storage, which is used in mass production. Shingo (1989) determines the characteristics of order-based production as follows:

- Order-based production requires overtime work.
- Machinery capacities are too much and they can be operated by temporary workers.
- Period of the order delivery must be longer than cycle time of production.
- Delivery of order-based product is fast.
- There is a necessity of strong market research.
- Scheduling of production is driven by order-based demand.

2.6 Benefits of Lean Production

All concepts discussed throughout this chapter principally present potential benefits of TPS and correspondingly those of lean production. Aim of this section is providing information from literature that directly express benefits of lean production. In this respect, researches regarding this subject are reviewed and, as a result, following paragraphs are organized.

One of the most remarkable advantages of lean production is that it is a holistic approach that tries to manage many aspects of a project together. Kosonen and Buhanist (1995) indicate that all the system parts have to be considered in production organization as a whole to achieve major changes, and offer the influence diagram shown in Figure 2.11 to specify areas to be considered when developing lean enterprise solutions. From this point of view, lean production gives opportunity of awareness related to all parts of a project.

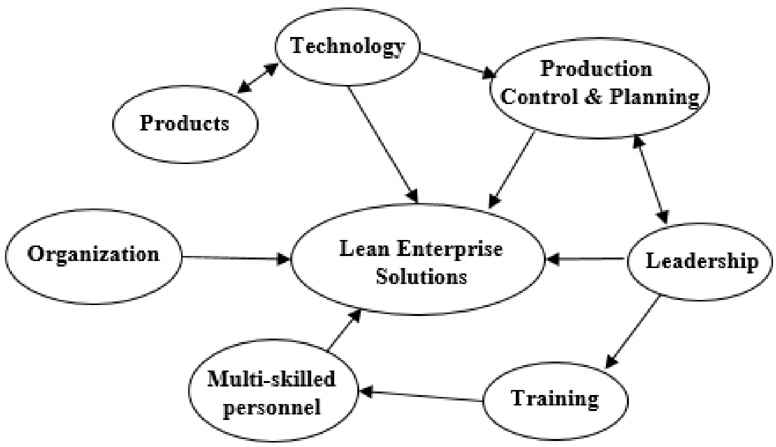

Figure 2.11: Areas to be Considered When Developing Lean Enterprise Solutions (adapted from Kosonen and Buhanist, 1995)

Another benefit of lean production is that resource inputs like materials, parts, production operations, time needed for set-ups, etc. are required less while there is pressure through better quality, higher technical specifications, greater product variety, etc. for higher output performance to be achieved. This approach increases customer satisfaction, which eventually provide a market share larger than the shares of competitors (Katayama and Bennett, 1996). Figure 2.12 shows the essential elements of lean production based on this explanation.

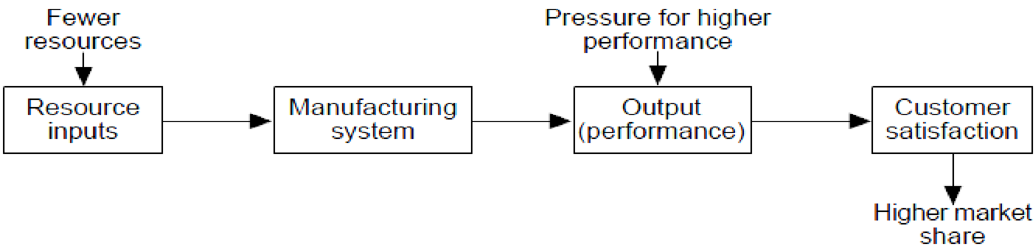

Figure 2.12: The Essential Elements of Lean Production (Katayama and Bennett, 1996)

Lean production also has benefits related to characteristics of workplace. Forza (1996) developed nine hypothesis that try to identify the work organization characteristics of lean production plants:

1. Lean production plants have advantage of greater employee commitment to continuous quality improvement.
2. Lean production plants have greater usage of small team of problem solving.
3. Worker suggestions for improvement are more considered in lean production plants.
4. Greater supervisory interaction facilities is enhanced in lean production plants.
5. Communication between managers, engineers, and workers is more in lean production plants.
6. Lean production plants provides greater and faster feedback.
7. Greater decentralization of authority is adopted in lean production plants.
8. Lean production plants have greater usage of multi-skilled employees.
9. Better documentation of shop floor procedures is developed in lean production plants.

Finally, a general summary of lean production benefits are arranged as follows: (“Kotelnikov”)

- Reduction of waste
- Reduction of production cost
- Decreased cycle times of manufacturing
- Reduction of labor
- Reduction of inventory
- Increase in capacity of facilities
- Higher quality
- Higher profits
- Higher system flexibility
- More strategic focus
- Improved cash flows

2.7 Lean Thinking

Lean production utilizes numerous tools and methodologies, which are mainly based on TPS, in order to change conventional manufacturing process. Womack et al. (1990) explains many of these tools and methodologies to the West in order to show them the potential of Japan’s production system. However, in the preface of their following books Womack and Jones (1996), state that in their trips around the world, managers, employees, investors, suppliers, and customers are always asking them how they implement lean principles, which are thought by “The Machine That Changed the World”. Starting point of lean thinking is effort of Womack and Jones to answer this question. As a result, they published “Lean Thinking” to express how to implement lean production methods. This book is also very important in terms of adding eighth waste to seven waste type of Ohno (1988), which are described in Section 2.2.1.1: goods and services that do not meet the needs of the customer. Lean thinking can be regarded as a theory or philosophy behind lean production. It shows how to adopt change, process of becoming Toyota, and what can be done after. Womack and Jones (1996) summarizes lean thinking into five principles.

“1. Precisely specify value by specific product.

2. Identify the value stream for each product.

3. Make value flow without interruptions.

4. Let the customer pull value from the producer

5. Pursue perfection.”

“Specify value” means to provide specific products, information, and services with specific capabilities or applications offered at a specific cost and time from the perspective of the customer and stakeholders. “Identifying the value stream” stands for developing a hierarchical model of current value stream and eliminating non-value adding processes and activities by analyzing the value stream. “Make value flow without interruption” aims to design and implement the desired value stream to make flow of value added steps possible. Jorgensen and Emmitt (2008) indicate that the central of lean thinking is the concept of customer. Therefore, “let the customer pull value from the producer” covers producing a plan in which activities, their workloads, and objectives are determined based on customer preferences. Finally, “pursue perfection” means continuously seeking ways to increase value provision, reducing to cost of non-value adding but necessary activities, and removing successive layers of waste (Haque and Moore, 2004).

CHAPTER 3

LEAN CONSTRUCTION

Lean construction efforts in construction industry have started in 1990s as a consequence of tremendous impacts of lean production on manufacturing industry. Various sources (Koskela, 2004a; Sayer and Anderson, 2012) agree that the term “lean construction” was initially introduced in the first meeting of IGLC. IGLC is an organization that brings together researchers and professionals of architecture, engineering, and construction (AEC) industry who want to contribute lean construction research, practice, and education. It has organizing annual conferences that started in 1993 (Espoo-Finland) and the latest conference was held in Brazil in 2013. There are another organizations, such as LCI, which are also holding the conferences and publishing researches to spread lean construction principles. Lean construction idea, which is shaped by the efforts of these organizations is not an imitation of lean production. Although Koskela (2004b) agrees that theory of lean thinking or TPS have contributed manufacturing industry significantly, these theories are insufficient for general description of production, at least for construction industry. In this respect, he proposed a new production theory from which lean construction has taken its core principles.

Throughout this chapter, current situation of the construction industry, change efforts of it, Koskela’s new production theory, origination and basic principles of lean construction, application techniques of lean construction, and measuring the effects of lean construction principles will be discussed based on a detailed literature survey.

3.1 Current Situation of the Construction Industry

Based on Flyvbjerg et al. (2004) research, Tezel and Nielsen (2013) state that among 258 major public transport infrastructure projects, which were conducted between 1927 and 1998 in USA, Japan, Europe, and many other developing countries and had total value of 90 billion US Dollars, approximately 30% of them have exceeded their budgets and 40% of them failed to meet client revenues. These numbers indicate the enormous problems regarding the construction industry. Characteristics like on-site production, on-of-a kind projects, and complexity distinguish construction industry from manufacturing. Combined effects of these three characteristics as well as weather conditions, owner changes, and the interaction between multiple operations can produce unique situations and creates high level of uncertainty that induce underachievement of construction projects (Salem et al., 2006).

Koskela et al. (2002) indicate that today's projects are complex, uncertain, and quick (CUQ) by referencing Shenhar and Laufer (1995). There is a pressure of shorter durations, and too much complexity and uncertainty arises from changing demands of clients. Bertelsen (2004) explains the sources of complexity in construction as: Nature of its products, undocumented production processes, shared resources between parties, changing participants, and complex social relationships with the client. These complexity sources affect performance of the construction projects.

Current practice of construction management revolves around activities or contract (Howell and Ballard, 1998). Although CPM is used widely in scheduling of construction projects, it includes deficiencies such as cumbersome repetition of similar activities and relationships, and it neglects important production information like production rate and work location (Yang and Ioannou, 2001). Even highly detailed CPM schedules fail to manage process because they simply link activities with sequential chains and try to manage them separately. Circumstances are changing rapidly when projects are CUQ and it is almost impossible to manage projects within schedule and budget units targeted at the beginning. Howell and Ballard (1998) state that CUQ projects are most likely to fail when only traditional approaches are used.

Traditional model of project management uses project execution techniques of Project Management Body of Knowledge (PMBOK). Howell and Koskela (2000) explain tools and techniques offered by PMBOK (Duncan, 1996) in five steps:

1) Determination of an overall plan.
2) Scope definition of work to be performed.
3) Breaking the scope into smaller packages or activities.
4) Management of time and cost for each activity.
5) Management of quality and change.

According to Koskela and Howell (2001), primary processes of project management defined by PMBOK, namely planning process, executing process, and controlling process constitute a closed loop as shown in Figure 3.1. Accordingly, planning processes produce plans, which are conducted by executing processes. If plans and results do not match up with each other, controlling processes implement changes to planning processes. Reliability of plans is checked by performance data and improved by corrections, which are transferred from controlling processes to executing processes and vice versa. However, this system includes some bottlenecks in practice, which are identified by Koskela and Howell (2001) as follows:

- Planning is conducted for other purposes instead of execution and it do not have a self-control system.
- Execution does not try to carry out plans since they are unrealistic.
- Control mechanism causes negative impacts on execution instead of correction.

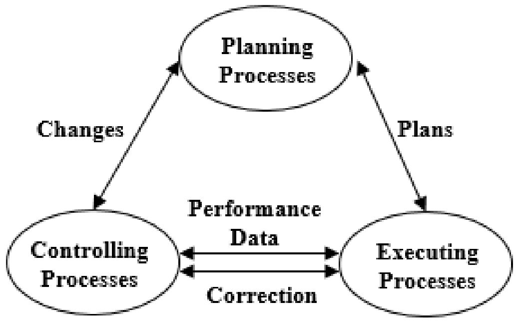

Figure 3.1: Primary Processes of Project Management According to PMBOK (adapted from Koskela and Howell, 2001)

As a result, due to problems explained in this section, poor performance of construction industry has augmented for many years. This situation has triggered the change efforts in the construction industry, which are discussed in the following section.

3.2 Change Efforts

Alteration of construction industry has been desired since two decades. Reports like Koskela (1992), Egan (1998) and Koskela (2000) exhibited performance problems of construction industry and offered rethinking current construction management theories. Egan (1998) states that many people are dissatisfied with the overall performance of construction industry because profitability rates are falling as well as investments to research, development, and training are very low; and identifies five areas of change to improve performance of construction industry as follows: *"committed leadership", "a focus on the customer", "integrated process and teams", "a quality driven agenda", and "commitment to people"*. These areas are parallel with principles of lean thinking. Similarly, Koskela (1992) and Koskela (2000) indicate the necessity of adaptation of new production theory to construction, which improved competitiveness in manufacturing industry by identifying and eliminating the waste.

Despite limited efforts to adopt lean principles are gaining momentum, assimilation of innovations in construction domain is slower than those of other industries (Koerckel and Ballard, 2005). Cultural barriers within the construction industry constitute a challenge for adoption of innovations (Johansen et al., 2004). As a result, the industry resists to change that take other industries such as manufacturing a step further (Halpin and Kueckmann, 2002). Diekmann et al. (2004) underline that manufacturing outweigh construction in terms of customer focus, culture of doing business and people performing operations, work place organization and standardization, waste minimization, and continuous improvement practices. Although both manufacturing and construction industry have same goal of generating products that meets customer's requirement within the minimum time and at the lowest cost, construction industry does not apply lean principles as successful as manufacturing industry (Mao and Zhang, 2008). Implementation of lean practices is not easy task despite existence of proven benefits. Engrained doctrines of the current practices make people hesitate for change. Lean based project management requires an alteration in both individual and organizational behaviors. Koskela et al. (2002) determines urgency, leadership, focus, structure, discipline, and trajectory as themes to be followed in order to internalize the change.

Although change efforts are not widespread yet, there are some initiatives to adopt lean principles in the construction industry. By referencing Ballard and Howell (2003), Tezel and Nielsen (2013) reported that countries including Australia, Brazil, Denmark, Ecuador, Finland, Peru, Singapore, the United Kingdom, and the United States implement lean construction in their industries.

3.3 Transportation-Flow-Value Theory

It is an indispensability to have a production theory regardless of types of the industry or sector. According to Koskela et al. (2002), existence of the theory results in an improved performance in the production and "*it provides an ultimate benchmark for practice.*" Therefore, construction industry should adopt a reliable theory. At first glance, lean thinking theory may be perceived to satisfy this requirement, but it does not precisely comply with definition of the theory. Koskela (2004b) emphasizes that "Lean Thinking" (Womack and Jones, 1996) helped many practitioners to learn core principles of lean production and encouraged them to convert themselves from mass production to lean. However, five principles that it brought, which were previously described in Section 2.7, do not systematically encapsulate value generation and other core topics. Furthermore, application of them for construction is out of scope. For this reason, Koskela (2004b) concludes that "lean thinking", under these circumstances, is an ill-defined theory and there is a need for a generic theory of production that procures a solid foundation for designing, operating, and improving production systems. Therefore, TPS or lean production of the West, is not a starting point for theory of production. The starting point is rather Koskela's transformation-flow-value (TFV) theory (Ballard et al., 2001). Barshani et al. (2004) indicate that combined view of Koskela (1992), which includes transformation of inputs to outputs, flow of material and information, and value generation process, formed basis for integration of craft, mass, and lean production paradigms. As a result, TFV theory has emerged (Koskela, 2000).

There are three basic views on production. First of all, transformation view of production has been dominant throughout the twentieth century. According to this view, production is accepted as a transformation of inputs and outputs. It decomposes the total transformation into smaller transformations and try to separately manage these small transformations, called as tasks, by trying to minimize the cost associated with them. Although transformation view has been widely used in economics, it has two important shortcomings: Firstly, it misses out that there are other phenomena in production other than transformation. Secondly, it does not pay attention how to ensure customer requirements or how to avoid waste even though it figures out how tasks need to be realized in a production. Second view on production is production as flow. This view has sprung from lean production of Toyota. The main target of this view is elimination of waste from the production. In this sense, lead time reduction, decrease on variability, and simplification are promoted as principles of flow theory. Third view on production is value generation that aims to reach best possible value from the point of customer (Koskela et al., 2002). These three view of production separately introduce practical tools and methods. However, there was not any explicit theory of production that embraces all three views of production. This is the reason why TFV theory of production was offered by Koskela (2000). TFV theory of production creates a unified conceptualization of production. The vital importance of TFV theory is that it places emphasis on modelling, structuring, controlling, and improving production from combined view of transformation, value, and, flow. Table 3.1 presents the elements of TFV theory of production in terms of; conceptualization of production, main principle, methods and practices, practical contribution, and suggested name of practical application.

Table 3.1: TFV Theory of Production (adapted from Koskela et al., 2002)

	Transformation View	**Flow View**	**Value Generation View**
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 fulfillment of his/her requirements
Main Principle	Getting production realized efficiently	Elimination of waste (Non-value-adding activities)	Elimination of value loss (Achieve value in relation to best possible value)
Methods and Practices	Work breakdown structure, material requirements planning, organizational responsibility chart	Continuous flow, pull production control, continuous improvement	Methods for requirement capture, quality function deployment
Practical Contribution	Taking care of what has to be done	Making sure that unnecessary things are done as little as possible	Taking care that customer requirements are met in the best possible manner
Suggested Name of Practical Application	Task management	Flow Management	Value Management

Bertelsen and Koskela (2002) identify a cyclic relationship between TFV elements that produce value management, contract management, and process management as shown in Figure 3.2. Based on this cycle, the authors explain six different types of relationships:

- Value-Task relationship concern the preparation of work breakdown structure (WBS), contracting and contract management.
- Task-Value relationship is about the classical quality view such as conformance to specification.
- Task-Flow relationship develops teambuilding.
- Flow-Task relationship ensures that flows provide the requirements needed by tasks.
- Flow-Value relationship manages the delivery of value to the client.
- Value-Flow relationship determines whether the user requirements are clear to outsider or not.

By means of these relationships, construction turns into a value generation process for the customer.

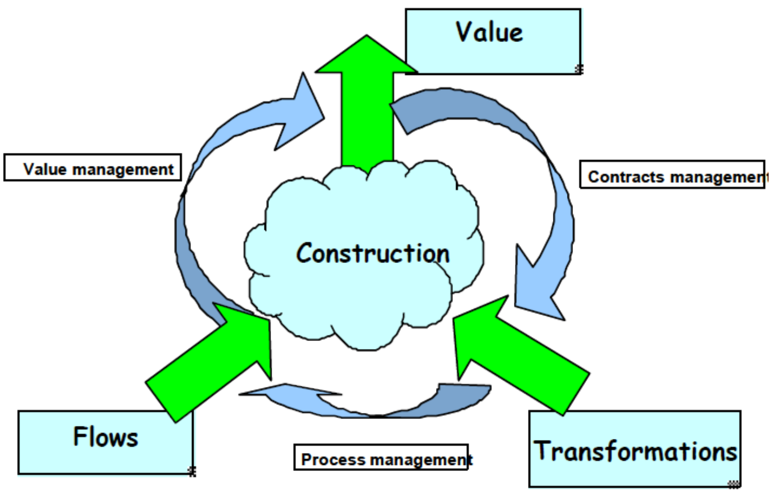

Figure 3.2: Three Part Management in Construction (Bertelsen and Koskela, 2002)

Koskela (2000) mentions another benefit of TFV theory by expressing positive impacts of its each component on the other components. These impacts are summarized at Table 3.2.

Table 3.2: Interaction between TFV Components (adapted from Koskela, 2000)

	Impact on Transformation	**Impact on Flow**	**Impact on Value Generation**
Impact from Transformation on Another Concept		More expensive transformation technology will provide for less variability	More expensive inputs contribute to better product
Impact from Flow on Another Concept	Flows with less variability require less capacity. It is easier to introduce new transformation technology, if there is less variability		More flexible production system allows the satisfaction of more variable demand pattern. Production system with less internal variability is capable of producing products of higher quality
Impact from Value Generation on Another Concept	More variable demand patterns prevent scale benefits and high utilization	Perfection of internal customer-supplier relationships contributes to reduction of waste	

Ballard et al. (2001) indicate production system design can be lean when it is prepared based on TFV goals; and accordingly proposed hierarchical production system design as shown in Figure 3.3.

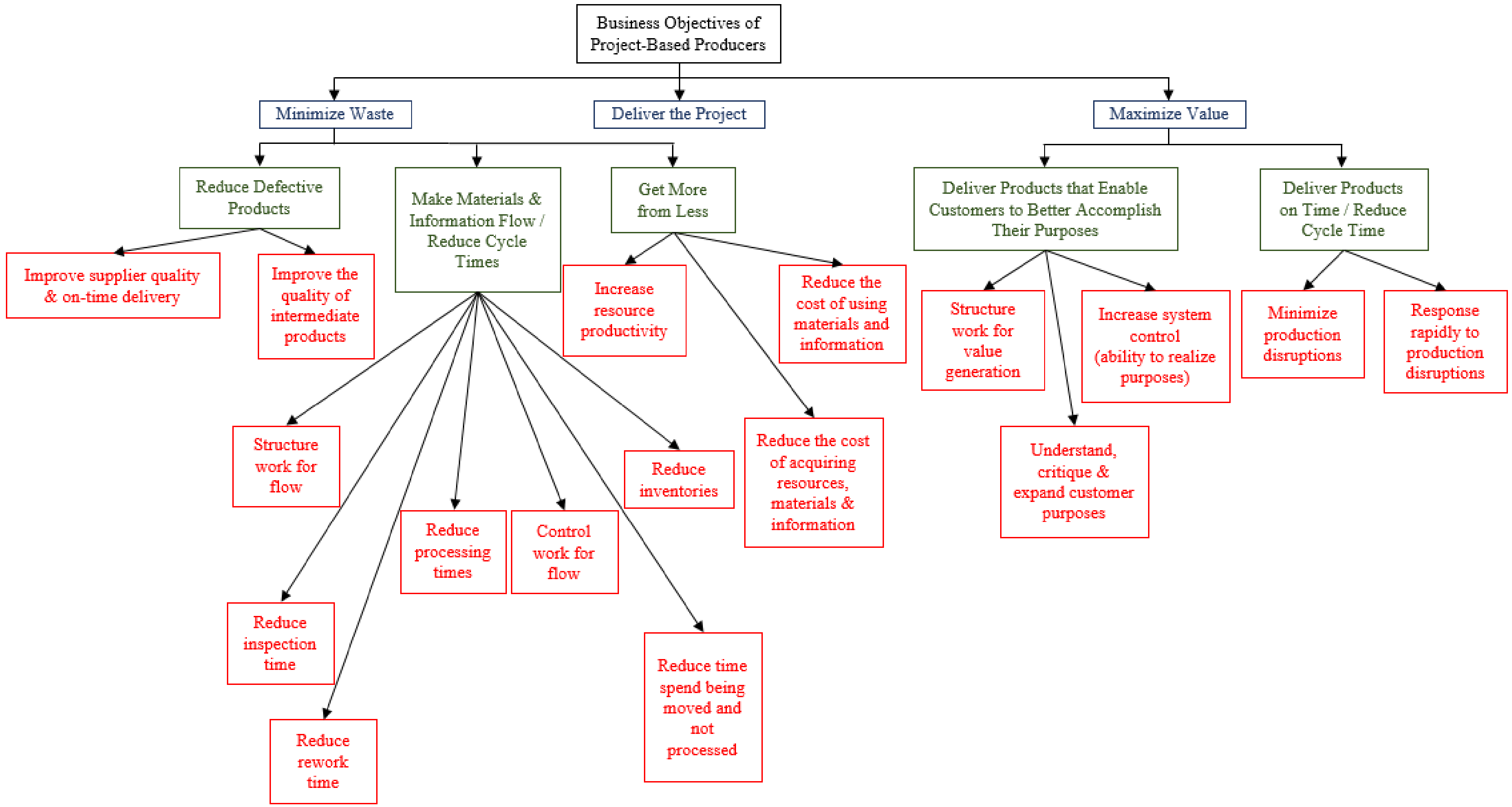

Figure 3.3: Lean Production System Design (adapted from Ballard et al., 2001)

3.4 Origination and Basic Principles of Lean Construction

Similar to lean production, lean construction puts effort in minimizing waste in flows and improving value to customer. Although it is mainly affected by lean production, there are contributions of several theories in its development. Jorgensen (2006) created a schematic overview to illustrate the emergence of lean construction. Figure 3.4 explains that lean construction is subjected to too many interpretations and adaptions to take its current shape.

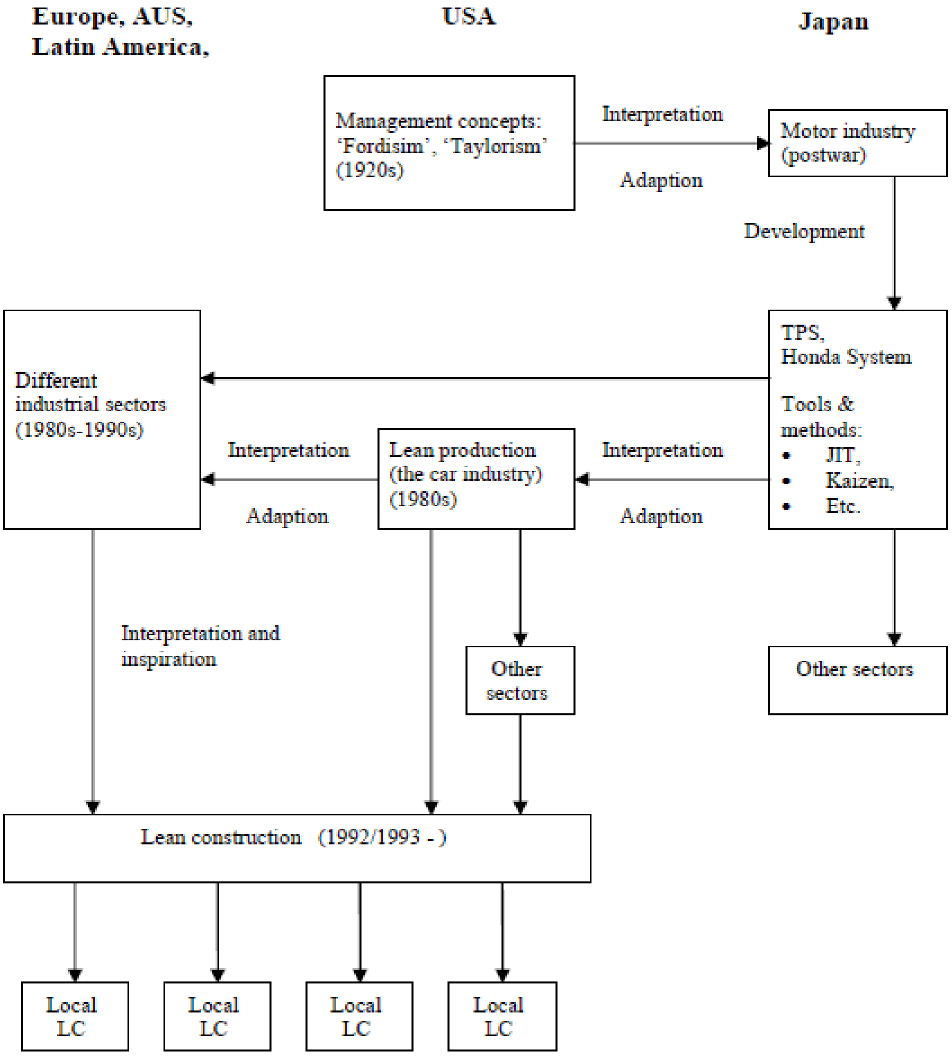

Figure 3.4: Schematic Overview of Lean Construction (Jorgensen, 2006)

Interactions shown in Figure 3.4 creates a lot of local lean construction interpretations. For this reason, lean construction is associated with many application methods, which are discussed further in the following sections; but as one of the basic principles, it aims to eliminate non-value adding activities from the process. Thomas et al. (2002) demonstrate this principle with a simple example shown in Figure 3.5. When lean principles are used erecting scaffolding activity becomes internal part of erecting formwork. By this way, non-value adding activities like waiting or inspecting are tried to be minimized.

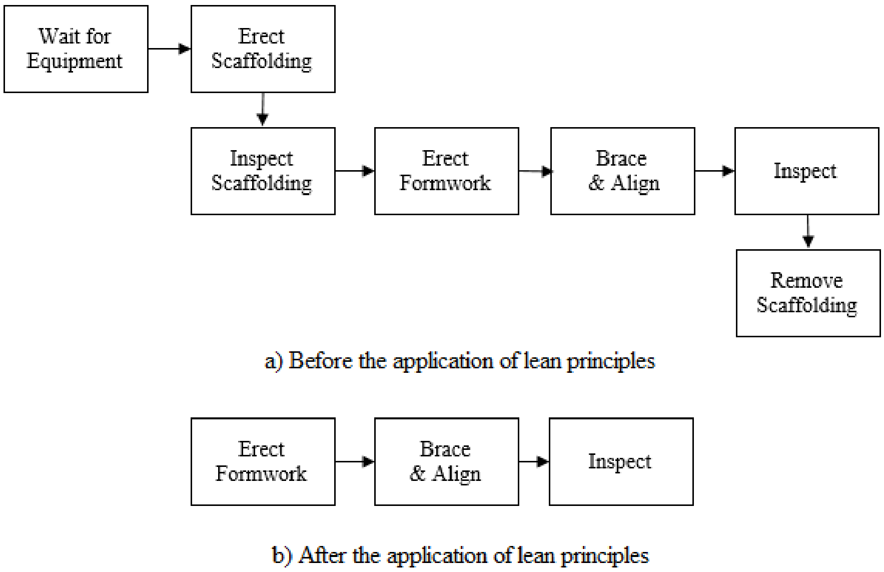

Figure 3.5: Elimination of Non-Value Adding Activities by Lean Approach (adapted from Thomas et al., 2002)

In addition to previously mentioned principle, lean construction targets to meet expectations of the customers by means of concurrent design of both construction products and construction process (Mao and Zhang, 2008). Moreover, according to Bertelsen (2004), the most important contribution of lean construction is introduction of flow type concept. Flow types are identified by Koskela (2000) as follows: previous work, space, crew, equipment, information, materials, and external conditions such as weather. Lean construction systematically makes an endeavor to improve these work flows in order to generate value and suppress waste.

Basic principles of lean construction is expanded by comparing its unique features with conventional construction management principles and by highlighting waste concept of lean construction in following subsections.

3.4.1 Comparison between conventional practices and lean construction

Mao and Zhang (2008) explain three features of lean construction that distinguish it from the conventional management practices based on article of Howell (1999) as follows:

1) Lean construction concentrates on reducing waste that may be in form of inspection, transportation, waiting, and motion.
2) Lean construction targets to reduce variability and irregularity in order to ensure the material and information flow without interruptions.
3) Lean construction aims to have construction material on site only when it is needed.

In addition, lean construction differentiate itself from the conventional system in terms of planning system. In traditional planning system, construction work is planned according to CPM scheduling by calculating early and late activity starts and finishes. Although some adjustments are made by resource leveling algorithms, an activity is expected to start at its earliest possible time. This approach requires availability of labor, materials, equipment, space and necessary instructions to start an activity. Performing an activity depends on release of its predecessor activities. This system of planning is called push driven scheduling. Although it is possible to model the uncertainty, most of the time variation in durations results in unsuccessful project management. Pull driven process management, on the other hand, aims to produce optimal products in terms of quality, time, and cost. In order to apply a pull driven scheduling, resources for an activity are determined selectively. This selection is made not only based on availability of resources coming from preceding activity, but also giving emphasis on WIP and successor activities. Resources will get priority in selection if it is predicted that similar resources will be available in further downstream processes. By this way, waiting time for resources is aimed to be minimized (Tommelein, 1998).

3.4.2 Waste concept of lean construction

Waste is a very important concept for construction management due to the fact that waste management is an area from which construction industry suffers deeply. Aziz and Hafez (2013) prove this proposal by comparing manufacturing and construction industry in terms of waste percentages of time as shown in Figure 3.6. When compared to manufacturing, construction industry spends far more time as waste.

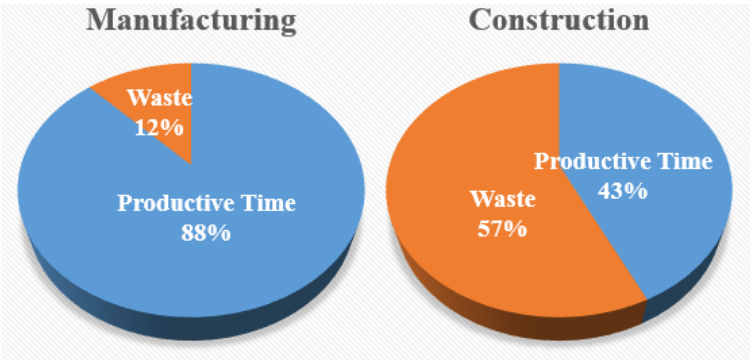

Figure 3.6: Comparison of Waste Percentages in Manufacturing and Construction (adapted from Aziz and Hafez, 2013)

Although there are too many waste interpretations for the construction works, waste is usually associated with usage of resources more than necessary. In this respect, Formoso et al. (1999) define waste as: "*any inefficiency that results in the use of equipment, materials, labor, or capital in larger quantities than those considered as necessary in the production of a building.*"

In terms of material usage, Garas et al. (2001) identifies sources of waste as: "*over-ordering*", "*overproduction*", "*wrong handling*", "*wrong storage*", "*manufacturing defects*", and "*theft or vandalism*" and those of waste in time as "*waiting periods*", "*stoppages*", "*clarifications*", "*variation in information*", "*re-work*", "*ineffective work*", "*interaction between various parties*", "*delays in plan activities*", and "*abnormal wear of equipment*".

Moreover, Polat and Ballard (2004) introduce some statistics regarding amount of waste in Dutch construction industry based on research of Bossink and Brouwers (1996): in terms of weight, 9 % of total materials are wasted on site; and 1 % to 10 % of each material leaves site as solid waste. Same research classifies main causes of waste and their frequencies according to six different source as shown in Table 3.3.

Table 3.3: Main Causes of Material Waste (adapted from Polat and Ballard, 2004)

Source	Causes of Material Waste	Frequency
Design	Lack of information about types and size of materials on design documents	13 %
	Design changes and revisions	12 %
	Error in information about types and sizes of materials on design document	10 %
	Determination of types and dimension of materials without considering waste	3 %
Procurement	Ordering of materials that do not fulfill project requirements defined on design documents	86 %
	Over-ordering or under-ordering due to mistakes in quantity surveys	8 %
	Over-ordering or under-ordering due to lack of coordination between warehouse and construction crews	4 %
Material Handling	Damage of materials due to deficient stockpiling and handling of materials	16 %
Operation	Imperfect planning of construction	61 %
	Workers' mistakes	32 %
	Damage caused by subsequent trades	3 %
Residual	Conversion waste from cutting uneconomical shapes	22 %
Other	Lack on site materials control	23 %
	Lack of waste management plans	10 %

Furthermore, Sacks and Goldin (2007) prepare the waste types in high-rise apartment building as shown in Table 3.4.

Table 3.4: Waste in High-Rise Residential Projects
(adapted from Sacks and Goldin, 2007)

Waste	Observations
Undesired products	Apartments built to standard designs are less attractive to potential buyers.
Rework	Client changes performed as change orders require demolition of work completed earlier; management effort is required to coordinate late change orders and to control their execution; repair of damage done by successive subcontractors to work performed earlier.
Inventories	Inventories of completed (but not yet purchased) apartments are accumulated; finish materials are delivered in batches from each supplier, not per apartment, and stored until used; work in progress encompasses 100% apartments.
Unnecessary activities	Unfinished apartments must be cleaned and repaired after periods during which they are not worked on; temporary measures are taken to protect work partially completed, such as security doors installed to lock incomplete apartments.
Unnecessary movement of workers and/or materials	Work stoppages are frequent when apartments are sold during finishing, to allow time for clients to reach design decisions-specially contractors are forced to move other apartments and then back again later; small sections of work left incomplete when information is lacking requires return of numerous contractors to the same apartment.
Waiting for materials of information	Delays due to unavailable information reduce productivity; materials that wait to be delivered in batches delay potential work.
Products that do not meet clients' needs	Apartments built to standard design do not fully meet the client's needs; clients often forego customization where the cost of change orders is considered prohibitive.

Finally, Hosseini et al. (2011) propose an innovative waste categorization as shown in Figure 3.7 to categorize construction waste according to lean thinking approach.

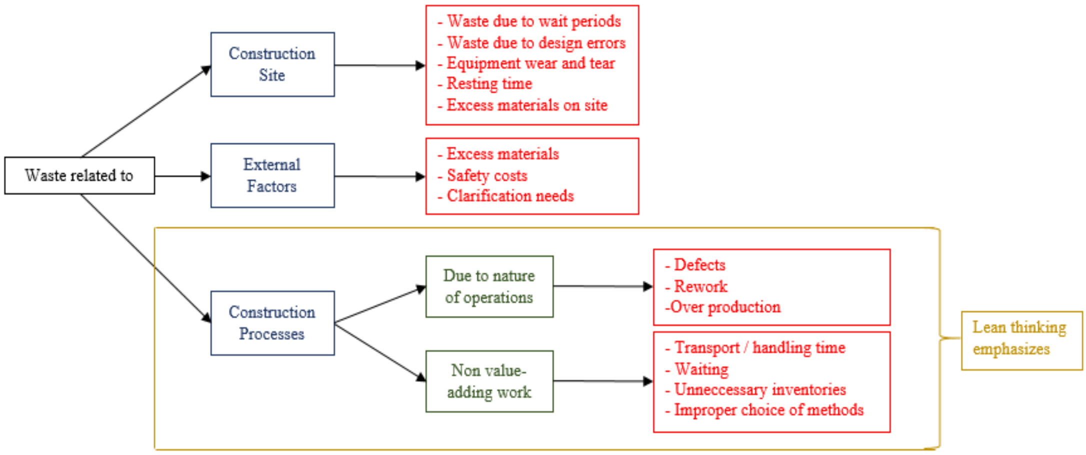

Figure 3.7: Waste Categorization According to Lean Thinking (adapted from Hosseini et al., 2011)

In order to eliminate waste, a clear description of it is essential. The researches introduced in this section, define and categorize waste with different methodologies. In a similar vein, lean construction aims to identify all types of wastes in construction works and to minimize them. Elimination of waste also contributes to other lean construction principles in terms of being executed more effectively.

3.5 Application Techniques of Lean Construction

Many positive results like enhanced value, reduced cost, and increased customer satisfaction have been achieved worldwide by applying lean principles in several areas of construction (Mao and Zhang, 2008). Egan (1998) exemplifies the success of lean construction practices by some real cases. For example, The Neenan Company in Colorado have reduced project times and costs by 30 % and the time they spent to produce a schematic design by 80 % thanks to lean construction techniques. Furthermore, Pacific Contracting, a cladding and roofing subcontractor, have increased their productivity by 20 % in eighteen mounts by using lean construction techniques.

Examples regarding benefits of lean construction can be increased but the more important point is determining how lean construction improves performance of construction works. In this respect, application techniques of lean construction are investigated thoroughly within this section. As a result, lean construction application are categorized under three main headings: Lean Project Delivery System^{TM} (LPDS), Last Planner System^{TM} (LPS), and practical application techniques. LPDS and LPS are theory-based lean construction methods. They require long term commitment and applying them in practice compel both people and organizations to internalize the change. With these aspects, LPDS and LPS are hard to be utilized in real cases, but lean construction practitioners indicate that when they are successfully implemented, performance of construction projects are significantly improves. For this reason, Section 3.5.1 and 3.5.2 cover these subjects in detail. Practical application techniques, on the other hand, are composed of more general lean construction practices. These methods are easier to apply when compared to LPDS and LPS, and they contribute to project performance in the short term. However, their impacts on project performance are not as significant as those of LPDS and LPS. Their full potential can be reached when they are systematically utilized as supplementary services for LPDS and LPS applications. Section 3.5.3 explains many practical application techniques suggested in the literature.

3.5.1 Lean Project Delivery System (LPDS)

Traditional project delivery systems in construction domain focuses highly on the task view of project delivery. They emphasize the transportation view of production, and flow and value views, which have aim of waste reduction and value generation are not interested. Bertelsen (2002) states that transformation view assumes separate contributions of lowest cost for each operation, order, contract or purchase move whole process to an optimized condition. However, transformation view does not guarantee optimum project delivery by itself. There is a need for more holistic project delivery approach. In this respect, Ballard (2000a) proposed a lean project delivery system that structured, controlled, and improved based on three goals of production. LPDS includes many elements from current construction practices but it integrates them into a complete delivery system instead of using them separately. LPDS is represented in Figure 3.8 by four phases, which are composed of overlapping triangles. Overlapping triangles indicate the common points of project phases. These phases are project definition, lean design, lean supply, and lean assembly. Instead of separate management of them, LPDS integrates and manages these phases simultaneously.

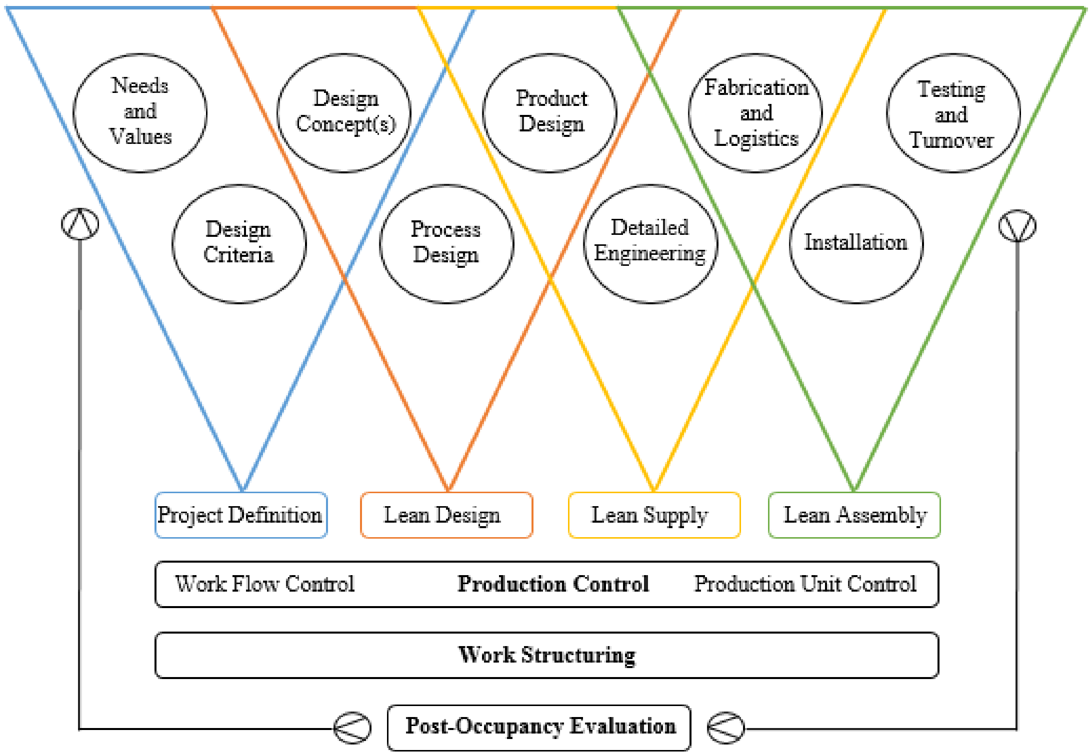

Figure 3.8: Triads of the Lean Project Delivery System
(adapted from Ballard, 2000a)

Ballard (2000a) summarizes essential features of LPDS as follows:

- Management and structuring of the projects are based on value generation process.
- Downstream stakeholders are included the design and planning process through cross functional teams.

- Project control has the job of execution in case of variance detection.
- Work flow is made more reliable by optimization efforts.
- Pull techniques are implemented to ensure flow of materials and information.
- Capacity and inventory buffers are utilized to absorb variability.
- Learning is realized through feedback loops.

With these features LPDS, differentiate itself from the conventional project delivery systems. Table 3.5 presents comparison between LPDS and traditional project delivery systems.

Table 3.5: Comparison of Traditional and Lean Project Delivery Systems (adapted from Koskela et al., 2002)

Lean	Traditional
Focus is on the production system	Focus is on transactions and contracts
TFV goal	T goal
Downstream players are involved in upstream decisions	Decisions are made sequentially by specialists and 'thrown over the wall'
Product and process are designed together	Product design is completed, then process design begins
All product life cycle stages are considered in design	Not all product life cycle stages are considered in design
Activities are performed at the last responsible moment	Activities are performed as soon as possible
Systematic efforts are made to reduce supply chain lead times	Separate organizations link together through the market, and take what the market offers
Learning is incorporated into project, firm, and supply chain management	Learning occurs sporadically
Stakeholder interests are aligned	Stakeholder interests are not aligned
Buffers are size and located to perform function of absorbing system variability	Participants build up large inventories to protect their own interests

The elements of LPDS that are presented in Figure 3.8 as well as facility use phase, and benefits of LPDS are discussed individually in the following subsections.

3.5.1.1 Project definition

Project definition phase of LPDS is composed of needs and values, design criteria, and design concepts. First of all, needs and values clarifies what is wanted by the customer and limitations of the customer. Secondly, design criteria generates specifications based on customer purposes and constraints like funds, time, location, and regulations. Finally, design concepts translate the customer purposes and constraints into the design for the use of facility. Figure 3.9 summarizes project definition process. There is a conversation between what is wanted, what provides, and constraints. When purposes, values, and design criteria more clearly defined, design for the facility use is improved. By this way, constraints are also better described (Ballard, 2008).

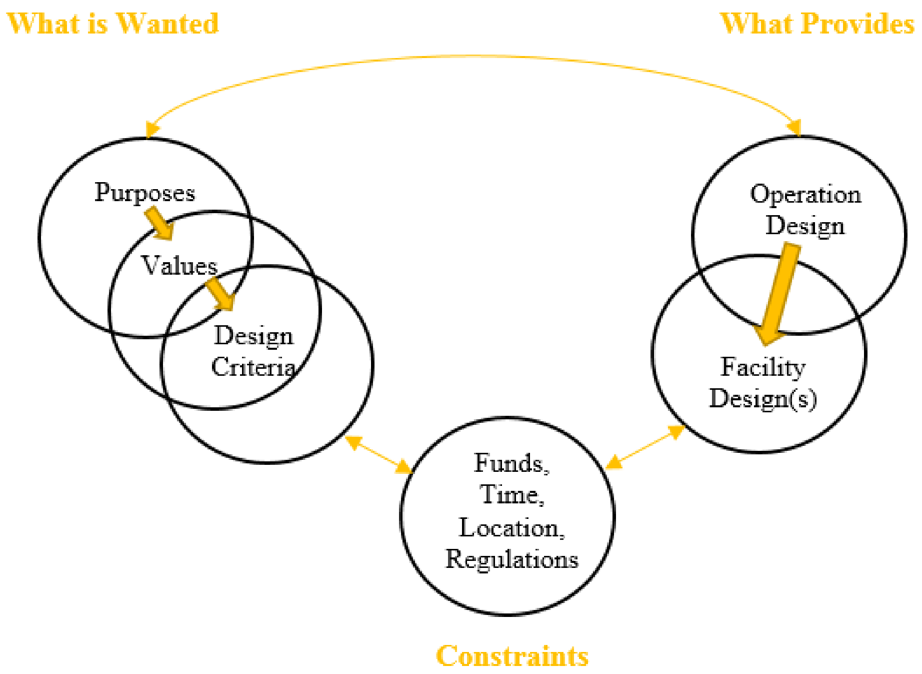

Figure 3.9: Project Definition Process (adapted from Ballard, 2008)

Orihuela et al. (2011) shows similar representation of project definition as demonstrated in Figure 3.10. Firstly, the purposes of project participants, which are owners of the projects and user of the end-products, are determined. Then constraints such as rule and regulations and site conditions are evaluated by design team. Finally, based on previous two modules design concepts are determined with different alternatives. This process generates a lean design. Following section covers lean design subject.

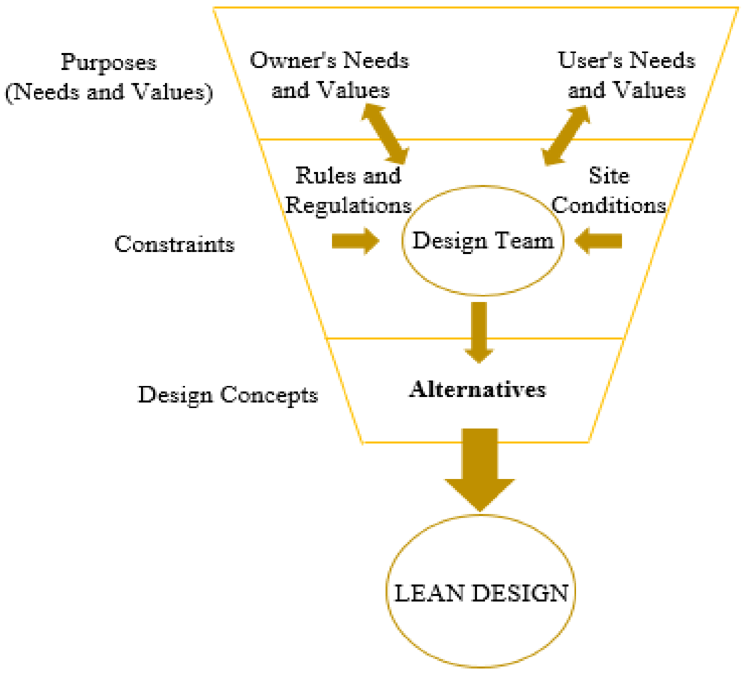

Figure 3.10: Modules of Project Definition (adapted from Orihuela et al., 2011)

3.5.1.2 Lean design

Lean design enhance design concepts developed in project definition into process design and product design (Ballard, 2000a). Table 3.6 summarizes basic principles utilized in lean design. These principles are organize in cross functional teams, pursue a set based strategy, structure design work to approach the lean ideal, minimize negative iterations, use last planner system of production control, and use technologies that facilitate lean design. They are explained further below.

Table 3.6: Lean Design Principles (adapted from Ballard and Zabelle, 2000)

Lean Design Principles	
Organize in cross functional teams	Involve downstream players in upstream decisions
	Alternate between all-group meetings and task force activities
Pursue a set based strategy	Create and exploit opportunities to increase value in every project phase
	Select from alternatives at the last responsible moment
	Share incomplete information
	Share ranges of acceptable solutions
Structure design work to approach the lean ideal	Simultaneous design of product and process
	Consider operations, maintenance, decommissioning, commissioning, assembly, fabrication, purchasing, logistic, detailed engineering, and design
	Shift detailed design to fabricators or installers
	Reduce design batch sizes
Minimize negative iterations	Pull scheduling
	Design structure matrix (DSM)
	Strategies for managing irreducible loops
Use last planner system of production control	Try to make only quality assignments
	Make work ready within a look ahead period
	Measure Plan Percent Complete (PPC)
	Identify and act on reasons for plan failure
Use technologies that facilitate lean design	Shared geometry; single model
	Web-based interface

1. **Organize in cross functional teams:** This lean design principle advocates that all project participants should understand and participate in key decisions. Although it is not possible to bring together all participants every time, information technology (IT) can be utilized through visible models to increase project awareness (Ballard et al., 2002).
2. **Pursue a set based strategy:** Traditional design processes have a point based approach. With this approach, architectures select the most appropriate design alternatives and produce sketches and models accordingly. Then, engineers criticize the model in terms of constructability and architects revise it, if necessary. Finally, key systems are selected and dimensions are fixed as soon as possible, and same process is repeated for subsystems and components. However, this design system includes risk of rework and wasted effort especially if there exists time pressure. Set based design strategy, on the other hand, works with sets of design alternatives. In addition, cooperation between

participants are promoted. Incomplete information between design teams are shared at every level and the design turns into value generation process (Ballard and Zabelle, 2000).

3. **Structure design work to approach the lean ideal:** Lean design structures design work in pursuit of lean ideals: designing the product in terms of customer needs, designing it on time and designing it without waste. Lean work structure requires consideration of all processes within product design. Concurrent design of process (how to build) and products (what to build) makes it possible to involve all project participants to increase value (Ballard et al., 2002).
4. **Minimize negative iterations:** Due to its nature, design process includes some irreducible loops, such as collective determination of structural and mechanical loads. Such a process causes negative iterations and does not add value to design process. Lean design minimizes negative iterations by team meetings that accelerate iterations. Design is not completed unless some critical items of information is obtained (Ballard et al., 2002; Ballard and Zabelle, 2000).
5. **Use last planner system of production control:** LPS is applicable both design and construction process. For lean design, it determines value adding works to be executed, measures performance of planned works, and identifies reasons for plan failure. Details of LPS is explained in Section 3.5.2.
6. **Use technologies that facilitate lean design:** A database capable of representing product design in 3D and also capable of modelling the project phases is a key support tool for lean design. Designing within a single model allows improved visualization, minimizes interferences between different models, and helps to conduct post-construction operations (Ballard et al., 2002). Building Information Modelling (BIM) technology used for compiling the virtual models of the construction throughout the lean design. Sacks et al. (2010) claim that integration of BIM and lean construction can bring a successful improvement of construction when they are in the integrated project delivery approach. Similarly, Khanzode et al. (2006) indicate that virtual

design & construction (VDC) technologies, such as BIM, contribute to phases of LPDS.

3.5.1.3 Lean supply

Lean supply phase of the LPDS consists of three parts. First of all, detailed engineering of the product design produced in lean design is determined. Then components and materials are fabricated or purchased. Finally, the logistics management of deliveries and inventories is conducted (Ballard, 2000a). The supply process integrates a two way flow of exchange of information, a one way flow of goods or services from supplier to customer, a one way flow of funds from customer to supplier as shown in Figure 3.11.

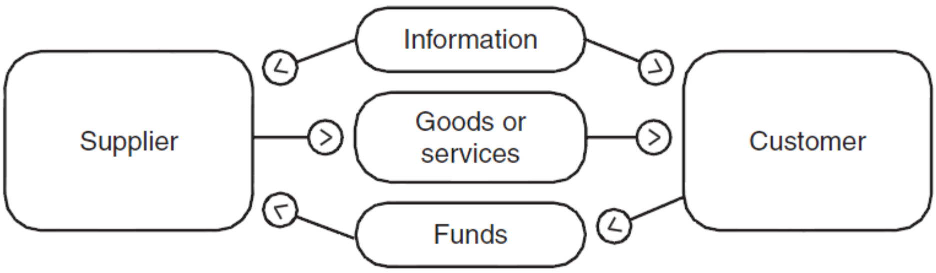

Figure 3.11: Supply Flows of Information, Physical Goods or Services, and Funds (Ballard et al., 2002)

There are many problems in supply chain mechanisms of the construction industry due to complexity of them. Supply chain mechanism in construction industry includes owners, designers, engineering specialists, contractors and sub-contractors, manufacturers, shipping agents, and other suppliers of goods and services (Ballard et al., 2002). Therefore, a successful supply chain management (SCM) is foundation of the lean supply. According to Vrijhoef and Koskela (2000), there are four roles of SCM in construction as shown in Figure 3.12.

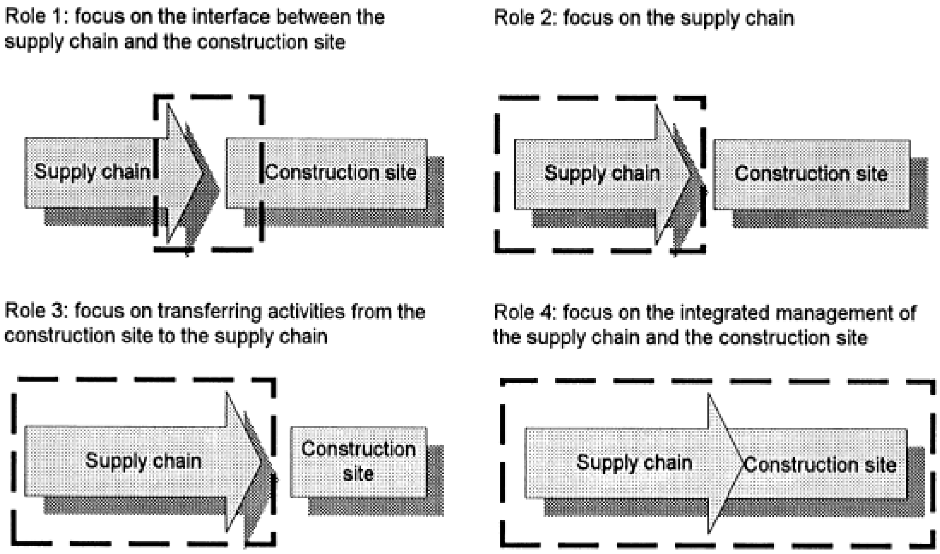

Figure 3.12: The Four Roles of SCM in Construction (Vrijhoef and Koskela, 2000)

First role of SCM focuses on the influence of supply chain on construction site activities and intends to decrease the cost and duration of those activities. Second role of SCM focuses only on the supply chain. It aims to decrease costs, which are related to logistics, lead time, and inventory. Role 3 of SCM focuses on relocating the places of activities from site to early stages of the supply chain. This role has target of reducing installing cost and duration by avoiding poor condition of the site, and aims to get wider concurrency between activities, which is not possible to be achieved in construction site. Finally, SCM focuses on the integrated management of the SC and site production (Ballard et al., 2002).

Due to abovementioned difficulties of SCM, lean supply offers some principles to improve management practices of supply chains. Organizing in cross functional teams, which is emphasized in Section 3.5.1.2, improves relationships in supply chain mechanism. For example, regular meeting of specialty contractors and key component suppliers during conceptual design discussions will inform both parties regarding emerging requirements and make explicit the productions constraints. Long term supplier relationships is another principle of lean supply. Lean production support longer-term, multi project, and relational agreements for buyers and sellers relationships. Since they make quality products reliable deliveries, involvement of suppliers to design will lead to reduction of waste as well. Lean supply also attach importance to location of suppliers. The supply chain can be made leaner by procuring from suppliers that reside in the closer geographic locations. In addition, *"physical movement of products"*, *"change in unit of hand-off"*, *"temporary storage or velocity adjustment to allow for synchronization"*, and *"providing timely information"* must be considered as value adding task for the design of supply chains. As a result, lean supply phase of LPDS has many principles to improve SCM, and LPDS treats suppliers as essential part of the project delivery system (Ballard et al., 2002).

3.5.1.4 Lean assembly

Lean assembly phase, which is the fourth triad of LPDS, starts with the first delivery of tools, labor, materials or components to the site and concludes the product is turned over to the customer. It includes fabrication and logistics, installation, and commissioning. Lean assembly is associated with LPS, which is explained in Section 3.5.2. LPS practices are utilized to perform lean assembly, but there are another tools and techniques. For example, a continuous flow process (CFP) is one of the pillars of lean assembly phase. CFP aim to maximize throughput of the system while minimizing idle time of the resources and WIP. In this respect, utilization of multi-skilled work force that can perform broader range of work, reduces variability of work flows and contributes CFP. Moreover, pre-assembled or pre-fabricated components are advocated by lean assembly because they enable more straightforward final assembly. Utilization of standardized and interchangeable parts are also another important principles in lean assembly. The repeated use of standardized parts eases the assembly considerably, and use of a limited number of parts prevents matching problems. Finally coordination between lean supply and lean assembly is provided by JIT principle, which is explained in Section 2.2.2, of lean assembly (Ballard, 2000a; Ballard et al., 2002).

3.5.1.5 Facility use

LPDS also integrates facility use to itself because, in lean construction, customer use is accepted as an important part of project delivery. For this reason, customer use is represented by a fifth triad. It contains commissioning, operations and maintenance, and alteration and decommissioning as shown in Figure 3.13.

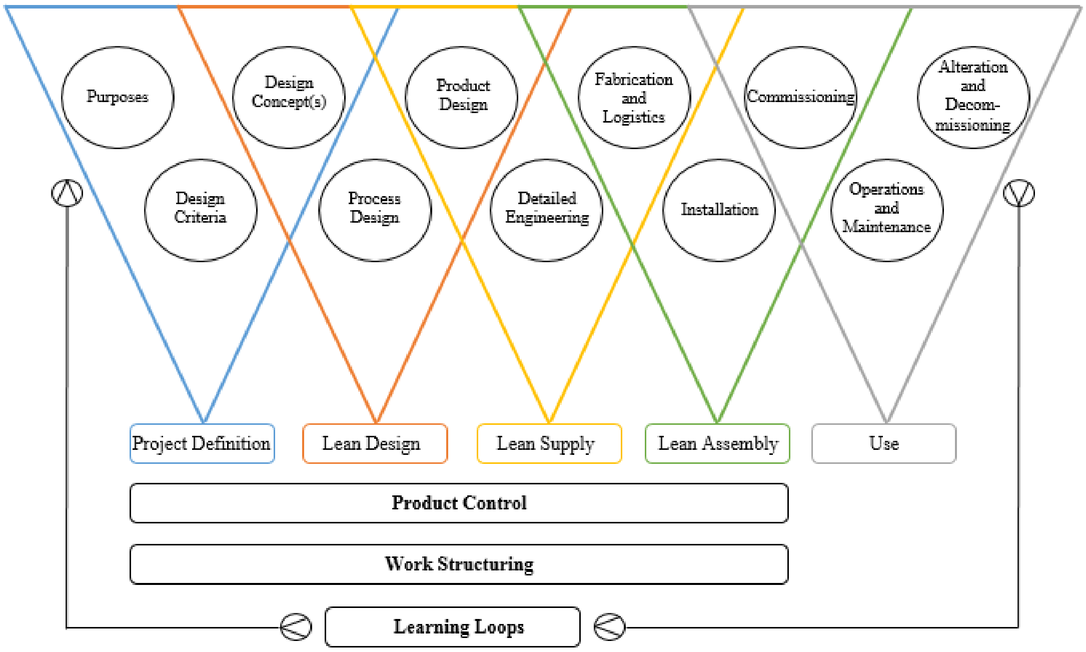

Figure 3.13: Triads of the Lean Project Delivery System with Facility Use (adapted from Koskela et al., 2002)

3.5.1.6 Production control

Production control module of LPDS is applied during project definition, lean design, lean supply, and lean assembly phases. As distinct from the conventional control mechanism, production control of LPDS primarily aims to prepare project a desired future state rather than measuring differences between plans and actuals. Such a control mechanism is realized by utilizing LPS of production control (Ballard, 2000a), which is detailed in section 3.5.2.

3.5.1.7 Work structuring

Similar to production control module, work structuring module is applied to first four phases of a project. Work structuring has the purposes of making work flows more reliable and quick. In this regard, optimizing supply chains, resources leveling, and design for assembly constitute example applications of work structuring module (Ballard, 2000a).

3.5.1.8 Benefits of LPDS

Integrated and holistic approach of LPDS as well as tools and techniques generated within it promise a more reliable project delivery. All phases of LPDS focus on waste reduction, value generation, and improving work flows. Production control and work structuring modules support project phases in order to realize these focuses. Furthermore, post-occupancy evaluation carries experience and knowledge acquired in previous projects into the following project. Besides, facility use phase of LPDS expands project delivery period throughout life cycle of the project, which advocates customer-oriented project delivery approach. Finally, broad fields of application of LPDS lead utilization of other lean construction tools and techniques, particularly LPS, within itself.

These aspects of LPDS contributes greatly to project performance metrics. Ballard (2008) present some real case evidences that exemplify effects of LPDS on project time and cost. Firstly, Shawano Clinic project is presented as case study of lean project delivery. With LPDS practices, the actual cost of the project falls 14.6 % below the target project cost. In addition, the project is completed 3.5 months ahead of schedule, which generates $ 1 million of extra revenue for the owner. Second case study is Fairfield Medical Office Building project. The target cost of the project is $ 18.9 million. LPDS principles reduce actual cost of the project to $ 17.9 million, which results in approximately 5.3 % reduction of target cost.

3.5.2 Last Planner System (LPS) of production control

Ballard (1993) introduced the LPS of production control and developed it further (Ballard, 2000b). It basically serves for work structuring and control mechanism of lean construction. It is composed of three components: look-ahead planning, commitment planning, and learning. The scheme of the LPS is shown in Figure 3.14.

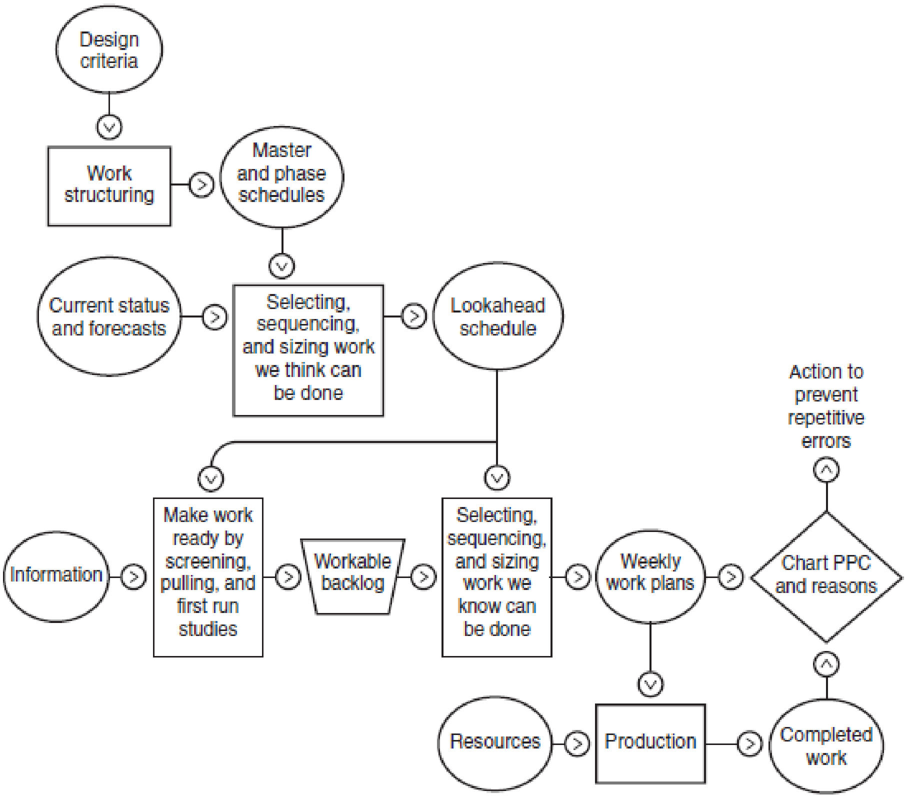

Figure 3.14: Last Planner System of Production Control (Ballard et al., 2002)

The basic rules of LPS is summarized by Ballard et al. (2002) as follows:

- Activities are dropped from the phase schedule into a six week, in general, look-ahead window.

- Constraint analysis is performed and they should be removed in order to continue the process.
- It is tried to be performed only the assignments that bring value.
- Percentages of completed assignments are calculated for each plan period.
- Reasons for plan failure are determined and failed plans are tried to be fixed.

Figure 3.15 reveals the difference between traditional planning systems and LPS. Traditional planning systems schedule the project with a push-driven approach, which is explained in the Section 3.4.1. This approach conducts planning of the works based on the assumptions. Execution of the activities are decided without taking into account what can be done. The activities that should be done are pushed to construction site. LPS, on the other, acts as a sieve, which distinguish activities that will be performed from the activities that should be performed. By this way, activities that will be truly executed are pulled to construction site. According to Kim and Jang (2005), the pull approach of LPS shields activities from work flow uncertainty, and improves productivity of them.

Following sections encapsulate components of LPS. Each component is discussed in sequence, then implementation of LPS is explained, and finally benefits of LPS are emphasized with example case studies.

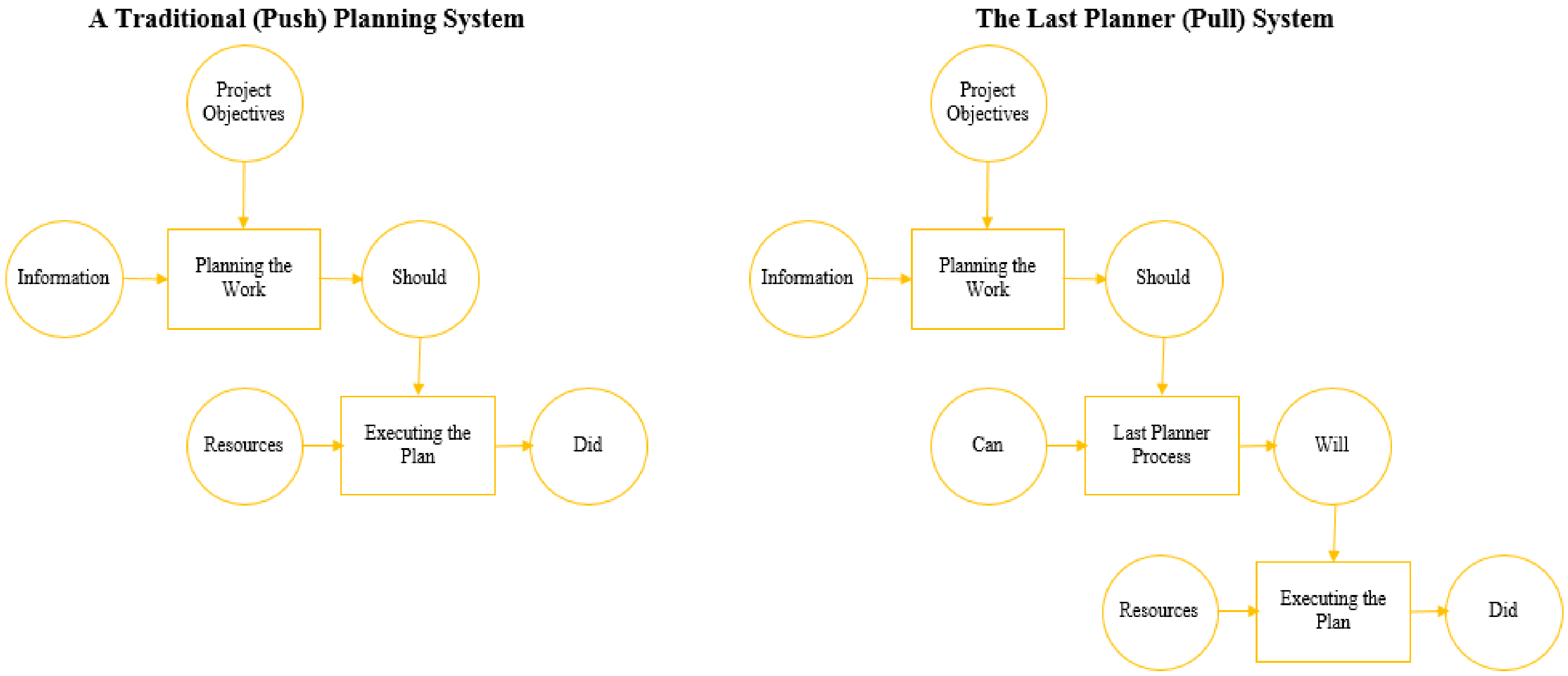

Figure 3.15: Comparison between Traditional Push Planning System and The Last Planner System (adapted from Ballard, 2000b)

3.5.2.1 Look ahead planning

Look ahead planning is a key principle in the LPS. It provides awareness in terms of project planning and decreases production variations of the project (Hamzeh and Aridi, 2013). According to Ballard et al. (2002), look-ahead planning component of LPS serves for:

1. Shaping work flow sequence and rate.
2. Matching work flow and capacity.
3. Maintaining a workable backlog of ready work.
4. Developing detailed plans to determine how work will be performed.

Tools and techniques used in look-ahead planning include constraint analysis, the activity definition model (ADM), and first run studies, which are explained further in following sections.

3.5.2.1.1 Constraint analysis

The purpose of constraint analysis is to examine each activity, which are scheduled to start in next six weeks. Six weeks is a general duration, which may be shorter or longer depending on the project situation. The essential rule of constraint analysis is that an activity can only be allowed to stay its scheduled date if all constraints are removed or it is certain to remove them early enough. Constraint analysis ensures that problems will be identified earlier, and unsolved problems will not be introduced in any production level of the project unless they are solved (Ballard et al., 2002). A typical constraint analysis is exemplified in Table 3.7.

Table 3.7: Example Constraint Analysis (Ballard et al., 2002)

Project: Mega Building
Report date: 3 Nov

			Constraints				
Activity	**Responsible party**	**Scheduled duration**	**Directives**	**Prerequisites**	**Resources**	**Comments**	**Ready?**
Design slab	Structural engineer	15 Nov to 27 Nov	Code 98 Finish? Levelness?	Soils report	10 hours labour, 1 hour plotter		No
Get information from client re floor finish and level	*Structural engineer's gofer*	*3 Nov to 9 Nov*	OK	OK	OK		Yes
Get soils report from Civil	*Structural engineer*	*By 9 Nov*	OK	OK	OK		Yes
Layout for tool install	Mechanical engineer	15 Nov to 27 Nov	OK	Tool Configurations from mfger	OK	May need to coordinate with HVAC	No

3.5.2.1.2 Activity definition model

ADM is a tool examining phase schedule activities into greater detail. It provides main classes of constraints as directives, prerequisite work, and resources. Directives are guiding rules that explain which product will be produced. Assignments, design criteria, and specifications are some examples for directives. Prerequisite work is the bottom layer for work to be performed. To illustrate, materials or information that will be used in calculations are prerequisite work. Finally, labor, tools, equipment, and space are components of resources (Ballard et al., 2002). Figure 3.16 explains the scheme of ADM.

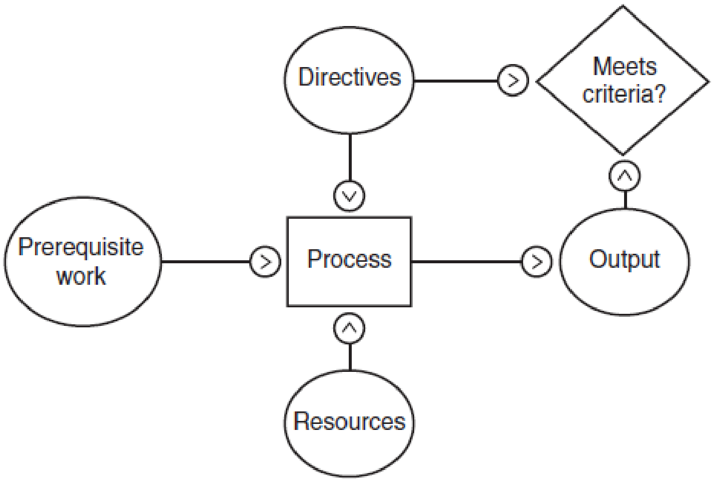

Figure 3.16: Activity Definition Model (Ballard et al., 2002)

3.5.2.1.3 First run studies

Based on Howell and Ballard (1999), Ballard et al. (2002) indicate that first run studies must be a routine part of planning and performed three to six weeks before the start of a new operation. They serves for identification of skills and tools available or needed, and for determination of interaction of the operation with other processes. First run studies typically include process, crew balance, and flow charts. Moreover, they determine space schedule that demonstrates movement of resources through spaces and work progresses.

3.5.2.2 Commitment planning

Second component of LPS is commitment planning. In order to protect production units from uncertainty, quality criteria in terms of definition, soundness, sequence, size, and learning is committed. The success of the plan is measured in terms of plan percent complete (PPC). PPC determines percentage of the accomplished work in the plan by the end of the week. The primary causes for plan failure are determined based on PPC ratios and they are tired to be eliminated so that future problems may be avoided. Figure 3.17 shows a PPC chart. Increasing PPC indicates improved performance (Ballard et al., 2002; Koskela and Howell, 2002).

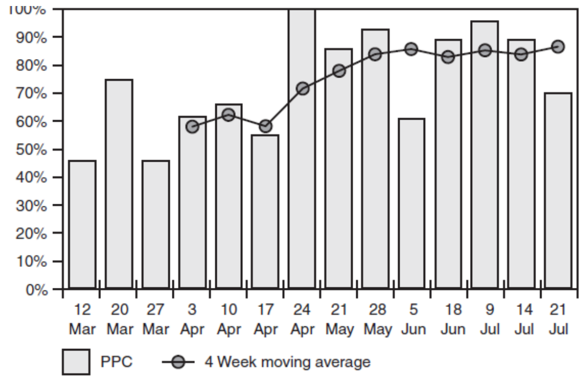

Figure 3.17: Example PPC Chart (Ballard et al., 2002)

3.5.2.3 Learning

The last component of LPS is learning. Each week, weekly work plan of last week is examined and commitments that has not been kept are determined. Then the reasons for plan failure are specified as illustrated in Figure 3.18. Failure reasons are systematically analyzed and preventive actions are implemented (Ballard et al., 2002).

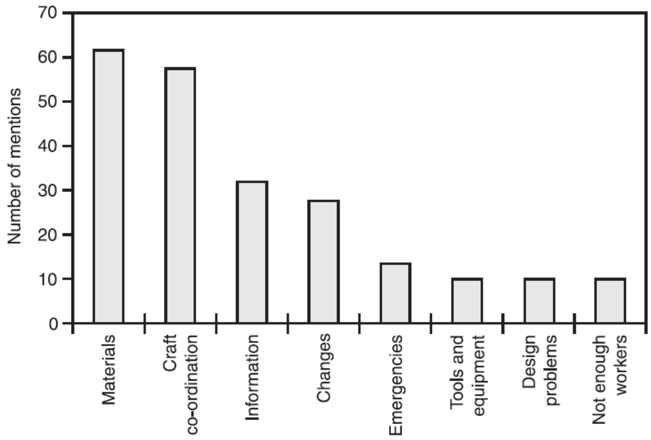

Figure 3.18: Example Reasons for Plan Failure (Ballard et al., 2002)

3.5.2.4 Implementation of LPS

Components of LPS are discussed in previous sections, but integrated utilization of them and application procedure of LPS constitute the subjects of this section. According to Nieto-Morote and Ruz-Vila (2012), LPS has three level of hierarchy of schedules as shown in Figure 3.19.

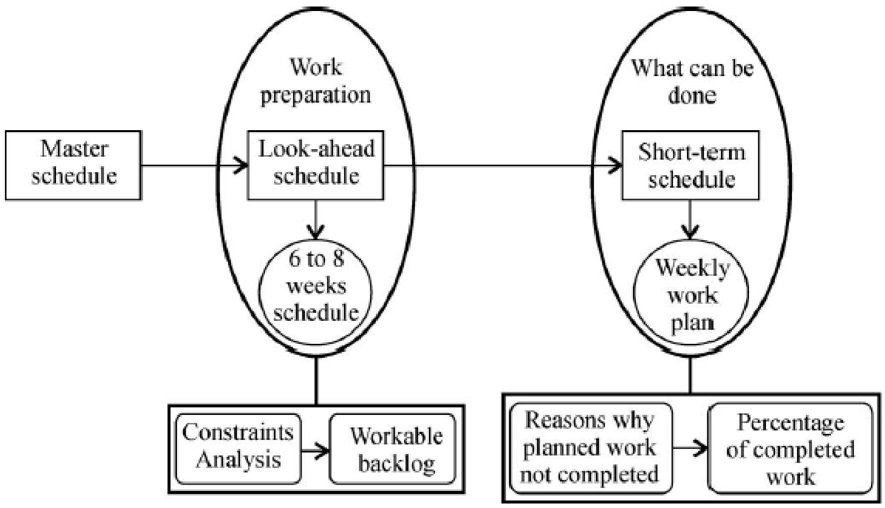

Figure 3.19: Three Level of Hierarchy of LPS (Nieto-Morote and Ruz-Vila, 2012)

First level of scheduling is preparation of master schedules. Master schedules include major milestones only. The milestones are identified starting from the project completion date through the beginning of the project. Look ahead schedule is the second level of hierarchy. It converts milestones into the major activities. These activities are analyzed during the look ahead schedule period in terms of constraints that have potential to interrupt the performance of them. An activity cannot be transferred to short-term schedule unless all constrains affecting it are eliminated prior to start date of the activity. Activities rescued from the constraints generate workable backlog of look ahead schedule. Management continues the analyze activities while breaking them into more detail throughout the look-ahead window. This process is repeated until the activities become assignment level tasks. Assignment level tasks form the third hierarch level, which is short-term schedule. Short term schedule consists of weekly work plans. Activities included in weekly work plans should get rid of constraints, including predecessors, and resource of them must be available and accurately assigned in order to complete the task. PPC weekly measures reliability of work plans. For the non-completed task, the root cause analysis is performed and reoccurrence is tried to be prevented (Nieto-Morote and Ruz-Vila, 2012).

3.5.2.5 Benefits of LPS

LPS systematically offers reliable work plans, which aims to protect downstream work processes from uncertainty of upstream processes by using commitment planning and matching work load to available resources (De la Garza and Leong, 2000). Generic nature of construction that obstruct performing of works can be solved by implementation of LPS since it prevents the uncertainty and complexity through short horizon for the planning, and promote cooperation between parties with learning processes (Bertelsen, 2002). Moreover, according to Formoso and Moura (2009), LPS has potential to improve project performance in terms of cost and time. Benefits of LPS is emphasized by Aziz and Hafez (2013) with a comparison of CPM and LPS as shown in Table 3.8.

Table 3.8: Comparison of CPM and LPS (adapted from Aziz and Hafez, 2013)

Critical Path Method (CPM)	Last Planner System (LPS)
CPM logic embedded in software	Applied common sense
High maintenance	Low maintenance
Managing critical path	Managing variability
Focus on managing work dates	Focus on managing work flow
Planning based on contracts	Planning based on interdependencies

There are also many case studies that demonstrate tangible benefits of LPS. Some of them are introduced below.

Firstly, Leal and Alarcon (2010) applied LPS principles to three industrial mining projects in the North of Chile. First project is construction of a system of piling up of copper mineral. Second project is the construction of a copper extraction process plant. Finally, third project is the construction of new warehouses for copper mineral and transportation systems in a port. Application of LPS is evaluated by a survey that measures satisfaction of the customer by comparing LPS case studies with previous projects of the company. Table 3.9 presents survey results, which indicate that LPS improved client satisfaction in terms of all aspects of the projects.

Table 3.9: Customer Satisfaction Percentages of LPS Case Projects (adapted from Leal and Alarcon, 2010)

Key Aspect	Case Project 1	Case Project 2	Case Project 3	Average of LPS Case Projects	Historic Company Average
1. Organization	92 %	95 %	75 %	**87 %**	**70 %**
2. Response To Client Suggestions	100 %	95 %	81 %	**92 %**	**80 %**
3. Response Capacity	100 %	95 %	75 %	**90 %**	**77 %**
4. Conflicts Resolution	100 %	100 %	88 %	**96 %**	**80 %**
5. Safety	75 %	95 %	88 %	**86 %**	**77 %**
6. Quality	92 %	100 %	81 %	**91 %**	**78 %**
7. Execution Time	83 %	90 %	75 %	**83 %**	**67 %**
8. Commitment with Project	100 %	100 %	88 %	**96 %**	**81 %**
9. Global Project Satisfaction	83 %	95 %	81 %	**87 %**	**69 %**

In the second example of case studies, AlSehaimi et al. (2009) implemented LPS for the two pilot projects in Saudi Arabia. First project is the construction of faculty and business and administrative sciences in a university. Second project, on the other hand, includes construction of general classrooms and laboratories. LPS implemented in both projects when 50 % of the jobs is completed. Table 3.10 summarizes PPC ratios of first week and last week of the LPS implementation. Results show that LPS considerably improves percentages of completed works.

Table 3.10: PPC Values at the First and Last Weeks of the LPS Implementation (adapted from AlSehaimi et al., 2009)

	PPC at the first week of the LPS Implementation	**PPC at the last week of the LPS Implementation**
Case Project 1	69 %	86 %
Case Project 2	56 %	82 %

Last case study, which is performed by Nieto-Morote and Ruz-Vila (2012), demonstrates that six weeks implementation of the LPS to construction project of a chemical plant clears the reasons for non-completion of planned activities as shown in Figure 3.20. It is indicated that, by using the LPS, the supervisors improved their knowledge regarding activities, which leads to execution of an increasing number of planned activities.

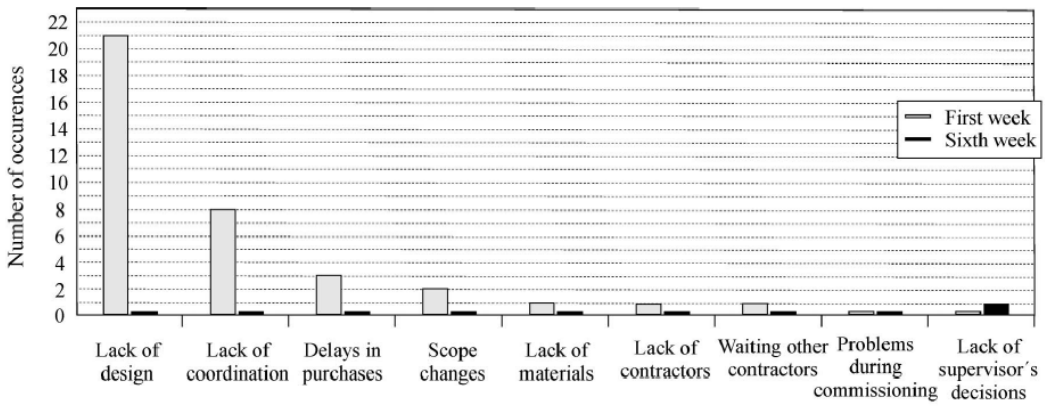

Figure 3.20: Number of Reasons for Non-Completion during LPS Practice (Nieto-Morote and Ruz-Vila, 2012)

3.5.3 Practical application techniques of lean construction

Practical application techniques that lean construction exploit are discussed within this section. In this respect, related literature is analyzed in detail and Table 3.11 is prepared. It shows different application methodologies of lean construction along with reference studies.

This paragraph includes general information related to Table 3.11. First of all, methodologies shown in the table are either directly implemented in reference articles, or attributed as recommended lean construction techniques. Furthermore, reference studies are not limited to numbers shown in the table. There are many additional researches regarding these application techniques. Table 3.11 is composed of example studies only. Another important point is that some of the techniques shown in the table are interrelated as a consequence of holistic structure of lean construction. Some techniques may be source or outcome of another techniques. To illustrate, prefabrication and pre-casting, shown with ID 13, serves for batch size and inventory reduction, shown with ID 4. Finally, many of these lean construction methods are associated with LPDS and LPS, which are covered in the Section 3.5.1 and 3.5.2 respectively. As explained in the Section 3.5, these application techniques are not theory based principles. On the contrary, they are practical methods that can be utilized as reinforcing ideas for LPDS and LPS. For example, utilization of multi-skilled labor, shown with ID 5, is also mentioned in lean assembly section (3.5.1.4) of LPDS.

All practical application techniques of lean construction are briefly explained in the paragraphs succeeding Table 3.11.

Table 3.11: Practical Application Techniques of Lean Construction

ID	Lean Construction Technique	Reference Studies
1	Increasing Visualization through Process Transparency and Computer Advanced Visualization	Aziz and Hafez (2013), Formoso et al. (1999), Mao and Zhang (2008), Rischmoller et al. (2006), Salem et al. (2006), Tezel and Nielsen (2013)
2	3D and 4D Design with BIM and Digital Prototyping	Egan (1998), Koerckel and Ballard (2005), Moghadam et al. (2012), Sacks et al. (2009)
3	Utilization of Plan or Schedule Buffers	Alarcon and Ashley (1999), Ballard et al. (2001), De la Garza and Leong (2000), Koskela et al. (2002)
4	Batch Size and Inventory Reduction	Ballard et al. (2001), Diekmann et al. (2004), Hosseini et al. (2011), Polat and Ballard (2004), Sacks and Goldin (2007), Howell and Ballard (1998)
5	Utilization of Multi-Skilled Labor	Ballard et al. (2002), Diekmann et al. (2004), Maturana et al. (2003), Polat and Ballard (2004), Sacks et al. (2007)
6	Increasing Workflow Throughput	Koerckel and Ballard (2005), Mao and Zhang (2008), Thomas et al. (2002), Thomas et al. (2003), Tommelein et al. (1998)
7	Cross Functional Process Charts	Tuholski et al. (2009)
8	Construction Process Analysis	Lee et al. (1999)
9	Concept of Pull (Pull Scheduling, Pull Flow, and Pull of Resources)	Becker et al. (2012), Howell and Ballard (1998), Oskouie et al. (2012), Tommelein (1998), Sacks et al. (2009), Yang and Ioannou (2001)
10	Application of Five S(s) Principles to Construction	Becker et al. (2012), Diekmann et al. (2004), Polat and Ballard (2004), Salem et al. (2006)
11	Poka-Yoke	Aziz and Hafez (2013), Bertelsen (2004), Bertelsen and Koskela (2002), Hosseini et al. (2011)
12	Value Stream Mapping	Aziz and Hafez (2013), Freire and Alarcon (2002)
13	Prefabrication and Pre-casting	Diekmann et al. (2004), Egan (1998),
14	Utilization of the Data Collected from the Previous Projects	Tezel and Nielsen (2013)
15	Utilization of Risk Management Techniques	Tezel and Nielsen (2013), Issa (2013)
16	Safety & Quality Control Plans	Misfeldt and Bonke (2004), Sacks et al. (2009), Tezel and Nielsen (2013)
17	Optimizing Site Conditions (Keeping Material Close to Location of Use, Minimum Material Storage, Improving Construction Access, Reducing Setup Times, Minimizing Equipment Movement)	Diekmann et al. (2004), Ballard et al. (2001), Tezel and Nielsen (2013), Tuholski et al. (2009)

Table 3.11 (Cont'd): Practical Application Techniques of Lean Construction

ID	Lean Construction Technique	Reference Studies
18	Leveling the Production and Crews	Sacks et al. (2010)
19	Provide Training at Every Level	Diekmann et al. (2004)
20	Involvement of all Project Participants including Client, Contractors, Sub-Contractors, Inspector, Suppliers, and Labor Force to Decision Making Process	Bertelsen and Koskela (2002), Koskela et al. (2002), Oskouie et al. (2012), Sacks et al. (2010), Tezel and Nielsen (2013)

- **ID 1:** Computer advanced visualization tools (CAVT) shown in ID 1 are utilized to improve understanding of shareholders regarding the project by improving visualization. CAVT are defined as collection of all necessary tools, which not only used for visualization of the process but also used to provide necessary information to accomplish design and construction projects. In this respect, CAVT may include a 3D rendering, a 2D plot, a bill of materials, a work order report, or a virtual reality environment (Rischmoller et al., 2006). Transparency is another component of ID 1. Howell and Ballard (1998) give transparency definition as:

> *Transparency means that state of the system is made visible to people making decisions throughout the production system so that they will take decisions locally in support of systems objectives. Transparency implies decentralized decision making which in turn, allows people to coordinate through mutual adjustment.*

Besides, Sacks et al. (2009) list some benefits of process transparency according to study of Formoso et al. (2002) as follows:

- It helps people to identify workstations and pathways, in workplaces where the layout changes frequently.
- It improves the effectiveness of production planning and control by displaying information.

- It increases involvement of workers.
- It simplifies controls and reduces probability of errors by making them more visible.
- It has a positive effect on motivation.

➢ **ID 2:** 3D and 4D Design concept serves for lean design purposes. Sacks et al. (2010) indicate that if accurate implementation is ensured, BIM provides a more integrated design and construction process that brings about better quality buildings at lower cost and reduced project durations. Figure 3.21 indicates that when both BIM and lean construction principles are embodied in conceptual understanding of the theory of production, they will generate benefits.

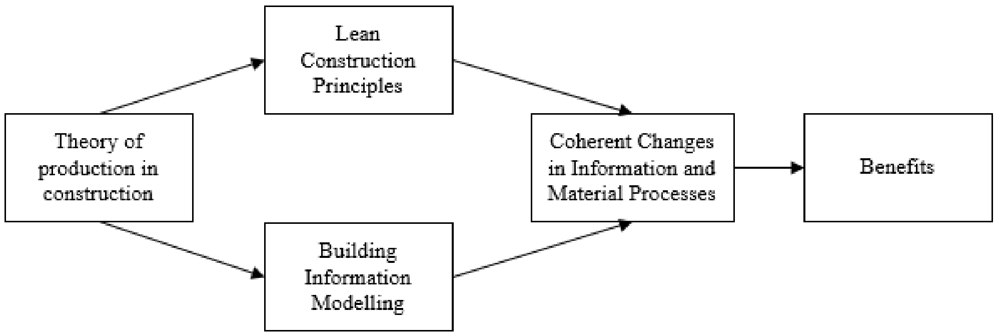

Figure 3.21: Role of Theory on Benefit Realization of Lean Principles & BIM (adapted from Sacks et al., 2010)

➢ **ID 3:** Lean construction advocates utilization of buffers if their sizes are manageable. De la Garza and Leong (2000) categorize buffers into two types: a schedule buffer and a plan buffer. Schedule buffers promotes intentional storage of extra inventory to continue work even if there is a problem in upstream process. Plan buffer, on the other hand, focuses on production of a backlog of workable activities to make sure continuous flow. This backlog prevent mobilization and demobilization of crews due to unexpected problems. Buffers help to reduce variability in production.

- **ID 4:** Batch size reduction and inventory reduction are lean construction principles that translated from lean production. Batch size in construction can be defined from an apartment construction example. If the construction is composed of five apartments and all of these apartments are being constructed concurrently then batch size is defined as five. Lean construction suggests to decrease number of concurrently constructed apartments. Moreover, Howell and Ballard (1998) explain the types of inventories that are need to be minimized as: "*materials and design information, labor and its tools, and intermediate work product that is not being exploited*."

- **ID 5:** Multi-skilled work force can generate significant benefits for the construction process. By referencing the study of Haas et al. (1997), Maturana et al. (2003) indicate that even with partially multi-skilled workers it is possible to make 30 to 35 % reduction in the number of required workforce. Therefore, it is frequently used in lean construction. However, though its contribution to lean construction practices is inevitable, multiskilling requires significant investments, training, and changes in labor management.

- **ID 6:** The treatment of work flow provides significant improvement in performance of the construction. Thomas et al., (2003) explains the importance of workflow management as follows:

  > *Since material, information, and equipment resources are components of workflow, smooth workflow means managing the availability of needed resources and components as they are modified and incorporated (value is added) into the completed product or structure. Through better workflow management, waste is eliminated, and cost and schedule performance is improved.*

- **ID 7:** Cross functional process chart is a lean construction application tool that serves for process description and assessment. In general, it shows parties of project at left side, and by horizontal lines responsibility boundaries are determined. Rectangular boxes indicate activities to be performed, and responsible party of them is shown on the left side. Arrows that crosses lines represent material or information handoffs between the corresponding parties. The contribution of these charts is identification of unnecessary processes or complexity. They are essential tools for value generation effort because they enable to identify inefficiencies and presents desired future state of processes. An example of cross functional process chart is provided in Figure 3.22.

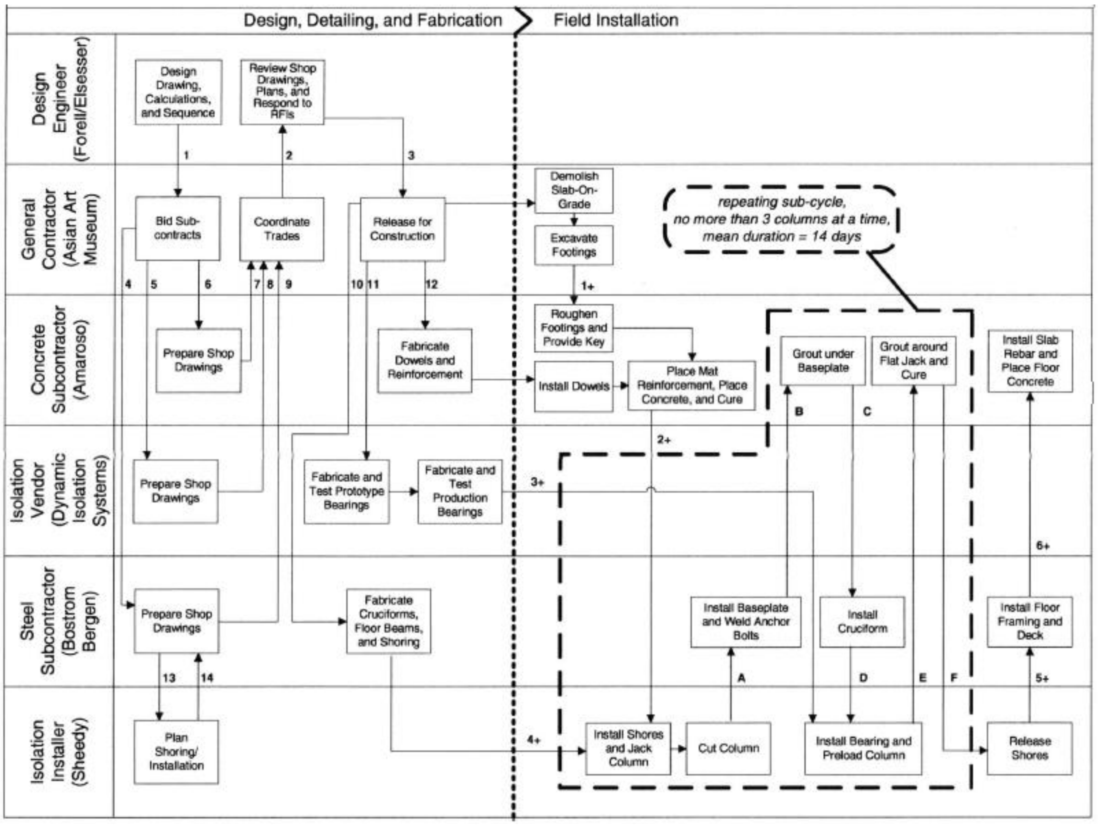

Figure 3.22: Cross Functional Process Chart Example (Tuholski et al., 2009)

- **ID 8:** Construction process analysis is a tool composed of process charts and top-view flow diagrams that is utilized to describe the flow of processes and identify the problems in the process quickly by means of some symbols. The basic symbols, which are operation, transportation, storage, delay, volume inspection, and quality inspection are described in Table 3.12. The process chart records flow within a unit, a section, a department, or between departments and each step of construction process (Lee et al., 1999).

Table 3.12: Basic Graphic Symbols (Lee et al., 1999)

No.	Basic Step	Specific Step	Symbol	Meaning	Comment
1	Operation	Operation	◯	Alters the shape or other characteristics of a material, semi-finished product, or product	
2	Transpor-tation	Transpor-tation	○ (⇨)	Changes the location of a material, semi-finished product, or product	The transportation symbol is a circle measuring half the diameter of the circle used as the operation symbol. An arrow can be used in place of this small circle. The direction of the arrow does not imply the direction of transportation.
3	Retention	Storage	▽	A scheduled accumulation of materials, parts, or products	
4		Delay	D	An unscheduled accumulation of materials, parts, or products	
5	Inspection	Volume Inspection	□	Measurement of amounts of materials, parts, or products for comparison with the specified amounts to judge whether a discrepancy exists	
6		Quality Inspection	◇	Testing and visual inspection of materials, parts, or products for comparison with quality standards to judge whether defective (substandard) products are being produced.	

- **ID 9:** The concept of pull is associated with LPS as explained in Section 3.5.2. In this respect, this lean construction principle is directly related to LPS. However, LPS is not the only way to apply pull concept. Some adjustments in planning systems, such as pulling of resources, enable the application of this principle without LPS.

- **IDs 10-11-12:** Application of Five S(s) principles to construction, poka-yoke (error proofing), and value stream mapping, which are discussed in Sections 2.2.6, 2.2.3.4, and 2.2.7 respectively, are applications of some lean production techniques to construction. Application of them to construction is quite similar to using them in manufacturing, which are explained in related sections.

- **ID 13:** Prefabrication and pre-casting allow more standardized production while they decreasing WIP and production variability. From these point of views, they serve for needs of lean construction idea, and used in practice as lean construction application techniques.

- **IDs 14-15-16:** Utilization of the data collected from the previous projects, risk management techniques, and safety and quality control plans are lean construction techniques that need to be implemented in organizational level. They all contribute the value generation in the planning stage and improve performance of the execution stage.

- **ID 17:** Optimizing site conditions is a must not only for lean construction applications but also traditional construction management practices. Keeping material in the closest location of use, minimum material storage, improving construction access, reducing setup times, and minimizing equipment movement are some optimization techniques for lean construction applications. Optimizing site conditions has also important effects on the waste reduction.

- **ID 18:** Resource allocation assists lean construction in terms of reducing variability and improving work flow. Moreover, as explained in "Heijunka" section (2.2.5) of lean production, levelled production fixes the workload, which lead to minimization of the waste.

- **IDs 19-20:** Involvement of downstream players in upstream decisions (Koskela et al., 2002) is always emphasized in lean construction. In this respect client, contractors, sub-contractors, inspector, suppliers, and labor force are all encouraged to involve in decision making process of lean construction. In order to achieve such a consolidation, providing training activities at every level is vital.

3.6 Measuring the Effects of Lean Construction Principles

The best way of measuring the effects of lean construction principles on the project performance is tracing the impact by directly implementing them on the construction site. Salem et al. (2006) has applied lean construction principles to a case study. Six lean construction techniques, namely LPS, increased visualization, first run studies, huddle meetings, the five S(s), and fail safe for quality, are implemented to a parking garage project during a six month period. By applying these principles, the project is completed under budget, three weeks ahead of schedule, and more satisfied relationships between subcontractors and general contractor is achieved. No major injuries occurred and incident rates was below that for similar projects in the same company. This example measures direct benefits of lean construction in terms of project performance. Nonetheless, project managers, who are accustomed to conventional construction project management techniques hesitate to implement lean principles on the construction sites. As a result, many simulation techniques are adopted to identify the effects of lean construction practices. Lean construction and simulation have strong relationships because simulation makes it possible to efficiently model and analyze processes from practical perspective. (Halpin and Kueckmann, 2002). Simulating lean construction physically, especially for mega projects, is impossible. For this reason, computer enabled virtual simulation is utilized, which is a very effective and cheap way of testing proposed processes because computer technology allows fast computing even though there are great numbers of combinations of process arrangements. Computer simulation can be used as a validation tool before implementing lean principles on the site (Mao and Zhang, 2008). In this respect, discrete-event simulation, as one of the most widely used simulation techniques among the lean construction practitioners, is preferred for the validation of lean construction (Hosseini et al., 2011; Sacks et al., 2007; Tommelein, 1998).

Discrete-event simulation basically models the operation of a system and explains the system behavior according to sequence of event in time. In addition to discrete-event simulation, Monte Carlo simulation is utilized, which simulates lean construction principles based on probabilistic techniques (Maturana et al., 2003). Furthermore, for training purposes some management games are used that demonstrate potential benefits of lean construction (Alarcon and Ashley, 1999). Tommelein et al. (1998) indicate that better understanding of lean construction principles can be obtained by means of simulation games that can be played either manually or using computer.

CHAPTER 4

RESEARCH METHODOLOGY AND QUESTIONNAIRE STUDY

Qualitative analyses of lean construction and stimulating concepts are carried out in previous chapters based on a broad literature survey. Furthermore, current practices for measuring the effects of lean construction principles are discussed in the Section 3.6. In this respect, this chapter aims to propound a model that quantitatively identifies the effects of some lean construction principles on project duration and its variation.

In accordance with this purpose, a methodology is developed to measure lean construction effects. The methodology depends on constructing a Monte Carlo simulation based model that stochastically compares lean scenario of a case study project with non-lean scenario of it. In order to develop lean and non-lean scenarios, a questionnaire, which is answered by three experts, is prepared. Experts have extensive knowledge in construction planning as well as they are familiar with lean construction concept.

In the light of this information, the chapter starts with the description of the research methodology used in this study. The methodology is composed of five basic steps. Each step of the methodology is explained in detail. Then, second part of the chapter explains the details of the questionnaire. The questionnaire consists of three parts. The chapter is concluded by describing each part of the questionnaire.

4.1 Research Methodology

The research methodology of this study is based on developing a procedure in order to assess the effects of lean construction principles in a quantitative manner. This procedure includes five basic steps. First of all, lean construction principles utilized in this study are determined. Then, by using these principles two different scenarios, named as lean and non-lean scenario, are generated. Next step is choosing a case study project that will be tested in this study. Afterwards, activity durations of the specified scenarios are determined for the case study project by gathering necessary information from the experts. Finally, a Monte Carlo simulation is performed according to results of the previous step. The steps are described below and they are further clarified throughout the following subsections.

- **Step 1:** Identifying which lean construction principles are applicable to the practice.
- **Step 2:** Generating scenarios to test the impact of applying lean principles to construction projects.
- **Step 3:** Choosing a case study project.
- **Step 4:** Determining activity durations of the scenarios generated in Step 2 for the case study project chosen in Step 3 by collecting the necessary data from the experts.
- **Step 5:** Carry out Monte Carlo simulation to quantitatively assess the impacts of lean principles.

4.1.1 Step 1 of the research methodology

This step includes determination of the lean construction principles used in the study. First of all, 14 lean construction principles are specified according to their applicability in residential building projects as the case study, which is explained in detail in Section 4.1.3, is such type of project. Most of the principles are similar to practical application techniques of lean construction, which are covered in Section 3.5.3. LPDS and LPS are not directly used in this study, but principles advocated by them are included. After the principles are determined, their relative importance are evaluated according to expert opinions. Following paragraphs summarize the principles used in the research methodology.

- **Training Activities:** Regular training activities are intended to improve existing knowledge and capabilities of the employees. By improving skills of them, they contribute to the lean construction philosophy. A more skilled staff will intensify the value generated in the construction process and help to eliminate construction wastes. In addition, if training activities are evaluated by the participants and they are modified based on feedback of the employees, the benefits of them will be improved further.

- **Long-Term Employee Relationships:** If most of the employees of the current project worked in similar projects of the company, they would have better knowledge about the work environment and culture of the company. On the other hand, if there is statistical data about productivity rates of employees, the company benefits from them more efficiently. Compendiously, long-term employee relationships has mutual advantages for both the employees and the company, which helps to improve value generation process.

- **Using Multi-Skilled Workforce:** Importance of multiskilling is mentioned in lean production as well as lean construction chapters. Lean idea suggests the utilization of such a labor in order to increase flexibility. When the workforce used in the project have skill of performing more than one operations, they are able to shift other works where labor shortage arises.

- **Improving Process Transparency:** One of the lean construction targets is getting employees involved and improving general awareness of them. In this respect, visual tools, 3D models, documents, and pictures are utilized in construction site to inform all employees about work progress. By this way, they become aware of project targets and milestones, and take a part in decision making process more actively.

- **Clean Construction Principles:** Clean construction principles stem from five S(s) rule of lean production. Keeping construction process in order allows for more standardized production and reduces the wastes. Starting from this point, lean construction advocates to employing some people who keep the construction site clean and prevent dirtiness on the site. Furthermore, it should make into a rule to placing materials, devices, and equipment in a fixed positions, which are known by everybody, when their utilization is finished.

- **Minimum Material Storage:** Minimum inventory and batch size principles are pillars of the lean production, by which it differentiates itself from the mass production. Although reducing material storage contributes to waste reduction significantly in lean production, its application to construction is a controversial issue. However, when successfully implemented, it is expected to reduce the construction wastes. For example steel reinforcements held in the site for a long period of time suffer from rusting. Besides, workers tend to disuse parts that they cut. For this reason, lean construction offer minimum material storage on the construction site. They should be delivered to the site just before their use.

- **Optimum Site Conditions:** There is no doubt that optimizing site conditions promotes to value generation and waste reduction. Therefore, lean construction attach importance to improve site access and to place materials to closest location of their use when they arrive to the construction site.

- **Long-Term Supplier Relationships:** Similar to benefits mentioned in long-term employee relationships principle, suppliers worked with the company in previous projects enable procurements that are based on trust. If both parties are aware of working principles of each other, more reliable and timely delivery of the materials will be possible. Long-term supplier relationships also serves for applicability of minimum material storage principle.

- **Consensus-Based Decision-Making:** Work planning conducted by a single party is most likely to fail in further stages of the project. Construction projects have too much complexity, and considerable amount of which arisen from presence of numerous parties. For a leaner construction, these parties should involve the decision-making process. In this regard, work planning should be decided by participation of all parties related to the project. Representatives of the owner, main contractor, sub-contractors, consultants, inspectors, suppliers, and workforce should come together in order to evaluate all opinions.

- **Cooperation between Different Departments:** Lack of integrity between different departments of construction process generates wastes that are inconvenient to compensate. To illustrate, it is very common in traditional construction practices to have conflicting mechanical, electrical, and civil projects. Lean construction, by its holistic approach, offers to cooperation between different departments. They should share incomplete information with each other during execution of activities.

- **Regular Meetings:** Regular meetings are indispensable for a successful lean construction implementation. They enable to gather information regarding the execution of the project from the viewpoints of different people. Therefore, attendance of representatives from all project participants is vital. Subjects of the meetings may include constraint analysis, production planning, evaluation of completed works, identification of reasons for non-completed works, and lessons learned. In this respect, regular meetings contribute to the transition from conventional planning systems to LPS. Another important point is that downstream players should be encouraged to be involved in upstream decisions during these meetings. By this way, value of the project will be improved.

- **Using Time Buffers:** Time buffers are placed between activities to compensate uncertainties in activity durations. Instead of calculating the activity durations for the shortest time possible, buffers are utilized to prevent delays caused by different risk factors. By this way, a continuous work is ensured and variations are minimized, as suggested by lean construction philosophy. For this reason, optimum time buffers should be placed for each activity.

- **4-D Scheduling and Simulation:** Interactions of lean construction and BIM is emphasized by lean construction practitioners as explained in previous sections. BIM is used for the purpose of 4-D scheduling that allows shared geometry in a single model. By this way, conflicts and, consequently, wastes are minimized. In addition, visual simulation of the construction process allows to detect problems before execution of the activities

- **Risk Management:** In terms of lean perspective, risk management techniques serves for earlier identification of the construction wastes. Along with waste reduction, having plans against identified risk factors enables a reliable workflow and enhanced value. Therefore, risk factors associated with the activities should be identified and risk reduction strategies should be prepared during the planning and execution phases.

4.1.2 Step 2 of the research methodology

Step 2 of the methodology constructs the scenarios that enable to measure the effects of lean construction principles. In this regard, two different scenarios are identified as lean scenario and non-lean scenario. These scenarios show differences in terms of applying 14 lean construction principles, which are introduced in previous step. Accordingly, two scenarios are described as follows:

- For the lean scenario, all of the lean construction principles described in the Step 1 are implemented together successfully.
- For the non-lean scenario, none of the lean construction principles described in the Step 1 are implemented in practice.

These scenarios form a basis for step 4 in which activity durations of a case study project are determined according to lean and non-lean scenarios. By this way, impacts of lean construction principles on project duration are evaluated.

4.1.3 Step 3 of the research methodology

This step introduces a case study project that enables to apply two scenarios generated in previous step. As mentioned previously, the case study project is a residential building project. It is composed of two 8-storey and three 5-storey buildings as shown in Figure 4.1. The buildings are identical in terms of floor area. Although the number of activities performed in 8-storey buildings is more than those of 5-storey buildings, activity types and their durations are same for all buildings.

Figure 4.1: 3D View of the Case Study Project

The reason why a residential building project is chosen as case study project is that these types of works have a repetitive nature. In other words, activities performed in an area are performed with exactly same way in another areas. Various sources indicate that lean construction principles are quite appropriate to be used in repetitive projects (Yang and Ioannou, 2001; Mao and Zhang, 2008; Hosseini et al., 2011). For this reason, many researchers test their proposed lean construction methodologies through case studies of multi-storey buildings (Maturana et al., 2003; Sacks and Goldin, 2007; Hosseini et al., 2011). As a result, a residential building project is selected to examine effects of lean construction principles.

4.1.4 Step 4 of the research methodology

In this step, activity durations of the scenarios generated in Step 2 are determined for the case study project described in Step 3. Activity durations are appointed by collecting the necessary data from the experts. Durations of the two different scenarios are compared by means of a Monte Carlo simulation.

Planning engineers generally use the most likely durations of activities while they are preparing the schedules. However, most of the time, the actual duration of the activity is different from the most likely duration due to predictable and unpredictable risks that construction works are accompanied with. For such cases, planners prefer to use probabilistic techniques like program evaluation and review technique (PERT) and Monte Carlo simulation to take into account both optimistic and pessimistic scenarios as well as the most likely scenario. The reason why Monte Carlo simulation is utilized in this study, instead of PERT, is explained by Barraza (2011) with following advantages of Monte Carlo Simulation;

- Monte Carlo simulation provides more realistic estimations by taking into account the probability of each activity to become critical.

- As compared to Monte Carlo simulation, PERT provides extremely optimistic projects.

In Monte Carlo simulation, the duration of an activity is shown by the probability distribution curve presented in Figure 4.2. In the figure, X_{min}, X, and X_{max} stand for the optimistic, the most likely, and pessimistic durations of the activity, respectively. These durations enable to obtain three different scenarios. A probability distribution curve can be defined in any shape by the person who conducts the simulation. For example, if possibility of occurrences are equal for X_{min}, X, and $X_{max,}$ then a uniform distribution should be utilized. If the probability of activity duration is ensured to get a very close duration to the most likely duration (X), then triangular distribution curve should be preferred. The curve shown in Figure 4.2 exemplifies a normal distribution. There are many other types of distributions, such as beta, singular or trapezoidal distribution.

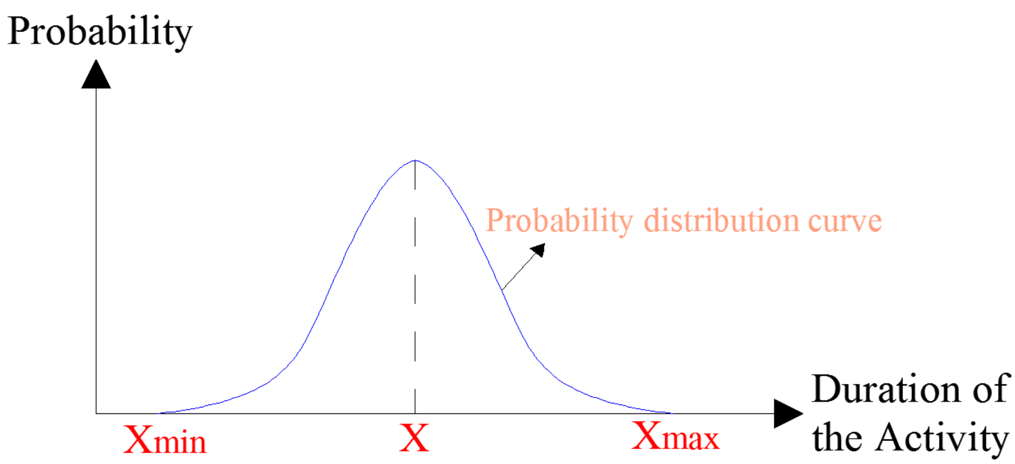

Figure 4.2: The Probability Distribution Curve of an Activity

To sum up, data collected from the experts is utilized in order to obtain minimum, most likely, and maximum durations of the case study project for lean and non-lean scenarios. Simulation results help to compare variation of the case study project durations for two different scenarios.

In order to ascertain X_{min}, X, and X_{max} durations of the activities for lean and non-lean scenarios, most likely durations of the case study project for non-lean scenario is determined. Table 4.1 shows all types of activities in the schedule, most likely durations of non-lean scenario, and the distribution curves of these durations. According to interpretations of the experts, minimum and maximum durations of the non-lean scenario as well as minimum, maximum, and most likely durations of the lean scenario are determined from the estimated durations shown in Table 4.1.

First two IDs of the table stand for start milestone and mobilization. IDs A1020 to A1080 shows foundation works, and IDs A1090 to A1240 represent all activities of the first floor of the first 8-storey building. IDs A1250 to A6320 are repeated identically for remaining 7 stories of the first 8-storey building, second 8-storey building, and three 5-storey buildings. Finally, the last two IDs show demobilization and finish milestone.

Table 4.1: Activity Types of the Case Study Project

Activity ID	Activity Name	Most Likely Duration of the Activity According to Non-Lean Scenario (days)	Distribution Curve of the Activity Duration
A1000	Start Milestone	0	-
A1010	Mobilization	10	Singular
A1020	Excavation	4	Triangular
A1030	Soil Compaction	2	Normal
A1040	Lean Concrete	0.5	Triangular
A1050	Rebar for Foundation	4	Triangular
A1060	Formwork for Foundation	2	Triangular
A1070	Concrete for Foundation	1	Triangular
A1080	Backfill for Foundation	3	Triangular
A1090	F1-SX Column Rebar	1	Triangular
A1100	F1-SX Column Formwork	2	Triangular
A1110	F1-SX Column Concrete	0.25	Triangular
A1120	F1-SX Beam Slab Rebar	2	Triangular
A1130	F1-SX Beam Slab Formwork	3	Triangular

Table 4.1 (Cont'd): Activity Types of the Case Study Project

A1140	F1-SX Beam Slab Concrete	0.5	Triangular
A1150	F1-SY Column Rebar	1	Triangular
A1160	F1-SY Column Formwork	2	Triangular
A1170	F1-SY Column Concrete	0.25	Triangular
A1180	F1-SY Beam Slab Rebar	2	Triangular
A1190	F1-SY Beam Slab Formwork	3	Triangular
A1200	F1-SY Beam Slab Concrete	0.5	Triangular
A1210	F1 Walls	5	Triangular
A1220	F1 Electrical Installation	2	Triangular
A1230	F1 Mechanical Installation	3	Triangular
A1240	F1 Plastering	11	Triangular
A1250-A6320	…	…	…
A6330	Demobilization	3	Trapezoidal
A6340	Finish Milestone	0	-

There are 9 basic activity types that experts evaluate their lean and non-lean scenarios. These basic activity types are; excavation, reinforcement, formwork, concrete, backfill, walls, electrical installation, mechanical installation, and plastering. Experts are given most likely durations of non-lean scenario for the basic activities in terms of some coefficients. As explained previously, they are required to estimate; minimum and maximum durations of the non-lean scenario and minimum, maximum, and most likely durations of the lean scenario by using given coefficients. Coefficients obtained from the experts for 9 basic activities are distributed to all related activities and optimistic, pessimistic, and most likely durations are obtained for both scenarios. Table 4.2 indicates the relationships of the nine basic activities with activity types of the case study project.

Table 4.2: Relationships of the Basic Activities with Case Study Project Activities

Basic Activity Types Introduced to the Experts	Related Activity Types of the Case Study Project
Excavation	Excavation
Reinforcement	Rebar for Foundation, Section X Column Rebar, Section X Beam Slab Rebar, Section Y Column Rebar, Section Y Beam Slab Rebar
Formwork	Formwork for Foundation, Section X Column Formwork, Section X Beam Slab Formwork, Section Y Column Formwork, Section Y Beam Slab Formwork
Concrete	Lean Concrete, Concrete for Foundation, Section X Column Concrete, Section X Beam Slab Concrete, Section Y Column Concrete, Section Y Beam Slab Concrete
Backfill	Backfill for Foundation
Walls	Walls
Electrical Installation	Electrical Installation
Mechanical Installation	Mechanical Installation
Plastering	Plastering

Probabilistic distributions of the activity durations, which are obtained in this step, are not only serve for carrying out Monte Carlo simulation for lean and non-lean scenarios but also enable to compare basic activity types in terms of their sensitivity towards lean construction principles. The application of this step is performed by means of the questionnaire. Related part of the questionnaire is explained in Section 4.2.3.

4.1.5 Step 5 of the research methodology

Once the necessary distributions are made according the relationships given in Table 4.2, all data needed for the simulation is generated. This data includes minimum, the most likely, and maximum durations of the activities for the lean and non-lean scenarios. In this respect, last step of the methodology is carrying out Monte Carlo simulation to measure tangible impacts of lean construction principles. The software utilized to carry out Monte Carlo simulation is @Risk (1997). @Risk works as an add-in of MS Excel. It allows to use practical functions of the spreadsheet. Moreover, thanks to its simple interface, simulation is performed in an easy and understandable manner. Before simulating the activity durations of the case study project, the following assumptions are adopted:

- Land purchasing and design activities are completed.
- Finishing works are not included.
- Conventional formwork systems are used for concrete operations, which requires separate concreting operations for columns and beam & slabs.
- Rebar, formwork, and concrete activities of the floors are performed in two successive sections, which are Section X (SX) and Section Y (SY).
- For reinforcement, formwork, concrete, and plastering activities, each building has one team. In other words, there are five teams for each of these activities.
- For walls, electrical installation, and mechanical installation activities, 8-storey buildings has one team and 5-storey buildings has another team. In other words, there are two teams for each of these activities.
- The availability of the excavator is one for excavation and backfill activities.
- Holidays are not considered and a working day equals to 8 hours.

A work schedule is developed according to these assumptions. Since used version of @Risk is compatible with MS Excel, the schedule is prepared in the spreadsheet. The schedule consists of 535 activities in total. The high number of activities and complex activity relationships create a need for ensuring the accuracy of the MS Excel model. For this reason, the schedule is reorganized by using Primavera P6, which is a commonly used planning software. The accuracy of the MS Excel model is validated by obtaining same schedule results with Primavera P6. After the validation, the simulation is performed for lean and non-lean scenarios separately by iterating activity durations 10,000 times via @Risk. The Simulation enables to compare lean and non-lean scenarios in terms of total duration of the project and variability of the project duration.

In conclusion, the research methodology explained throughout the aforementioned steps serves for identifying the effects of lean construction principles by means of a Monte Carlo simulation model. However, Monte Carlo simulation considerably relies on subjective judgment. For this reason, a questionnaire is developed to reflect expert opinions into the model. Following section introduces the content of the questionnaire.

4.2 Questionnaire Study

The data required to apply proposed methodology is acquired from the experts by means of the questionnaire. Therefore, this section explains all necessary information regarding the questionnaire. It is composed of three different parts. First part includes general question to evaluate participant profile. Second part consists of questions that inquire of lean construction principles of this study in terms of their importance. Finally, third part asks for durations of basic activities of the case study project for lean and non-lean scenarios. Each part of the questionnaire individually serves for the purposes indicated in Section 4.1. These purposes are summarized as follows:

- Part I aims to filter participants in terms of their knowledge level of lean construction, and their qualification for responding the questions.
- Part II aims to compare lean construction principles used in the questionnaire in terms of their importance.
- Part III aims to identify the impacts of lean construction principles on basic activity types, project duration, and variation of the total duration by determining activity durations of the case study project for lean and non-lean scenarios.

The questionnaire is presented in the Appendix A. Following subsections describe details of each part.

4.2.1 Part I of the questionnaire

This part of the questionnaire is composed of general questions that help to identify participant profile. There are six questions to be answered in Part I. First five questions are oriented towards personal information of respondents. In this regard, name and surname, education level, occupation, professional experience in residential building projects, and size of the company that participants are currently worked or last worked are investigated. The data generated from the questionnaire is used in simulation of residential building projects. Therefore, the professional experience in residential building projects is emphasized. Besides, size of the company helps to understand magnitude of the projects that participants previously worked on. Since the case study project of the simulation is a small residential building project, participant from small-sized companies are preferable. Sixth question, on the other hand, helps to understand whether a participant knows lean construction term or not. For the ones who does not have any background information, a brief description of lean construction is provided.

Part I one of the questionnaire serves for selecting appropriate people who have enough knowledge in both scheduling of small-sized residential building projects and lean construction practices. At the end of the preliminary studies, three experts are chosen to use their responses in Monte Carlo simulation. Lean construction practices in Turkey is very limited. Therefore, the number of qualified people is scarce. This is the reason why the questionnaire is carried out with three people. Nonetheless, the accuracy of the data is improved by face to face meetings with participants. During these meetings, they are informed about the case study project, Monte Carlo model, and especially lean construction principles that are used in the questionnaire. Moreover, in order to increase multiplicity of the data, experts are chosen from different working fields. First participant is general manager of a consultancy firm. Second participant is a planning engineer working in a small-sized company. Finally, third participant is an associate professor working in one of the major universities of the country. In this respect, necessary information regarding the participants is provided in the following section.

4.2.1.1 Participant I profile

Participant I is the general manager of a consultancy form. He has master’s degree in civil engineering and he is highly experienced in residential building projects. The company that he managed provides consultancy services in all areas of project management for the construction and engineering sector. In this respect, Participant I travels widely in his job to different construction sites around the world. Thanks to his field observations, he knows the current construction management practices and their weaknesses very well. Therefore, he is very much aware of lean construction, which aims to remove these weaknesses. Thanks to his vast experience in consulting of many construction projects and his knowledge of lean construction practices, principles in the Part II and activity durations in the Part III are evaluated quite realistically. He also contributes to development of the case study project.

4.2.1.2 Participant II profile

Participant II is a civil engineer working in a small-sized construction firm that conduct small-sized building projects, in several of which the client is the government. He is also a PhD candidate in department of construction engineering and management. Participant II answers the questions from the viewpoint of a planning engineer who has more than five years of experience in residential building projects. In addition to his knowledge of work planning, he has general information regarding the lean construction concept by means of his studies in the university. For this reason, he has enough qualifications to accurately respond the questionnaire.

4.2.1.3 Participant III profile

Participant III is an associate professor in a well-known and respected university of the Turkey. He has specialized in construction planning and project management for many years and he is reputable with his studies in these fields. As an academician, he knows lean construction philosophy very well. Besides, his experiences as a field engineer early in his career make him very much aware of practical applications. In terms of his mastery in construction planning and lean construction, Participant III possesses a perfect competence to respond the questionnaire.

In conclusion, all respondents have enough knowledge and experience to precisely evaluate the questionnaire. In addition, their diversity in different fields gives opportunity to examine the effects of lean construction principles from the viewpoints of different professionals. Following sections demonstrate the remaining parts of the questionnaire, which are answered by these three participants.

4.2.2 Part II of the questionnaire

In this part, lean construction principles are introduced to participants. First of all, each principle is briefly described. Then, based on their subjective judgments and experiences, participants are asked to determine the frequency of using them in practice and the impact when they are used. Scale of evaluation is represented in Table 4.3. By using this scale, lean construction principles are requested to be evaluated by the participants in terms of their frequencies and impacts.

Table 4.3: Scale of Evaluation for Lean Construction Principles

Scale	How frequently the principle can be used in practice	Impact of the principle on project duration when it is used
1	Never	Very Low
2	Rarely	Low
3	Sometimes	Moderate
4	Usually	High
5	Always	Very High

As indicated before, this part aims to ascertain the most important lean construction principles from the viewpoints of respondents. There are 14 lean construction principles defined within the scope of this study. Principles are chosen according to their practicability in residential building projects as explained in Section 4.1.1. A simple practice is adopted for determining the importance of each lean construction principle. By multiplying frequencies and impacts, relative importance factors of lean construction principles are calculated. Finally, principles introduced in this part guide participants to realize lean and non-lean scenarios that they will evaluate in Part III.

4.2.3 Part III of the questionnaire

In the questionnaire, after explaining the basic concepts of Monte Carlo simulation, the case study project is briefly described to participants. Details of the case study project, which are explained in Section 4.1.3, are further clarified during face to face meetings. The project is composed of nine basic activities, namely: Excavation, reinforcement, formwork, concrete, backfill, walls, electrical installation, mechanical installation, and plastering. Respondents are given to most likely durations of non-lean scenario as ***t***. By considering what may go wrong in practice and possible changes, they are expected to determine 5 different durations for each activity in terms of ***t***, which are minimum and maximum durations of non-lean scenario and minimum, most likely, and maximum durations of lean scenario. An example estimation is provided in Table 4.4.

Table 4.4: Example Estimation of an Activity Duration for Two Scenarios

Activities	Durations Based on 3 Scenario (When none of the Lean Construction Principles are Implemented)			Durations Based on 3 Scenario (When all of the Lean Construction Principles are Successfully Implemented)		
	Xmin	X	Xmax	Xmin	X	Xmax
Formwork	As a function of t_1 (E.g.: 0.95 t_1)	t_1	As a function of t_1 (E.g.: 1.30 t_1)	As a function of t_1 (E.g.: 0.90 t_1)	As a function of t_1 (E.g.: 0.95 t_1)	As a function of t_1 (E.g.: 1.15 t_1)

Part III of the questionnaire serves for generating the data, which is used in Monte Carlo simulation. In this respect, duration estimations of the basic activities are distributed to all related activities of the case study project. To illustrate, coefficients of the formwork activity are multiplied with most likely durations of non-lean scenario for any formwork related activity. In other words, same coefficients are used for both formwork for foundation and formwork for column activities. The duration difference stems only from the original must likely durations of non-lean scenario. For the activities that have no relation with nine basic activities, same distributions are used for both lean and non-lean scenario. Details of the activity durations as well as shapes of the distribution curves for each activity are covered in Table 4.1. The results generated from this part enable to understand; which type of activities are lean sensitive, and how lean construction principles affects total project duration and its variability.

In conclusion, a methodology is developed to assess tangible benefits of lean construction principles in residential building projects. This methodology is supported by a questionnaire in order to use expert opinions in the proposed model. Results of the questionnaire are presented in the Chapter 5 according to both individual answers of the participants and to their average values.

CHAPTER 5

RESEARCH FINDINGS

Chapter 4 explains the methodology used in this study and clarifies the questionnaire that helps to realize procedure developed via methodology. This chapter, on the other hand, presents the responses of the questionnaire and analysis of the necessary results. Part II and Part III of the questionnaire are separately examined throughout following subsections. These subsections initially shows individual responses of three participants. Then, average results are indicated.

This chapter systematically aims to assess; relative importance of the lean construction principles, effects of lean construction principles on basic activity types, and impacts of lean construction principles on project duration and variability of project duration. In this respect, Section 5.1 and 5.2 present Part II and Part III results of the questionnaire, respectively. Afterwards, Section 5.3 concludes the chapter by broadly discussing the results in terms of aforementioned targets.

5.1 Results of Part II

As explained in the Section 4.2.2, Part II of the questionnaire asks respondents to determine frequencies and impacts of the 14 lean construction principles in terms of their practicability. In this respect, answers of the three participants are given in the following subsections via Tables from 5.1 to 5.3. At the end, average results are presented with Table 5.4.

5.1.1 Responses of Participant I

Table 5.1 shows how frequently the principle can be used in practice and impact of the principle on project duration when it is used, according to Participant I. Last column shows multiplication of them, which indicates the relative importance of each principle.

Table 5.1: Frequency and Impact Responses of Participant I

ID	Lean Construction Principle	Frequency	Impact	Frequency X Impact
P1	Training Activities	3	3	9
P2	Long-term Employee Relationships	3	3	9
P3	Using Multi-skilled Workforce	2	2	4
P4	Improving Process Transparency	3	3	9
P5	Clean Construction Principles	4	3	12
P6	Minimum Material Storage	2	3	6
P7	Optimum Site Conditions	4	4	16
P8	Long-term Supplier Relationships	4	4	16
P9	Consensus-based Decision-making	4	4	16
P10	Cooperation between Different Departments	4	4	16
P11	Regular Meetings	5	4	20
P12	Using Time Buffers	3	3	9
P13	4-D Scheduling and Simulation	2	5	10
P14	Risk Management	2	4	8
Pall	Average	3.21	3.50	11.42

5.1.2 Responses of Participant II

Table 5.2 shows how frequently the principle can be used in practice and impact of the principle on project duration when it is used, according to Participant II. Last column shows multiplication of them, which indicates the relative importance of each principle.

Table 5.2: Frequency and Impact Responses of Participant II

ID	Lean Construction Principle	Frequency	Impact	Frequency X Impact
P1	Training Activities	2	3	6
P2	Long-term Employee Relationships	3	4	12
P3	Using Multi-skilled Workforce	3	2	6
P4	Improving Process Transparency	1	2	2
P5	Clean Construction Principles	2	2	4
P6	Minimum Material Storage	4	2	8
P7	Optimum Site Conditions	3	3	9
P8	Long-term Supplier Relationships	3	4	12
P9	Consensus-based Decision-making	2	4	8
P10	Cooperation between Different Departments	3	4	12
P11	Regular Meetings	3	4	12
P12	Using Time Buffers	3	3	9
P13	4-D Scheduling and Simulation	1	3	3
P14	Risk Management	2	3	6
Pall	Average	2.50	3.07	7.78

5.1.3 Responses of Participant III

Table 5.3 shows how frequently the principle can be used in practice and impact of the principle on project duration when it is used, according to Participant III. Last column shows multiplication of them, which indicates the relative importance of each principle.

Table 5.3: Frequency and Impact Responses of Participant III

ID	Lean Construction Principle	Frequency	Impact	Frequency X Impact
P1	Training Activities	4	5	20
P2	Long-term Employee Relationships	3	4	12
P3	Using Multi-skilled Workforce	2	3	6
P4	Improving Process Transparency	3	4	12
P5	Clean Construction Principles	3	4	12
P6	Minimum Material Storage	3	4	12
P7	Optimum Site Conditions	3	4	12
P8	Long-term Supplier Relationships	4	5	20
P9	Consensus-based Decision-making	4	5	20
P10	Cooperation between Different Departments	5	5	25
P11	Regular Meetings	4	4	16
P12	Using Time Buffers	2	3	6
P13	4-D Scheduling and Simulation	3	4	12
P14	Risk Management	4	4	16
Pall	Average	3.36	4.14	14.36

5.1.4 Average of the responses

Table 5.4 shows how frequently the principle can be used in practice and impact of the principle on project duration when it is used, according to average results of all three participants. Last column shows multiplication of them, which indicates the relative importance of each principle.

Table 5.4: Frequency and Impact According to Average of the All Responses

ID	Lean Construction Principle	Frequency	Impact	Frequency X Impact
P1	Training Activities	3,00	3,67	11,00
P2	Long-term Employee Relationships	3,00	3,67	11,00
P3	Using Multi-skilled Workforce	2,33	2,33	5,44
P4	Improving Process Transparency	2,33	3,00	7,00
P5	Clean Construction Principles	3,00	3,00	9,00
P6	Minimum Material Storage	3,00	3,00	9,00
P7	Optimum Site Conditions	3,33	3,67	12,22
P8	Long-term Supplier Relationships	3,67	4,33	15,89
P9	Consensus-based Decision-making	3,33	4,33	14,44
P10	Cooperation between Different Departments	4,00	4,33	17,33
P11	Regular Meetings	4,00	4,00	16,00
P12	Using Time Buffers	2,67	3,00	8,00
P13	4-D Scheduling and Simulation	2,00	4,00	8,00
P14	Risk Management	2,67	3,67	9,78
Pall	Average	3,02	3,57	11,01

5.2 Results of Part III

As explained in Section 4.2.3, Part III of the questionnaire ask respondents to determine optimistic and pessimistic durations for both non-lean and lean scenarios as a function of the given most likely duration of the non-lean scenario. In this respect, following procedure is used for subsections within this section;

- Sections 5.2.1, 5.2.2, and 5.2.3 present the results of each participant, respectively. Section 5.2.4, on the other hand, presents the average results.
- Subsections initially present the duration estimations of the each participant in a tabular format.
- Then, coefficients assigned by the participants are multiplied with the related activities of the case study project, which are shown in Table 4.2. Probabilistic activity durations are presented in a table for both lean and non-lean scenarios.
- Afterwards, durations of lean and non-lean scenario are iterated 10,000 times via @Risk in order to obtain stochastic project durations of both scenario.
- After the simulation, the probability distribution curves of the total project duration are presented with 90 % confidence intervals, both for lean and non-lean scenario.
- Next, statistical estimations of the curves are tabulated under the graphs.
- Later, similar curves are presented and statistical estimations are tabulated for the average duration of two 8-storey buildings.
- Finally, previous step is repeated for average duration of three 5-storey buildings.

Throughout the following subsections, results of the Part III are demonstrated according to procedure described above.

5.2.1 Responses of Participant I

This section shows the coefficients of activity durations that Participant I has determined in the Part III of the questionnaire, for lean and non-lean scenarios as shown in Table 5.5.

Table 5.5: Coefficients Determined by Participant I

ID	Activities	Durations Based on 3 Scenario (When none of the Lean Construction Principles are Implemented)			Durations Based on 3 Scenario (When all of the Lean Construction Principles are Successfully Implemented)		
		Xmin	X	Xmax	Xmin	X	Xmax
A1	Excavation	0.85 t_1	t_1	1.45 t_1	0.8 t_1	0.95 t_1	1.2 t_1
A2	Reinforcement	0.85 t_2	t_2	1.2 t_2	0.8 t_2	0.925 t_2	1.15 t_2
A3	Formwork	0.8 t_3	t_3	1.25 t_3	0.775 t_3	0.975 t_3	1.2 t_3
A4	Concrete	0.9 t_4	t_4	1.15 t_4	0.85 t_4	0.975 t_4	1.125 t_4
A5	Backfill	0.9 t_5	t_5	1.25 t_5	0.85 t_5	0.95 t_5	1.15 t_5
A6	Walls	0.9 t_6	t_6	1.6 t_6	0.8 t_6	0.9 t_6	1.15 t_6
A7	Electrical Installation	0.85 t_7	t_7	1.5 t_7	0.8 t_7	0.95 t_7	1.15 t_7
A8	Mechanical Installation	0.85 t_8	t_8	1.6 t_8	0.8 t_8	0.975 t_8	1.2 t_8
A9	Plastering	0.9 t_9	t_9	1.5 t_9	0.85 t_9	0.95 t_9	1.2 t_9

These coefficients are introduced to the related activities of the case study project, and activity durations shown in Table 5.6 are calculated.

Table 5.6: Probabilistic Activity Durations of the Case Study Project Determined by Participant I for Lean and Non-Lean Scenarios

Activity ID	Activity Name	Distribution Curve of the Activity Duration	Non-Lean Activity Duration Distributions (days)	Lean Activity Duration Distributions (days)
A1000	Start Milestone	-	-	-
A1010	Mobilization	Singular	15%: 8 20%: 9 35%: 10 15%: 11 10%: 12 5%: 13	15%: 8 20%: 9 35%: 10 15%: 11 10%: 12 5%: 13
A1020	Excavation	Triangular	Min: 3.4 Most Likely: 4 Max: 5.8	Min: 3.2 Most Likely: 3.8 Max: 4.8
A1030	Soil Compaction	Normal	Mean: 2 Std. Dev.: 0.5	Mean: 2 Std. Dev.: 0.5
A1040	Lean Concrete	Triangular	Min: 0.45 Most Likely: 0.5 Max: 0.575	Min: 0.425 Most Likely: 0.488 Max: 0.563
A1050	Rebar for Foundation	Triangular	Min: 3.4 Most Likely: 4 Max: 4.8	Min: 3.2 Most Likely: 3.7 Max: 4.6
A1060	Formwork for Foundation	Triangular	Min: 1.6 Most Likely: 2 Max: 2.5	Min: 1.55 Most Likely: 1.95 Max: 2.4
A1070	Concrete for Foundation	Triangular	Min: 0.9 Most Likely: 1 Max: 1.15	Min: 0.85 Most Likely: 0.975 Max: 1.125
A1080	Backfill for Foundation	Triangular	Min: 2.7 Most Likely: 3 Max: 3.75	Min: 2.55 Most Likely: 2.85 Max: 3.45
A1090	F1-SX Column Rebar	Triangular	Min: 0.85 Most Likely: 1 Max: 1.2	Min: 0.8 Most Likely: 0.925 Max: 1.15
A1100	F1-SX Column Formwork	Triangular	Min: 1.6 Most Likely: 2 Max: 2.5	Min: 1.55 Most Likely: 1.95 Max: 2.4
A1110	F1-SX Column Concrete	Triangular	Min: 0.225 Most Likely: 0.25 Max: 0.288	Min: 0.213 Most Likely: 0.244 Max: 0.281
A1120	F1-SX Beam Slab Rebar	Triangular	Min: 1.7 Most Likely: 2 Max: 2.4	Min: 1.6 Most Likely: 1.85 Max: 2.3
A1130	F1-SX Beam Slab Formwork	Triangular	Min: 2.4 Most Likely: 3 Max: 3.75	Min: 2.325 Most Likely: 2.925 Max: 3.6
A1140	F1-SX Beam Slab Concrete	Triangular	Min: 0.45 Most Likely: 0.5 Max: 0.575	Min: 0.425 Most Likely: 0.488 Max: 0.563

Table 5.6 (Cont'd): Probabilistic Activity Durations of the Case Study Project Determined by Participant I for Lean and Non-Lean Scenarios

Activity ID	Activity Name	Distribution Curve of the Activity Duration	Non-Lean Activity Duration Distributions (days)	Lean Activity Duration Distributions (days)
A1150	F1-SY Column Rebar	Triangular	Min: 0.85 Most Likely: 1 Max: 1.2	Min: 0.8 Most Likely: 0.925 Max: 1.15
A1160	F1-SY Column Formwork	Triangular	Min: 1.6 Most Likely: 2 Max: 2.5	Min: 1.55 Most Likely: 1.95 Max: 2.4
A1170	F1-SY Column Concrete	Triangular	Min: 0.225 Most Likely: 0.25 Max: 0.288	Min: 0.213 Most Likely: 0.244 Max: 0.281
A1180	F1-SY Beam Slab Rebar	Triangular	Min: 1.7 Most Likely: 2 Max: 2.4	Min: 1.6 Most Likely: 1.85 Max: 2.3
A1190	F1-SY Beam Slab Formwork	Triangular	Min: 2.4 Most Likely: 3 Max: 3.75	Min: 2.325 Most Likely: 2.925 Max: 3.6
A1200	F1-SY Beam Slab Concrete	Triangular	Min: 0.45 Most Likely: 0.5 Max: 0.575	Min: 0.425 Most Likely: 0.488 Max: 0.563
A1210	F1 Walls	Triangular	Min: 4.5 Most Likely: 5 Max: 8	Min: 4 Most Likely: 4.5 Max: 5.75
A1220	F1 Electrical Installation	Triangular	Min: 1.7 Most Likely: 2 Max: 3	Min: 1.6 Most Likely: 1.9 Max: 2.3
A1230	F1 Mechanical Installation	Triangular	Min: 2.55 Most Likely: 3 Max: 4.8	Min: 2.4 Most Likely: 2.925 Max: 3.6
A1240	F1 Plastering	Triangular	Min: 9.9 Most Likely: 11 Max: 16.5	Min: 9.35 Most Likely: 10.45 Max: 13.2
A1250-A6320	Repeated Identically			
A6330	Demobilization	Trapezoidal	Min: 2 Most Likely Range: 2.5-3.5 Max: 4	Min: 2 Most Likely Range: 2.5-3.5 Max: 4
A6340	Finish Milestone	-	-	-

By using these durations, Monte Carlo simulations are conducted for lean and non-lean scenarios. Distribution curves of the total project duration are shown in Figures 5.1 and 5.2. Simulation results of the Participant I are summarized in Table 5.7.

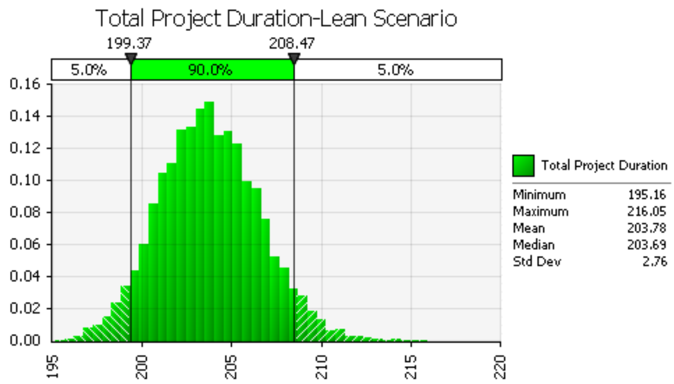

Figure 5.1: Probabilistic Total Project Duration of Lean Scenario According to Participant I

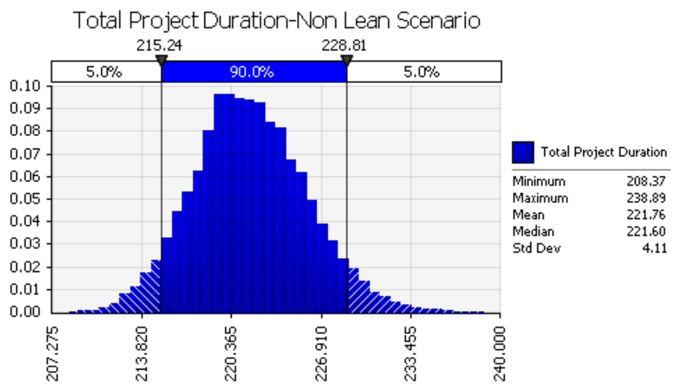

Figure 5.2: Probabilistic Total Project Duration of Non-Lean Scenario According to Participant I

Table 5.7: Summary of the Simulation Results for Total Project Duration According to Participant I

Performance Metric	Lean Scenario	Non Lean Scenario
Minimum Project Duration	195.16	208.37
Maximum Project Duration	216.05	238.89
Mean Project Duration	203.78	221.76
Median Project Duration	203.69	221.60
Standard Deviation	2.76	4.11

Moreover, average duration of 8-storey buildings is simulated as shown in Figures 5.3 and 5.4. Simulation results of these buildings are tabulated in Table 5.8.

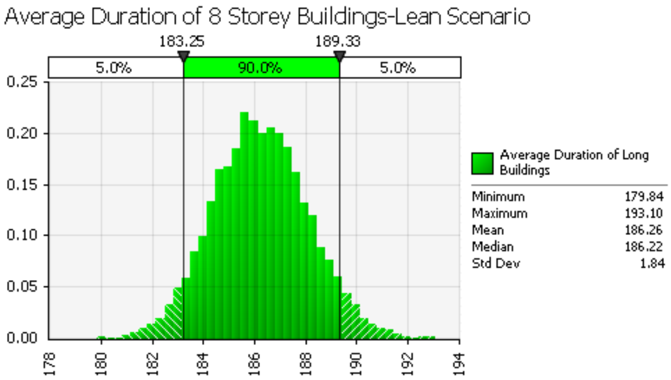

Figure 5.3: Probabilistic Average Duration of 8-Storey Buildings for Lean Scenario According to Participant I

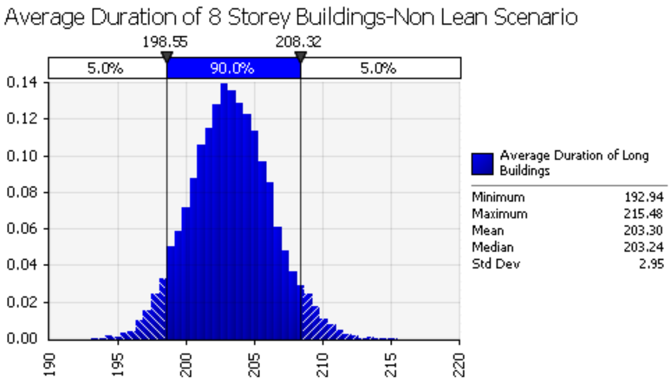

Figure 5.4: Probabilistic Average Duration of 8-Storey Buildings for Non-Lean Scenario According to Participant I

Table 5.8: Summary of the Simulation Results for Average Duration of 8-Storey Buildings According to Participant I

Performance Metric	Lean Scenario	Non Lean Scenario
Minimum Project Duration	179.84	192.94
Maximum Project Duration	193.10	215.48
Mean Project Duration	186.26	203.30
Median Project Duration	186.22	203.24
Standard Deviation	1.84	2.95

Finally, average duration of 5-storey buildings is simulated as shown in Figures 5.5 and 5.6. Simulation results of these buildings are tabulated in Table 5.9.

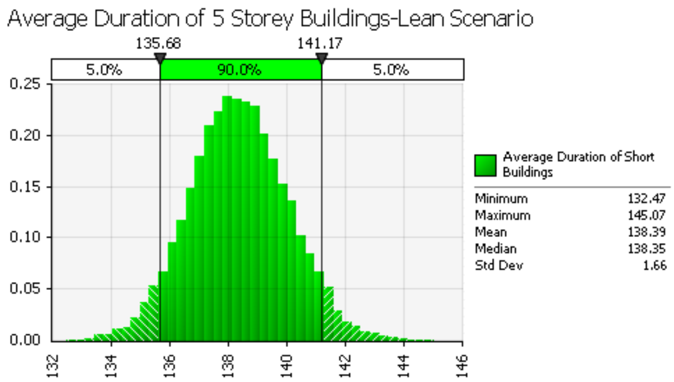

Figure 5.5: Probabilistic Average Duration of 5-Storey Buildings for Lean Scenario According to Participant I

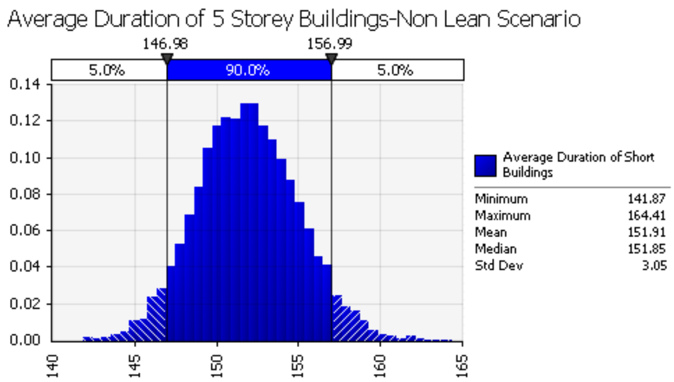

Figure 5.6: Probabilistic Average Duration of 5-Storey Buildings for Non-Lean Scenario According to Participant I

Table 5.9: Summary of the Simulation Results for Average Duration of 5-Storey Buildings According to Participant I

Performance Metric	Lean Scenario	Non Lean Scenario
Minimum Project Duration	132.47	141.87
Maximum Project Duration	145.07	164.41
Mean Project Duration	138.39	151.91
Median Project Duration	138.35	151.85
Standard Deviation	1.66	3.05

5.2.2 Responses of Participant II

This section shows the coefficients of activity durations that Participant II has determined in the Part III of the questionnaire, for lean and non-lean scenarios as shown in Table 5.10.

Table 5.10: Coefficients Determined by Participant II

ID	Activities	Durations Based on 3 Scenario (When none of the Lean Construction Principles are Implemented)			Durations Based on 3 Scenario (When all of the Lean Construction Principles are Successfully Implemented)		
		Xmin	X	Xmax	Xmin	X	Xmax
A1	Excavation	0.9 t_1	t_1	1.2 t_1	0.85 t_1	0.95 t_1	1.15 t_1
A2	Reinforcement	0.95 t_2	t_2	1.5 t_2	0.9 t_2	0.95 t_2	1.3 t_2
A3	Formwork	0.95 t_3	t_3	1.5 t_3	0.9 t_3	0.95 t_3	1.3 t_3
A4	Concrete	0.95 t_4	t_4	1.5 t_4	0.9 t_4	0.95 t_4	1.3 t_4
A5	Backfill	0.9 t_5	t_5	1.2 t_5	0.85 t_5	0.9 t_5	1.1 t_5
A6	Walls	0.95 t_6	t_6	1.5 t_6	0.9 t_6	0.95 t_6	1.3 t_6
A7	Electrical Installation	0.9 t_7	t_7	1.25 t_7	0.85 t_7	0.9 t_7	1.1 t_7
A8	Mechanical Installation	0.95 t_8	t_8	1.1 t_8	0.9 t_8	0.95 t_8	1.05 t_8
A9	Plastering	0.9 t_9	t_9	1.2 t_9	0.8 t_9	0.9 t_9	1.1 t_9

These coefficients are introduced to the related activities of the case study project, and activity durations shown in Table 5.11 are calculated.

Table 5.11: Probabilistic Activity Durations of the Case Study Project Determined by Participant II for Lean and Non-Lean Scenarios

Activity ID	Activity Name	Distribution Curve of the Activity Duration	Non-Lean Activity Duration Distributions (days)	Lean Activity Duration Distributions (days)
A1000	Start Milestone	-	-	-
A1010	Mobilization	Singular	15%: 8 20%: 9 35%: 10 15%: 11 10%: 12 5%: 13	15%: 8 20%: 9 35%: 10 15%: 11 10%: 12 5%: 13
A1020	Excavation	Triangular	Min: 3.6 Most Likely: 4 Max: 4.8	Min: 3.4 Most Likely: 3.8 Max: 4.6
A1030	Soil Compaction	Normal	Mean: 2 Std. Dev.: 0.5	Mean: 2 Std. Dev.: 0.5
A1040	Lean Concrete	Triangular	Min: 0.475 Most Likely: 0.5 Max: 0.75	Min: 0.45 Most Likely: 0.475 Max: 0.65
A1050	Rebar for Foundation	Triangular	Min: 3.8 Most Likely: 4 Max: 6	Min: 3.6 Most Likely: 3.8 Max: 5.2
A1060	Formwork for Foundation	Triangular	Min: 1.9 Most Likely: 2 Max: 3	Min: 1.8 Most Likely: 1.9 Max: 2.6
A1070	Concrete for Foundation	Triangular	Min: 0.95 Most Likely: 1 Max: 1.5	Min: 0.9 Most Likely: 0.95 Max: 1.3
A1080	Backfill for Foundation	Triangular	Min: 2.7 Most Likely: 3 Max: 3.6	Min: 2.55 Most Likely: 2.7 Max: 3.3
A1090	F1-SX Column Rebar	Triangular	Min: 0.95 Most Likely: 1 Max: 1.5	Min: 0.9 Most Likely: 0.95 Max: 1.3
A1100	F1-SX Column Formwork	Triangular	Min: 1.9 Most Likely: 2 Max: 3	Min: 1.8 Most Likely: 1.9 Max: 2.6
A1110	F1-SX Column Concrete	Triangular	Min: 0.238 Most Likely: 0.25 Max: 0.375	Min: 0.225 Most Likely: 0.238 Max: 0.325
A1120	F1-SX Beam Slab Rebar	Triangular	Min: 1.9 Most Likely: 2 Max: 3	Min: 1.8 Most Likely: 1.9 Max: 2.6
A1130	F1-SX Beam Slab Formwork	Triangular	Min: 2.85 Most Likely: 3 Max: 4.5	Min: 2.7 Most Likely: 2.85 Max: 3.9
A1140	F1-SX Beam Slab Concrete	Triangular	Min: 0.475 Most Likely: 0.5 Max: 0.75	Min: 0.45 Most Likely: 0.475 Max: 0.65

Table 5.11 (Cont'd): Probabilistic Activity Durations of the Case Study Project Determined by Participant II for Lean and Non-Lean Scenarios

Activity ID	Activity Name	Distribution Curve of the Activity Duration	Non-Lean Activity Duration Distributions (days)	Lean Activity Duration Distributions (days)
A1150	F1-SY Column Rebar	Triangular	Min: 0.95 Most Likely: 1 Max: 1.5	Min: 0.9 Most Likely: 0.95 Max: 1.3
A1160	F1-SY Column Formwork	Triangular	Min: 1.9 Most Likely: 2 Max: 3	Min: 1.8 Most Likely: 1.9 Max: 2.6
A1170	F1-SY Column Concrete	Triangular	Min: 0.238 Most Likely: 0.25 Max: 0.375	Min: 0.225 Most Likely: 0.238 Max: 0.325
A1180	F1-SY Beam Slab Rebar	Triangular	Min: 1.9 Most Likely: 2 Max: 3	Min: 1.8 Most Likely: 1.9 Max: 2.6
A1190	F1-SY Beam Slab Formwork	Triangular	Min: 2.85 Most Likely: 3 Max: 4.5	Min: 2.7 Most Likely: 2.85 Max: 3.9
A1200	F1-SY Beam Slab Concrete	Triangular	Min: 0.475 Most Likely: 0.5 Max: 0.75	Min: 0.45 Most Likely: 0.475 Max: 0.65
A1210	F1 Walls	Triangular	Min: 4.75 Most Likely: 5 Max: 7.5	Min: 4.5 Most Likely: 4.75 Max: 6.5
A1220	F1 Electrical Installation	Triangular	Min: 1.8 Most Likely: 2 Max: 2.5	Min: 1.7 Most Likely: 1.8 Max: 2.2
A1230	F1 Mechanical Installation	Triangular	Min: 2.85 Most Likely: 3 Max: 3.3	Min: 2.7 Most Likely: 2.85 Max: 3.15
A1240	F1 Plastering	Triangular	Min: 9.9 Most Likely: 11 Max: 13.2	Min: 8.8 Most Likely: 9.9 Max: 12.1
A1250-A6320	Repeated Identically			
A6330	Demobilization	Trapezoidal	Min: 2 Most Likely Range: 2.5-3.5 Max: 4	Min: 2 Most Likely Range: 2.5-3.5 Max: 4
A6340	Finish Milestone	-	-	-

By using these durations, Monte Carlo simulations are conducted for lean and non-lean scenarios. Distribution curves of the total project duration are shown in Figures 5.7 and 5.8. Simulation results of the Participant II are summarized in Table 5.12.

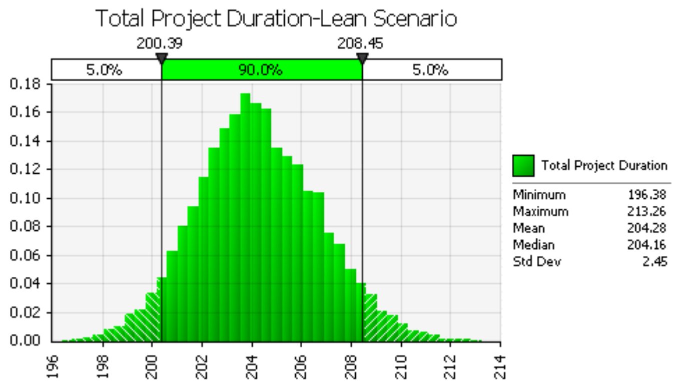

Figure 5.7: Probabilistic Total Project Duration of Lean Scenario According to Participant II

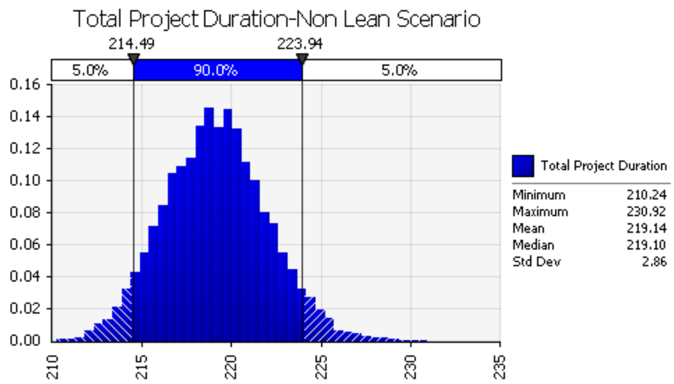

Figure 5.8: Probabilistic Total Project Duration of Non-Lean Scenario According to Participant II

Table 5.12: Summary of the Simulation Results for Total Project Duration According to Participant II

Performance Metric	Lean Scenario	Non Lean Scenario
Minimum Project Duration	196.38	210.24
Maximum Project Duration	213.26	230.90
Mean Project Duration	204.28	219.14
Median Project Duration	204.16	219.10
Standard Deviation	2.45	2.86

Moreover, average duration of 8-storey buildings is simulated as shown in Figures 5.9 and 5.10. Simulation results of these buildings are tabulated in Table 5.13.

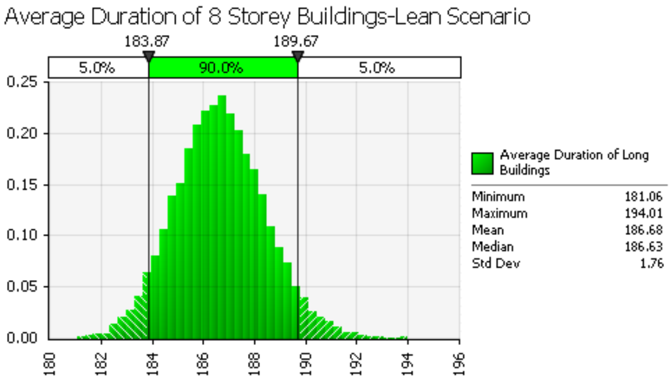

Figure 5.9: Probabilistic Average Duration of 8-Storey Buildings for Lean Scenario According to Participant II

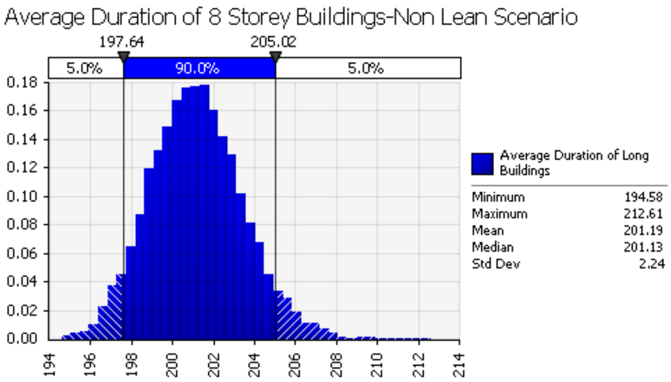

Figure 5.10: Probabilistic Average Duration of 8-Storey Buildings for Non-Lean Scenario According to Participant II

Table 5.13: Summary of the Simulation Results for Average Duration of 8-Storey Buildings According to Participant II

Performance Metric	Lean Scenario	Non Lean Scenario
Minimum Project Duration	181.06	194.58
Maximum Project Duration	194.01	212.61
Mean Project Duration	186.68	201.19
Median Project Duration	186.63	201.13
Standard Deviation	1.76	2.24

Finally, average duration of 5-storey buildings is simulated as shown in Figures 5.11 and 5.12. Simulation results of these buildings are tabulated in Table 5.14.

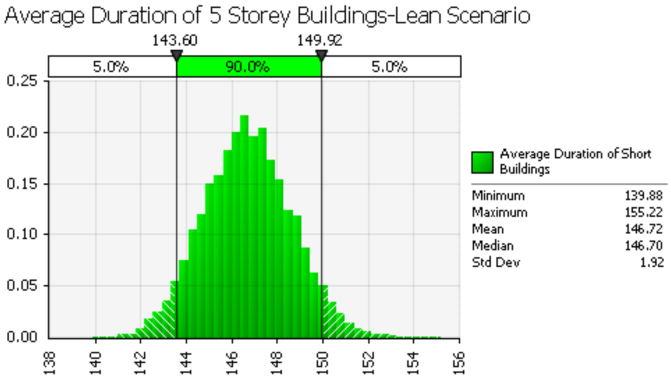

Figure 5.11: Probabilistic Average Duration of 5-Storey Buildings for Lean Scenario According to Participant II

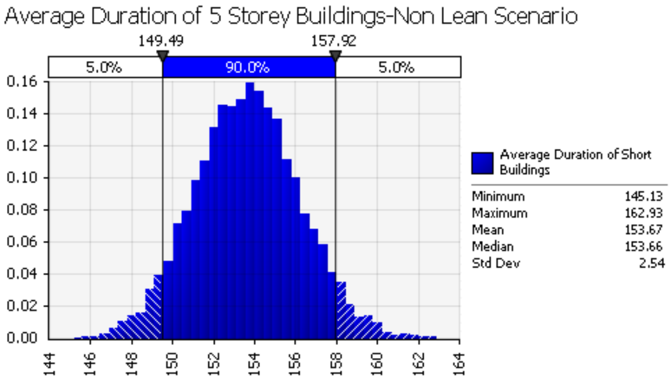

Figure 5.12: Probabilistic Average Duration of 5-Storey Buildings for Non-Lean Scenario According to Participant II

Table 5.14: Summary of the Simulation Results for Average Duration of 5-Storey Buildings According to Participant II

Performance Metric	Lean Scenario	Non Lean Scenario
Minimum Project Duration	139.88	145.13
Maximum Project Duration	155.22	162.93
Mean Project Duration	146.72	153.67
Median Project Duration	146.70	153.66
Standard Deviation	1.92	2.54

5.2.3 Responses of Participant III

This section shows the coefficients of activity durations that Participant III has determined in the Part III of the questionnaire, for lean and non-lean scenarios as shown in Table 5.15.

Table 5.15: Coefficients Determined by Participant III

ID	Activities	Durations Based on 3 Scenario (When none of the Lean Construction Principles are Implemented)			Durations Based on 3 Scenario (When all of the Lean Construction Principles are Successfully Implemented)		
		Xmin	X	Xmax	Xmin	X	Xmax
A1	Excavation	$0.75\ t_1$	t_1	$1.35\ t_1$	$0.75\ t_1$	$0.9\ t_1$	$1.15\ t_1$
A2	Reinforcement	$0.85\ t_2$	t_2	$1.3\ t_2$	$0.85\ t_2$	$0.9\ t_2$	$1.1\ t_2$
A3	Formwork	$0.8\ t_3$	t_3	$1.25\ t_3$	$0.85\ t_3$	$0.95\ t_3$	$1.15\ t_3$
A4	Concrete	$0.9\ t_4$	t_4	$1.1\ t_4$	$0.9\ t_4$	$0.95\ t_4$	$1.05\ t_4$
A5	Backfill	$0.8\ t_5$	t_5	$1.35\ t_5$	$0.8\ t_5$	$0.9\ t_5$	$1.2\ t_5$
A6	Walls	$0.85\ t_6$	t_6	$1.4\ t_6$	$0.85\ t_6$	$0.9\ t_6$	$1.1\ t_6$
A7	Electrical Installation	$0.8\ t_7$	t_7	$1.35\ t_7$	$0.85\ t_7$	$0.9\ t_7$	$1.15\ t_7$
A8	Mechanical Installation	$0.8\ t_8$	t_8	$1.35\ t_8$	$0.85\ t_8$	$0.9\ t_8$	$1.15\ t_8$
A9	Plastering	$0.85\ t_9$	t_9	$1.4\ t_9$	$0.85\ t_9$	$0.9\ t_9$	$1.2\ t_9$

These coefficients are introduced to the related activities of the case study project, and activity durations shown in Table 5.16 are calculated.

Table 5.16: Probabilistic Activity Durations of the Case Study Project Determined by Participant III for Lean and Non-Lean Scenarios

Activity ID	Activity Name	Distribution Curve of the Activity Duration	Non-Lean Activity Duration Distributions (days)	Lean Activity Duration Distributions (days)
A1000	Start Milestone	-	-	-
A1010	Mobilization	Singular	15%: 8 20%: 9 35%: 10 15%: 11 10%: 12 5%: 13	15%: 8 20%: 9 35%: 10 15%: 11 10%: 12 5%: 13
A1020	Excavation	Triangular	Min: 3.4 Most Likely: 4 Max: 5.4	Min: 3 Most Likely: 3.6 Max: 4.6
A1030	Soil Compaction	Normal	Mean: 2 Std. Dev.: 0.5	Mean: 2 Std. Dev.: 0.5
A1040	Lean Concrete	Triangular	Min: 0.45 Most Likely: 0.5 Max: 0.55	Min: 0.45 Most Likely: 0.475 Max: 0.525
A1050	Rebar for Foundation	Triangular	Min: 3.4 Most Likely: 4 Max: 5.2	Min: 3.4 Most Likely: 3.6 Max: 4.4
A1060	Formwork for Foundation	Triangular	Min: 1.6 Most Likely: 2 Max: 2.5	Min: 1.7 Most Likely: 1.9 Max: 2.3
A1070	Concrete for Foundation	Triangular	Min: 0.9 Most Likely: 1 Max: 1.1	Min: 0.9 Most Likely: 0.95 Max: 1.05
A1080	Backfill for Foundation	Triangular	Min: 2.4 Most Likely: 3 Max: 4.05	Min: 2.4 Most Likely: 2.7 Max: 3.6
A1090	F1-SX Column Rebar	Triangular	Min: 0.85 Most Likely: 1 Max: 1.3	Min: 0.85 Most Likely: 0.9 Max: 1.1
A1100	F1-SX Column Formwork	Triangular	Min: 1.6 Most Likely: 2 Max: 2.5	Min: 1.7 Most Likely: 1.9 Max: 2.3
A1110	F1-SX Column Concrete	Triangular	Min: 0.225 Most Likely: 0.25 Max: 0.275	Min: 0.225 Most Likely: 0.238 Max: 0.263
A1120	F1-SX Beam Slab Rebar	Triangular	Min: 1.7 Most Likely: 2 Max: 2.6	Min: 1.7 Most Likely: 1.8 Max: 2.2
A1130	F1-SX Beam Slab Formwork	Triangular	Min: 2.4 Most Likely: 3 Max: 3.75	Min: 2.55 Most Likely: 2.85 Max: 3.45
A1140	F1-SX Beam Slab Concrete	Triangular	Min: 0.45 Most Likely: 0.5 Max: 0.55	Min: 0.45 Most Likely: 0.475 Max: 0.525

Table 5.16 (Cont'd): Probabilistic Activity Durations of the Case Study Project Determined by Participant III for Lean and Non-Lean Scenarios

Activity ID	Activity Name	Distribution Curve of the Activity Duration	Non-Lean Activity Duration Distributions (days)	Lean Activity Duration Distributions (days)
A1150	F1-SY Column Rebar	Triangular	Min: 0.85 Most Likely: 1 Max: 1.3	Min: 0.85 Most Likely: 0.9 Max: 1.1
A1160	F1-SY Column Formwork	Triangular	Min: 1.6 Most Likely: 2 Max: 2.5	Min: 1.7 Most Likely: 1.9 Max: 2.3
A1170	F1-SY Column Concrete	Triangular	Min: 0.225 Most Likely: 0.25 Max: 0.275	Min: 0.225 Most Likely: 0.238 Max: 0.263
A1180	F1-SY Beam Slab Rebar	Triangular	Min: 1.7 Most Likely: 2 Max: 2.6	Min: 1.7 Most Likely: 1.8 Max: 2.2
A1190	F1-SY Beam Slab Formwork	Triangular	Min: 2.4 Most Likely: 3 Max: 3.75	Min: 2.55 Most Likely: 2.85 Max: 3.45
A1200	F1-SY Beam Slab Concrete	Triangular	Min: 0.45 Most Likely: 0.5 Max: 0.55	Min: 0.45 Most Likely: 0.475 Max: 0.525
A1210	F1 Walls	Triangular	Min: 4.25 Most Likely: 5 Max: 7	Min: 4.25 Most Likely: 4.5 Max: 5.5
A1220	F1 Electrical Installation	Triangular	Min: 1.6 Most Likely: 2 Max: 2.7	Min: 1.7 Most Likely: 1.8 Max: 2.3
A1230	F1 Mechanical Installation	Triangular	Min: 2.4 Most Likely: 3 Max: 4.05	Min: 2.55 Most Likely: 2.7 Max: 3.45
A1240	F1 Plastering	Triangular	Min: 9.35 Most Likely: 11 Max: 15.4	Min: 9.35 Most Likely: 9.9 Max: 13.2
A1250-A6320	Repeated Identically			
A6330	Demobilization	Trapezoidal	Min: 2 Most Likely Range: 2.5-3.5 Max: 4	Min: 2 Most Likely Range: 2.5-3.5 Max: 4
A6340	Finish Milestone	-	-	-

By using these durations, Monte Carlo simulations are conducted for lean and non-lean scenarios. Distribution curves of the total project duration are shown in Figures 5.13 and 5.14. Simulation results of the Participant III are summarized in Table 5.17.

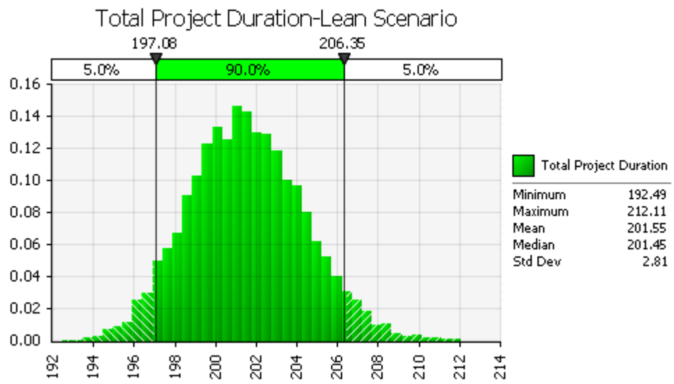

Figure 5.13: Probabilistic Total Project Duration of Lean Scenario According to Participant III

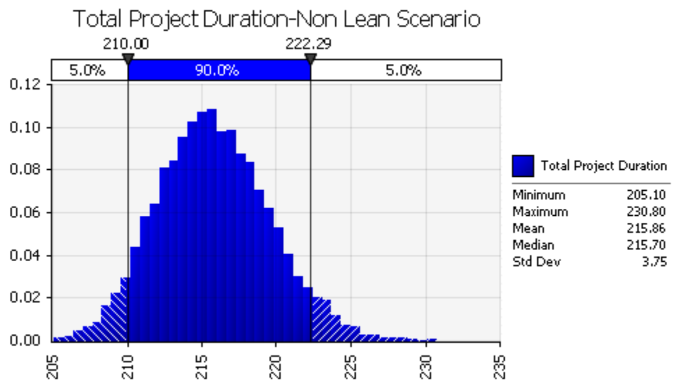

Figure 5.14: Probabilistic Total Project Duration of Non-Lean Scenario According to Participant III

Table 5.17: Summary of the Simulation Results for Total Project Duration According to Participant III

Performance Metric	Lean Scenario	Non Lean Scenario
Minimum Project Duration	192.49	205.10
Maximum Project Duration	212.11	230.80
Mean Project Duration	201.55	215.86
Median Project Duration	201.45	215.70
Standard Deviation	2.81	3.75

Moreover, average duration of 8-storey buildings is simulated as shown in Figures 5.15 and 5.16. Simulation results of these buildings are tabulated in Table 5.18.

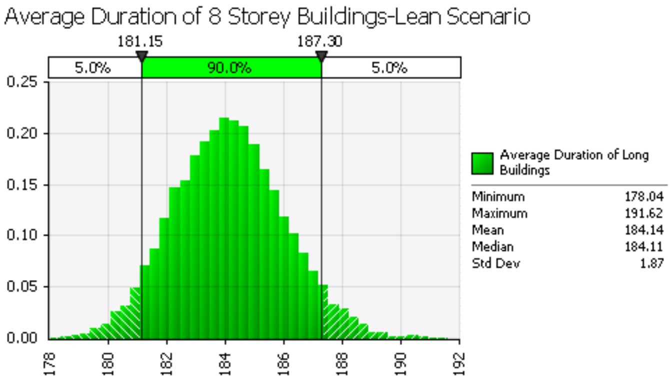

Figure 5.15: Probabilistic Average Duration of 8-Storey Buildings for Lean Scenario According to Participant III

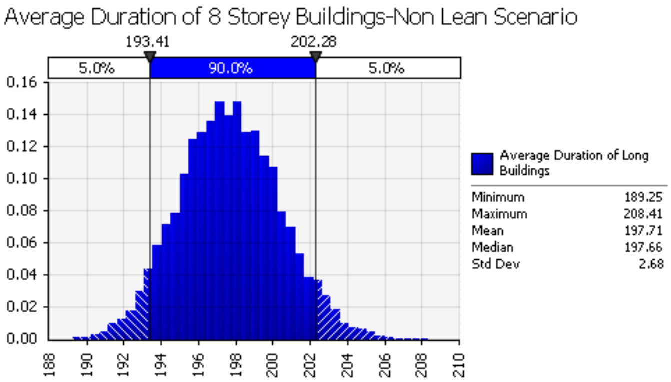

Figure 5.16: Probabilistic Average Duration of 8-Storey Buildings for Non-Lean Scenario According to Participant III

Table 5.18: Summary of the Simulation Results for Average Duration of 8-Storey Buildings According to Participant III

Performance Metric	Lean Scenario	Non Lean Scenario
Minimum Project Duration	178.04	189.25
Maximum Project Duration	191.62	208.41
Mean Project Duration	184.14	197.71
Median Project Duration	184.11	197.66
Standard Deviation	1.87	2.68

Finally, average duration of 5-storey buildings is simulated as shown in Figures 5.17 and 5.18. Simulation results of these buildings are tabulated in Table 5.19.

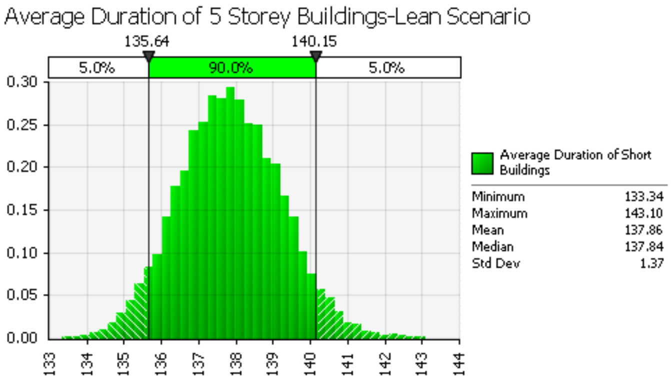

Figure 5.17: Probabilistic Average Duration of 5-Storey Buildings for Lean Scenario According to Participant III

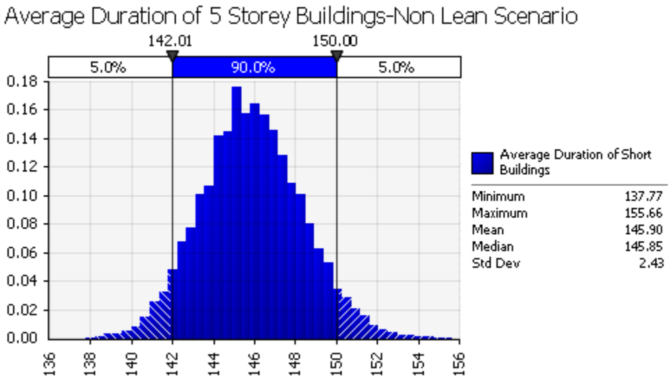

Figure 5.18: Probabilistic Average Duration of 5-Storey Buildings for Non-Lean Scenario According to Participant III

Table 5.19: Summary of the Simulation Results for Average Duration of 5-Storey Buildings According to Participant III

Performance Metric	Lean Scenario	Non Lean Scenario
Minimum Project Duration	133.34	137.77
Maximum Project Duration	143.10	155.66
Mean Project Duration	137.86	145.90
Median Project Duration	137.84	145.85
Standard Deviation	1.37	2.43

5.2.4 Average of the responses

This section shows the average coefficients of activity durations that all participants have determined in the Part III of the questionnaire, for lean and non-lean scenarios as shown in Table 5.20.

Table 5.20: Coefficients Determined by Average of All Participants

ID	Activities	Durations Based on 3 Scenario (When none of the Lean Construction Principles are Implemented)			Durations Based on 3 Scenario (When all of the Lean Construction Principles are Successfully Implemented)		
		Xmin	X	Xmax	Xmin	X	Xmax
A1	Excavation	0.833 t_1	t_1	1.333 t_1	0.800 t_1	0.933 t_1	1.167 t_1
A2	Reinforcement	0.833 t_2	t_2	1.333 t_2	0.850 t_2	0.925 t_2	1.183 t_2
A3	Formwork	0.850 t_3	t_3	1.333 t_3	0.842 t_3	0.958 t_3	1.217 t_3
A4	Concrete	0.917 t_4	t_4	1.250 t_4	0.883 t_4	0.958 t_4	1.158 t_4
A5	Backfill	0.867 t_5	t_5	1.267 t_5	0.833 t_5	0.917 t_5	1.150 t_5
A6	Walls	0.900 t_6	t_6	1.500 t_6	0.850 t_6	0.917 t_6	1.183 t_6
A7	Electrical Installation	0.850 t_7	t_7	1.367 t_7	0.833 t_7	0.917 t_7	1.133 t_7
A8	Mechanical Installation	0.867 t_8	t_8	1.350 t_8	0.850 t_8	0.942 t_8	1.133 t_8
A9	Plastering	0.883 t_9	t_9	1.367 t_9	0.833 t_9	0.917 t_9	1.167 t_9

These coefficients are introduced to the related activities of the case study project, and activity durations shown in Table 5.21 are calculated.

Table 5.21: Probabilistic Activity Durations of the Case Study Project Determined by Average of All Participants for Lean and Non-Lean Scenarios

Activity ID	Activity Name	Distribution Curve of the Activity Duration	Non-Lean Activity Duration Distributions (days)	Lean Activity Duration Distributions (days)
A1000	Start Milestone	-	-	-
A1010	Mobilization	Singular	15%: 8 20%: 9 35%: 10 15%: 11 10%: 12 5%: 13	15%: 8 20%: 9 35%: 10 15%: 11 10%: 12 5%: 13
A1020	Excavation	Triangular	Min: 3.333 Most Likely: 4 Max: 5.333	Min: 3.200 Most Likely: 3.733 Max: 4.667
A1030	Soil Compaction	Normal	Mean: 2 Std. Dev.: 0.5	Mean: 2 Std. Dev.: 0.5
A1040	Lean Concrete	Triangular	Min: 0.458 Most Likely: 0.5 Max: 0.625	Min: 0.442 Most Likely: 0.479 Max: 0.579
A1050	Rebar for Foundation	Triangular	Min: 3.533 Most Likely: 4 Max: 5.333	Min: 3.4 Most Likely: 3.7 Max: 4.733
A1060	Formwork for Foundation	Triangular	Min: 1.700 Most Likely: 2 Max: 2.667	Min: 1.683 Most Likely: 1.917 Max: 2.433
A1070	Concrete for Foundation	Triangular	Min: 0.917 Most Likely: 1 Max: 1.250	Min: 0.883 Most Likely: 0.958 Max: 1.158
A1080	Backfill for Foundation	Triangular	Min: 2.600 Most Likely: 3 Max: 3.800	Min: 2.500 Most Likely: 2.750 Max: 3.450
A1090	F1-SX Column Rebar	Triangular	Min: 0.883 Most Likely: 1 Max: 1.333	Min: 0.850 Most Likely: 0.925 Max: 1.183
A1100	F1-SX Column Formwork	Triangular	Min: 1.700 Most Likely: 2 Max: 2.667	Min: 1.683 Most Likely: 1.917 Max: 2.433
A1110	F1-SX Column Concrete	Triangular	Min: 0.229 Most Likely: 0.25 Max: 0.313	Min: 0.221 Most Likely: 0.240 Max: 0.290
A1120	F1-SX Beam Slab Rebar	Triangular	Min: 1.767 Most Likely: 2 Max: 2.667	Min: 1.700 Most Likely: 1.850 Max: 2.367
A1130	F1-SX Beam Slab Formwork	Triangular	Min: 2.550 Most Likely: 3 Max: 4.000	Min: 2.525 Most Likely: 2.875 Max: 3.650
A1140	F1-SX Beam Slab Concrete	Triangular	Min: 0.458 Most Likely: 0.5 Max: 0.625	Min: 0.442 Most Likely: 0.479 Max: 0.579

Table 5.21 (Cont'd): Probabilistic Activity Durations of the Case Study Project Determined by average of All Participants for Lean and Non-Lean Scenarios

Activity ID	Activity Name	Distribution Curve of the Activity Duration	Non-Lean Activity Duration Distributions (days)	Lean Activity Duration Distributions (days)
A1150	F1-SY Column Rebar	Triangular	Min: 0.883 Most Likely: 1 Max: 1.333	Min: 0.850 Most Likely: 0.925 Max: 1.183
A1160	F1-SY Column Formwork	Triangular	Min: 1.700 Most Likely: 2 Max: 2.667	Min: 1.683 Most Likely: 1.917 Max: 2.433
A1170	F1-SY Column Concrete	Triangular	Min: 0.229 Most Likely: 0.25 Max: 0.313	Min: 0.221 Most Likely: 0.240 Max: 0.290
A1180	F1-SY Beam Slab Rebar	Triangular	Min: 1.767 Most Likely: 2 Max: 2.667	Min: 1.700 Most Likely: 1.850 Max: 2.367
A1190	F1-SY Beam Slab Formwork	Triangular	Min: 2.550 Most Likely: 3 Max: 4.000	Min: 2.525 Most Likely: 2.875 Max: 3.650
A1200	F1-SY Beam Slab Concrete	Triangular	Min: 0.458 Most Likely: 0.5 Max: 0.625	Min: 0.442 Most Likely: 0.479 Max: 0.579
A1210	F1 Walls	Triangular	Min: 4.500 Most Likely: 5 Max: 7.500	Min: 4.250 Most Likely: 4.583 Max: 5.917
A1220	F1 Electrical Installation	Triangular	Min: 1.700 Most Likely: 2 Max: 2.733	Min: 1.667 Most Likely: 1.833 Max: 2.267
A1230	F1 Mechanical Installation	Triangular	Min: 2.600 Most Likely: 3 Max: 4.050	Min: 2.550 Most Likely: 2.825 Max: 3.400
A1240	F1 Plastering	Triangular	Min: 9.717 Most Likely: 11 Max: 15.033	Min: 9.167 Most Likely:10.083 Max: 12.833
A1250-A6320	Repeated Identically			
A6330	Demobilization	Trapezoidal	Min: 2 Most Likely Range: 2.5-3.5 Max: 4	Min: 2 Most Likely Range: 2.5-3.5 Max: 4
A6340	Finish Milestone	-	-	-

By using these durations, Monte Carlo simulations are conducted for lean and non-lean scenarios. Distribution curves of the total project duration are shown in Figures 5.19 and 5.20. Simulation results of the all participants are summarized in Table 5.22.

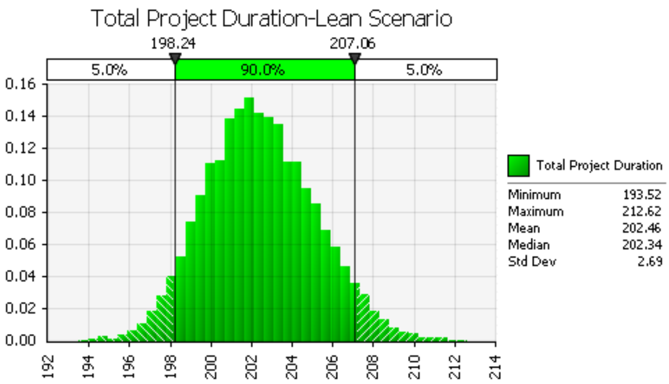

Figure 5.19: Probabilistic Total Project Duration of Lean Scenario According to Average of All Participants

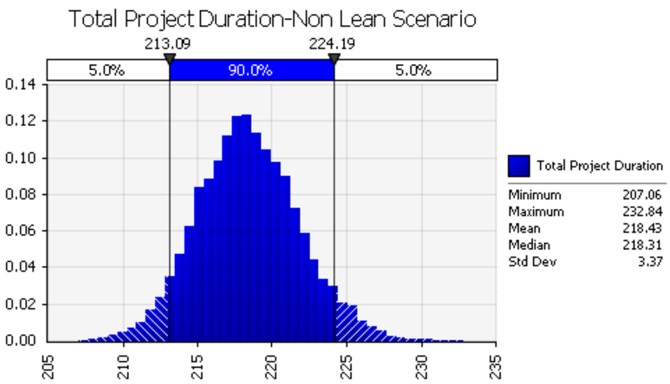

Figure 5.20: Probabilistic Total Project Duration of Non-Lean Scenario According to Average of All Participants

Table 5.22: Summary of the Simulation Results for Total Project Duration According to Average of All Participants

Performance Metric	Lean Scenario	Non Lean Scenario
Minimum Project Duration	193.52	207.06
Maximum Project Duration	212.62	232.84
Mean Project Duration	202.46	218.31
Median Project Duration	202.34	218.31
Standard Deviation	2.69	3.37

Moreover, average duration of 8-storey buildings is simulated as shown in Figures 5.21 and 5.22. Simulation results of these buildings are tabulated in Table 5.23.

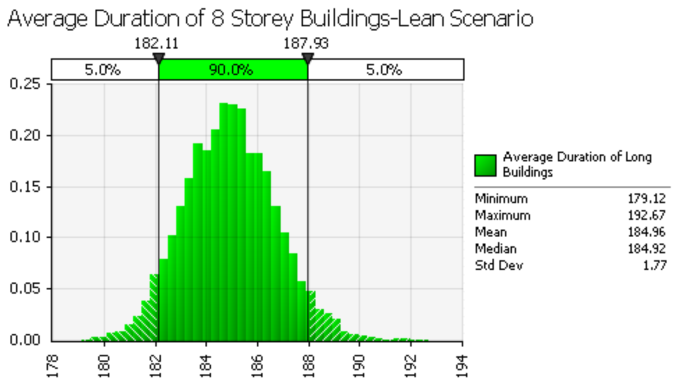

Figure 5.21: Probabilistic Average Duration of 8-Storey Buildings for Lean Scenario According to Average of All Participants

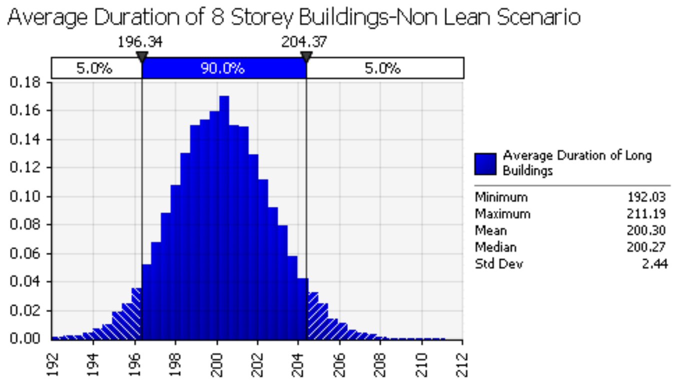

Figure 5.22: Probabilistic Average Duration of 8-Storey Buildings for Non-Lean Scenario According to Average of All Participants

Table 5.23: Summary of the Simulation Results for Average Duration of 8-Storey Buildings According to Average of All Participants

Performance Metric	Lean Scenario	Non Lean Scenario
Minimum Project Duration	179.12	192.03
Maximum Project Duration	192.67	211.19
Mean Project Duration	184.96	200.30
Median Project Duration	184.92	200.27
Standard Deviation	1.77	2.44

Finally, average duration of 5-storey buildings is simulated as shown in Figures 5.23 and 5.24. Simulation results of these buildings are tabulated in Table 5.24.

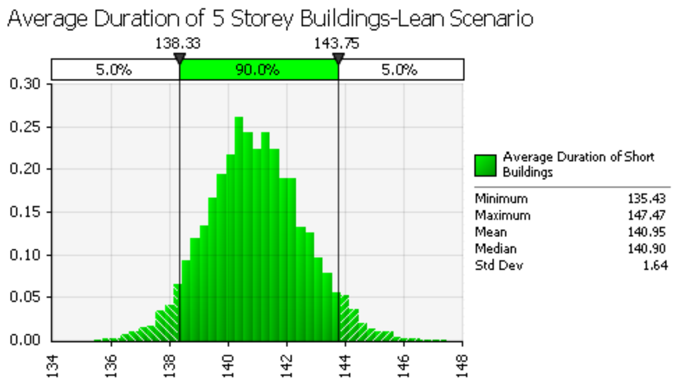

Figure 5.23: Probabilistic Average Duration of 5-Storey Buildings for Lean Scenario According to Average of All Participants

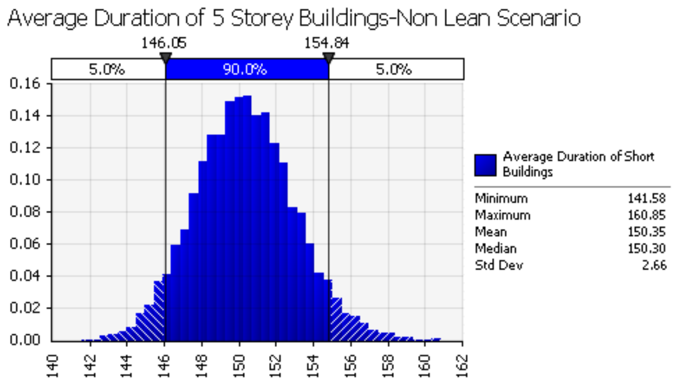

Figure 5.24: Probabilistic Average Duration of 5-Storey Buildings for Non-Lean Scenario According to Average of All Participants

Table 5.24: Summary of the Simulation Results for Average Duration of 5-Storey Buildings According to Average of All Participants

Performance Metric	Lean Scenario	Non Lean Scenario
Minimum Project Duration	135.43	141.58
Maximum Project Duration	147.47	160.85
Mean Project Duration	140.95	150.35
Median Project Duration	140.90	150.30
Standard Deviation	1.64	2.66

In conclusion, this section includes all results derived from the questionnaire and from the Monte Carlo simulation. These results are discussed in the following section.

5.3 General Findings

Section 5.2 presents all results derived from the questionnaire itself and from the Monte Carlo simulation, in a comprehensive manner. These results demonstrate the benefits of using the lean construction principles in terms of reducing the project duration and variability. In this regard, this section includes the interpretation of the questionnaire results and detailed analysis of the statistical results. To sum up, effects of lean construction principles are quantitatively identified within this section.

The results discussed within the scope of this section are separately handled. First of all, relative importance of the lean construction principles, which is evaluated by the participants in Part II of the questionnaire, is discussed. Then, effects of lean construction principles on basic activity types are discussed according to coefficients filled by participants in Part III of the questionnaire. Later impacts of lean construction on total project duration and average durations of 8-storey and 5-storey buildings are emphasized. Finally, influence of lean construction principles on variability of project duration is discussed in terms of standard deviation. Following subsections clarify these subjects in detail.

5.3.1 Relative importance of the lean construction principles

Frequencies and impacts of 14 lean construction principles, which are introduced in the Part II of the questionnaire, are determined by the participants, and relative importance of the principles are calculated by multiplying frequencies and impacts. Results are presented throughout tables from 5.1 to 5.4. According to these results, the most significant and the least significant lean construction principles are identified. Table 5.25 presents lean construction principles in terms of their relative importance according to each participant as well as to average results of the participants.

Table 5.25: Ranking of Lean Construction Principles in terms of Relative Importance

Evaluator	Most Significant Lean Construction Principles	Least Significant Lean Construction Principles
Participant I	1. Regular Meetings 2. Optimum Site Conditions 2. Long-term Supplier Relationships 2. Consensus-based Decision-making 2. Cooperation between Different Departments	1. Using Multi-skilled Workforce 2. Minimum Material Storage 3. Risk Management
Participant II	1. Long-term Employee Relationships 1. Long-term Supplier Relationships 1. Cooperation between Different Departments 1. Regular Meetings	1. Improving Process Transparency 2. 4-D Scheduling and Simulation 3. Clean Construction Principles
Participant III	1. Cooperation between Different Departments 2. Training Activities 2. Long-term Supplier Relationships 2. Consensus-based Decision-making	1. Using Multi-skilled Workforce 1. Using Time Buffers
Average of all Participants	1. Cooperation between Different Departments 2. Regular Meetings 3. Long-term Supplier Relationships	1. Using Multi-skilled Workforce 2. Improving Process Transparency 3. Using Time Buffers 3. 4-D Scheduling and Simulation

According to Participant I, regular meetings is the most important lean construction principle. During the face to face meetings, he emphasizes the importance of communication in construction works. In this respect, regular meetings are followed by long-term supplier relationships, consensus based decision-making, and cooperation between different departments, which support his valuation of communication. Optimum site conditions are also thought as an important lean construction principle by Participant I. On the other hand, using multi-skilled workforce, minimum material storage, and risk management are determined as least significant principles. In meetings, he indicates that contractors are not ready to implement some principles, such as using multi-skilled workforce and minimum material storage. Therefore, he assigned lower scores for both frequencies and impacts of these principles. In addition, despite believing the benefits of risk management, he thinks that contractors do not prefer to implement them in practice. As a result, due to lower frequency of risk management, it is determined as one of the least significant principles.

According to Participant II, long-term employee relationships, long-term supplier relationships, cooperation between different departments, and regular meetings shares the title of the most important lean construction principle. His responses indicates the importance of the communication as well as long term relationships. Improving process transparency, 4-D scheduling and simulation, and clean construction principles are regarded as the least significant principles, respectively. During the meetings, he explains that improving the involvement of workforce does not always improve project performance, especially in Turkey. This is the reason why improving process transparency is chosen as the least significant principle. Besides, according to him, 4-D scheduling and simulation, and clean construction principles are not very suitable and necessary to be implemented in small-sized residential building projects. For this reason, they are also commented as insignificant principles.

According to Participant III, cooperation between different departments is the most important lean construction principle, which is followed by training activities, long-term supplier relationships, and consensus-based decision-making. He also dignifies the importance of the communication. In addition, training the workforce is also considered as important by Participant III. Using multi-skilled workforce and using time buffers, on the other hand, are not given that much importance. Similar to Participant I, multi-skilled workforce is regarded as hard to be implemented. Moreover, during the face to face meetings, he indicates that some principles have negative effects on project duration although they contributes to overall performance. Results show that using time buffers is considered as such a principle. Therefore, it takes a lower score as compared to other principles.

When average scores of all participants are considered, cooperation between different departments is decided as the most significant lean construction principle. Regular meetings, and long-term supplier relationships are also considered as important principles. All of these principles highlight the importance of the communication. It seems that lack of communication is predominant factor in poor performance of the construction industry. This proposal improves the value of lean construction for the construction industry. Its holistic and communication-based approach has a great potential to lift the industry. Nevertheless, some lean construction principles seems not convenient yet to be implemented in practice. Using multi-skilled workforce is the primary of them. Improving process transparency also considered as impractical. Low importance score of 4-D scheduling and simulation is probably stems from its incompatibility with small-sized residential building projects, because two of the participants indicate that during the meetings. As explained by Participant III, using time buffers directly extends the duration of the project so it is determined as one of the least significant principles according to average of all participants. As a final note, when average frequencies and impacts are considered for all participants, it become clear that the frequency of implementing lean construction principles in practice is not as high as the impacts of them on project duration. In the light of these information, three important inferences can be reached as listed below;

- Lean construction principles are quite appropriate to remove communication barriers within the industry.
- Some lean construction principles are not validated by the construction practitioners yet. Applications of them should be further investigated.
- More frequent utilization of lean construction principles will result in a much better project performance in terms of project duration.

5.3.2 Effects of lean construction principles on basic activity types

Combined effects of lean construction principles on nine basic activity types can be traced by coefficients determined by the participants, in Part III of the questionnaire. The mean values of these coefficients are calculated according to a triangular distribution and results are presented in Table 5.26. As shown in the table, for all activity types and for all participants, mean values of the triangular distributions are reduced in lean scenario as compared to non-lean scenario.

Table 5.26: Mean Values of the Coefficients Determined by the Participants

Activities	Mean of the Coefficients For Non-Lean Scenario According to;				Mean of the Coefficients For Lean Scenario According to;			
	P I	P II	P III	P avg.	P I	P II	P III	P avg.
Excavation	1.100	1.033	1.033	1.055	0.983	0.983	0.933	0.967
Reinforcement	1.017	1.150	1.050	1.072	0.958	1.050	0.950	0.986
Formwork	1.033	1.150	1.017	1.061	0.983	1.050	0.983	1.006
Concrete	1.017	1.150	1.000	1.056	0.983	1.050	0.967	1.000
Backfill	1.050	1.033	1.050	1.045	0.983	0.950	0.967	0.967
Walls	1.167	1.150	1.083	1.133	0.950	1.050	0.950	0.983
Electrical Installation	1.117	1.050	1.050	1.072	0.967	0.950	0.967	0.961
Mechanical Installation	1.150	1.017	1.050	1.072	0.992	0.967	0.967	0.975
Plastering	1.133	1.033	1.083	1.083	1.000	0.933	0.983	0.972

Starting from this point, it is investigated that duration of which activity type can be reduced more through lean construction principles. In this regard, by using the values of Table 5.26, reduction percentages of each activity types are calculated as shown in Table 5.27.

Table 5.27: Reduction Percentages of the Activity Durations when Lean Construction Principles are Utilized

Activities	Reduction Percentages of the Activity Durations According to;			
	P I	P II	P III	P avg.
Excavation	10.61 %	4.84 %	9.68 %	8.40 %
Reinforcement	5.74 %	8.70 %	9.52 %	8.02 %
Formwork	4.84 %	8.70 %	3.28 %	5.22 %
Concrete	3.28 %	8.70 %	3.33 %	5.30 %
Backfill	6.35 %	8.06 %	7.94 %	7.47 %
Walls	**18.57 %**	8.70 %	**12.31 %**	**13.24 %**
Electrical Installation	13.43 %	9.52 %	7.94 %	10.38 %
Mechanical Installation	13.77 %	4.92 %	7.94 %	9.08 %
Plastering	11.76 %	**9.68 %**	9.23 %	10.25 %

Table 5.27 shows, Participant I and Participant III think that lean construction principles affect wall activities mostly. According to Participant II, on the other hand, plastering is influenced most from the lean construction principles. When average answers of the all participants are used in order to calculate mean of triangular distributions, once again walls are determined as most lean-sensitive activity type. The

reason behind this could be explained by that duration of the wall construction and plastering activities are considerably depends on the performance of workers. Since lean construction, as a principle, aims to improve productivity of the labor force, these type of activities are directly affected from the lean construction principles. In conclusion, the results derived from this section is summarized as follows:

- Lean construction principles have positive influences on all activity types in terms of reducing their durations.
- Performance of the wall construction and plastering activities are significantly improved when lean construction principles are utilized.

5.3.3 Effects of lean construction on project duration

Effects of the lean construction principles on project duration is identified from the simulation results. For this purpose, initially, total project durations are summarized in Table 5.28. The table includes simulation results for total project duration, average duration of 8-storey buildings, and average duration of 5-storey buildings. Simulation results are presented for lean and non-lean scenario from the point of views of all participants. Results of the simulation according to average coefficients of all participants are also given in the last column. Simulation results composed of minimum, maximum, mean, and median values. The reason why duration values are not integer is that @Risk calculates simulation with non-integer numbers. For this reason, numbers are presented as taken from the simulation.

Table 5.28: Project Durations According to Different Scenarios of All Participants

Performance Metric	Scenario	Duration Type	Participant I	Participant II	Participant III	Average of all Participants
Total Project Duration	Non-lean	Minimum	208.37	210.24	205.10	207.06
		Maximum	238.89	230.90	230.80	232.84
		Mean	221.76	219.14	215.86	218.31
		Median	221.60	219.10	215.70	218.31
	Lean	Minimum	195.16	196.38	192.49	193.52
		Maximum	216.05	213.26	212.11	212.62
		Mean	203.78	204.28	201.55	202.46
		Median	203.69	204.16	201.45	202.34
Average Duration of 8-Storey Buildings	Non-lean	Minimum	192.94	194.58	189.25	192.03
		Maximum	215.48	212.61	208.41	211.19
		Mean	203.30	201.19	197.71	200.30
		Median	203.24	201.13	197.66	200.27
	Lean	Minimum	179.84	181.06	178.04	179.12
		Maximum	193.10	194.01	191.62	192.67
		Mean	186.26	186.68	184.14	184.96
		Median	186.22	186.63	184.11	184.92
Average Duration of 5-Storey Buildings	Non-lean	Minimum	141.87	145.13	137.77	141.58
		Maximum	164.41	162.93	155.66	160.85
		Mean	151.91	153.67	145.90	150.35
		Median	151.85	153.66	145.85	150.30
	Lean	Minimum	132.47	139.88	133.34	135.43
		Maximum	145.07	155.22	143.10	147.47
		Mean	138.39	146.72	137.86	140.95
		Median	138.35	146.70	137.84	140.90

As shown in Table 5.28, all durations are decreased in lean scenario when compared to non-lean scenario. In this respect, Table 5.29 presents amount of reduction in durations when lean principles are implemented, and Table 5.30 shows reduction percentages of durations in lean scenario.

Table 5.29: Amount of Reduction in Durations when Lean Construction Principles are Utilized

Performance Metric	Duration Type	Participant I	Participant II	Participant III	Average of all Participants
Amount of Total Project Duration Reduction	Minimum	13.21	13.86	12.61	13.54
	Maximum	22.84	17.64	18.69	20.22
	Mean	17.98	14.86	14.31	15.85
	Median	**17.91**	**14.94**	**14.25**	**15.97**
Amount of Average Duration Reduction for 8-Storey Buildings	Minimum	13.1	13.52	11.21	12.91
	Maximum	22.38	18.6	16.79	18.52
	Mean	17.04	14.51	13.57	15.34
	Median	**17.02**	**14.5**	**13.55**	**15.35**
Amount of Average Duration Reduction for 5-Storey Buildings	Minimum	9.4	5.25	4.43	6.15
	Maximum	19.34	7.71	12.56	13.38
	Mean	13.52	6.95	8.04	9.4
	Median	**13.5**	**6.96**	**8.01**	**9.4**

Table 5.30: Reduction Percentages of Durations when Lean Construction Principles are Utilized

Performance Metric	Duration Type	Participant I	Participant II	Participant III	Average of all Participants
Reduction Percentage of Total Project Duration	Minimum	6.34 %	6.59 %	6.15 %	6.54 %
	Maximum	9.56 %	7.64 %	8.10 %	8.68 %
	Mean	8.11 %	6.78 %	6.63 %	7.26 %
	Median	**8.08 %**	**6.82 %**	**6.61 %**	**7.32 %**
Reduction Percentage of Average Duration for 8-Storey Buildings	Minimum	6.79 %	6.95 %	5.92 %	6.72 %
	Maximum	10.39 %	8.75 %	8.06 %	8.77 %
	Mean	8.38 %	7.21 %	6.86 %	7.66 %
	Median	**8.37 %**	**7.21 %**	**6.86 %**	**7.66 %**
Reduction Percentage of Average Duration for 5-Storey Buildings	Minimum	6.63 %	3.62 %	3.22 %	4.34 %
	Maximum	11.76 %	4.73 %	8.07 %	8.32 %
	Mean	8.90 %	4.52 %	5.51 %	6.25 %
	Median	**8.89 %**	**4.53 %**	**5.49 %**	**6.25 %**

Results show that, when average rounded up durations of all participants are considered with median values, as suggested by Barraza (2011) to have 50 % risk level for all activities, total project duration is decreased 16 days by using lean construction principles. Besides, average duration of 8-storey buildings and 5-storey buildings are reduced 16 days and 10 days, respectively. In terms of percentages, total project duration is lowered 7.32 percent while average duration of 8-storey buildings and 5-storey buildings are declining 7.66 percent and 6.25 percent. Consequently, the obvious result that becomes apparent in this section is emphasized as follows:

- Lean construction principles achieves a considerable amount of decrease in durations of the small-sized residential building projects.

5.3.4 Effects of lean construction on variability of project duration

Similar to previous section, effects of the lean construction principles on variability of project duration is measured from the simulation results. Accordingly, standard deviation values for total project duration, average duration of 8-storey buildings, and average duration of 5-storey buildings are presented in Table 5.31 for lean and non-lean scenarios of all participants. Besides, reduction percentages of standard deviation in lean scenario are presented in the same table.

According to results, when average of all participants is considered, standard deviation of the total project is decreased 20.18 percent. Similarly, standard deviation for average duration of 8-storey buildings and 5-storey buildings are reduced 27.46 percent and 38.35 percent, respectively. In conclusion, this section proves following argument;

- Lean construction reduces variability of duration in small residential building projects and allows for more levelled production.

Table 5.31: Standard Deviations and their Reduction Percentages According to Different Scenarios of All Participants

Performance Metric	**Participant I**	**Participant II**	**Participant III**	**Average of all Participants**
Standard Deviation for Total Project Duration in Non-Lean Scenario	4.11	2.86	3.75	3.37
Standard Deviation for Total Project Duration in Lean Scenario	2.76	2.45	2.81	2.69
Reduction Percentage of Standard Deviation for Total Project Duration	**32.85 %**	**14.34 %**	**25.07 %**	**20.18 %**
Standard Deviation for Average Duration of 8-Storey Buildings in Non-Lean Scenario	2.95	2.24	2.68	2.44
Standard Deviation for Average Duration of 8-Storey Buildings in Non-Lean Scenario	1.84	1.76	1.87	1.77
Reduction Percentage for Standard Deviation for Average Duration of 8-Storey Buildings	**37.63 %**	**21.43 %**	**30.22 %**	**27.46 %**
Standard Deviation for Average Duration of 5-Storey Buildings in Non-Lean Scenario	3.05	2.54	2.43	2.66
Standard Deviation for Average Duration of 5-Storey Buildings in Non-Lean Scenario	1.66	1.92	1.37	1.64
Reduction Percentage for Standard Deviation for Average Duration of 5-Storey Buildings	**45.57 %**	**24.41 %**	**43.62 %**	**38.35 %**

In conclusion, the results, which are presented and discussed throughout this chapter, reveal many positive aspects of lean construction principles. Within the scope of this thesis, these advantages are highlighted with regard to reduction of project duration and its variability. Next chapter concludes the research by emphasizing the important points, discussing the limitations, and making suggestions for future studies.

CHAPTER 6

CONCLUSION

When current problems of the construction industry are considered, lean construction emerges as a promising subject due to its potential of revolutionizing the industry. It is a very well-known fact that efficiency and profitability rates of the construction projects are consistently falling despite their great importance for national economies and development. Lean construction aims to prevent this inefficiency by its principles of eliminating the waste and increasing value to customer. There are many theories and movements that contribute to emergence of the lean construction concept. Lean production is one the fundamental concepts that significantly affects the principles of lean construction. It has been shaped by the automotive industry and spread to manufacturing applications. However, adaptation of lean production to construction industry is an onerous endeavor. Unique characteristics of the construction works, such as on-site production, on-of-a kind projects, and complexity require an interpretation of lean production, which is intrinsic to construction projects. Starting from this point, lean construction practitioners have developed a theory that unites together the transformation view of conventional construction management techniques with flow and value generation concepts of the lean production. TFV theory of lean construction paves the way for developing many lean techniques applicable to construction projects. LPDS and LPS are two of the most important application techniques developed by the researchers. Although case studies proves that application of these techniques improves the project performance in a considerable extent, using them in practice is hesitated due to their theory-based and abstruse approach. For this reason, many practical application techniques of lean construction is developed, which serve both as complementary principles to LPDS and LPS and as individual principles that contribute to project performance in the short term. Nevertheless, there is still a necessity for identifying the benefits of the practical application techniques and revealing quantitative results in order to encourage contractors to implement lean construction principles.

For this purpose, the main objective of this thesis is to propound a methodology that can be used to identify effects of lean construction principles on project duration and variability of project duration. In the content of the research, a stochastic model is generated and inputs of it are determined by means of a questionnaire, which is responded by three participants. Model serves for comparing the durations of a case study project for lean and non-lean scenarios. Following section is a summary of major findings. Subsequent sections explain limitations of the study, put forward some recommendations, and discuss possible future studies.

6.1 Major Findings

Outcomes of the study demonstrate that lean construction principles both enhance project delivery times and reduces work flow variability. When possible probabilistic results of the all participants are considered, including the most optimistic and the most pessimistic scenarios, the lean construction principles make 6.15 % to 9.56 % reduction in total project duration. Similarly, they decrease to standard deviation of the total project duration in the range of 14.34 % to 32.85 %. The major inferences obtained from this research can be summarized as follows:

- Lean construction principles have potential to ameliorate communication problems within the industry.
- There is a need for further researches to validate benefits of some controversial lean construction principles, such as minimum material storage.
- Lean construction principles should be utilized more frequently to exploit their positive impacts on project duration.

- Durations of all activities related to residential building projects are positively influenced from lean construction principles.
- Activities such as wall construction and plastering shows greater lean-sensitivity.
- Lean construction principles leads a considerably decrease durations of the small-sized residential building projects.
- Lean construction principles reduce variability of project duration in small residential buildings.

6.2 Limitations of the Study

Although this research propounds tangible benefits of lean construction principles in terms of project duration and its variability, there are some limitations associated with it. This section explains these limitations throughout the following paragraphs.

First limitation of the study stems from Monte Carlo simulation itself. Monte Carlo simulation, which used as basis of the methodology, heavily depends on subjectiveness. Poor data or misjudgment of the participants may result in inaccurate estimations. Moreover, probability distribution curves of the activity durations may not fully represents real life situations.

Secondly, as an important limitation of the study, the findings reflect only the subjective judgment of three experts. Current results of the study are obtained from the point of views of a consultant, a planning engineer, and an academician. Although they are reliable experts the inconsistency between their estimates is rather low, their estimations may not be generalized.

Next limitation is that participants answer the questionnaire according to practices in Turkey, which they are familiar with. Therefore, their evaluations may not reflect the effects of lean construction principles in global scale. Results obtained in this study could be different when participants from another countries respond the questions.

Fourth constraint that exist in this study is that sophisticated lean construction principles, such as LPDS and LPS, are not included to the study because their impacts cannot be measured through stochastic simulation. Only the effects of lean construction principles that can be practically employed are estimated.

Another limitation is that principles evaluated in the questionnaire are identified according to their applicability in the small-sized residential building projects. Therefore, impacts of the lean construction principles can be measured only for this type of projects. Effects of the lean construction in more sophisticated projects is not considered within the scope this study.

Finally, the only performance measurement criteria used in the study is project duration. Lean construction principles are evaluated in terms of reducing the project duration and its variation. However, there are many other metrics for performance measurement, such as budget, customer satisfaction, health and safety, quality, and sustainability. Lean construction principles are not examined in terms of their impact on these concepts.

6.3 Recommendations and Future Work

This thesis analyzes several aspects of lean construction and pioneering concepts. Result of the study indicate that, when successfully implemented in small-sized residential building projects, lean construction principles significantly reduce the total durations of the projects and their variations. Case study findings prove that lean construction possesses a great potential of improving schedule performance. Consequently, research studies oriented towards identifying the tangible effects of lean construction principles should be increased to eliminate disbelief in lean construction.

In this respect, as a possible future study, an “action research” type of study is proposed. Although it will require more time and effort, it is recommended that lean construction principles can be applied in practice in real projects and impacts are quantified. In addition to this, effects of LPDS or LPS may be examined either by real case studies or simulation techniques. There are another simulation techniques other than Monte Carlo simulation, such as discrete-event simulation. System behavior of lean construction cases may be explained via discrete-event simulation. Furthermore, future studies inspired from this study may be conducted by removing aforementioned limitations. Representatives of owners, suppliers, contractors, and workforce may be interviewed by means of the questionnaire in order to measure lean construction effects from the point of views of all construction project participants. The methodology employed in this study may be improved by adding new principles that are applicable to different types of construction works apart from residential building projects and cost performance as well as quality, health and safety, and sustainability can be considered while assessing the impacts of lean principles.

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APPENDIX A

LEAN CONSTRUCTION QUESTIONNAIRE

This questionnaire has been prepared for the purpose of determining the effects of lean construction principles on variability of project duration. Data generated from this questionnaire will be used in a thesis study entitled as “Identifying the Effects of Lean Construction Principles on Variability of Project Duration” at Middle East Technical University (METU) Department of Civil Engineering in supervisory of Prof. Dr. İrem Dikmen Toker.

The questionnaire is composed of three parts. Each part is explained and example answers are provided prior to questions of the related part. Please read carefully all the instructions and respond the questions accordingly.

Your questionnaire responses will be strictly confidential and used only for the academic purposes. If you have any questions and suggestions, you can contact through following e-mail address and phone number; herol@metu.edu.tr and (+90) …

Thank you for your cooperation.

<u>Prepared by</u>

Hüseyin Erol

Research Assistant

METU-Civil Engineering Department

PART I: This part is composed of general questions, which help to identify participant profile. There are six questions in this part. Please cross (X) to the relevant space for the multiple-choice questions.

1. **Name, Surname: ___________________________**
2. **Education:**

   PhD ( )

   MSc ( )

   BSc ( )

   Other: ( ) ___________________
3. **Occupation: _________________________**
4. **Professional experience in residential building projects:**

   < 2 Years ( )

   5-10 Years ( )

   > 10 Years ( )
5. **Size of the company that you are currently working or last worked:**

   Small ( )

   Medium ( )

   Large ( )
6. **Have you ever heard the term "Lean Construction"?**

   Yes ( )

   No ( )

Lean construction is one of the most recent movements in construction project management domain. The core principles of it are inspired from car manufacturing industry. Lean construction systematically aims to minimize all types of waste, such as design errors, overproduction, re-work, waiting periods, etc. and to maximize overall value in the production process by eliminating non-value adding activities. Lean construction differs from conventional project management ideologies in terms of its pull-driven approach. In traditional construction project management practices, activities and resources are pushed from proceedings units to subsequent units based on strict schedules. Lean project management, on the other hand, performs planning and controlling in accordance with pull-driven approach. Activities to be executed are periodically pulled from a master schedule. Constraints, such as design information, resource availability, and pre-requisite work are analyzed for all activities within planned period. An activity cannot start unless all related constraints are removed. Reasons for not completed works and lessons learned are investigated in detail to improve performance of following planning periods. Although lean construction requires intense commitment, communication, and cooperation between project participants, when lean construction principles are successfully implemented, it may result in reduced variability and irregularity, less amount of waste, better utilization of resources, and more satisfied owner and project participants.

PART II: At this part, based on their subjective judgment, participants are required to estimate potential/frequency of implementing the given lean construction principles in a real project and impact of these principles on project duration, in practice. There are 14 different lean construction principles that will be evaluated. Each of them are briefly explained to guide participants towards their implementation in practice. These lean principles are chosen according to their applicability in residential building projects since the data generated from this questionnaire will be used to evaluate duration variability of these type of projects. Scale of evaluation is represented in the following table.

Scale	How frequently the principle can be used in practice	Impact of the principle on project duration when it is used
1	Never	Very Low
2	Rarely	Low
3	Sometimes	Moderate
4	Usually	High
5	Always	Very High

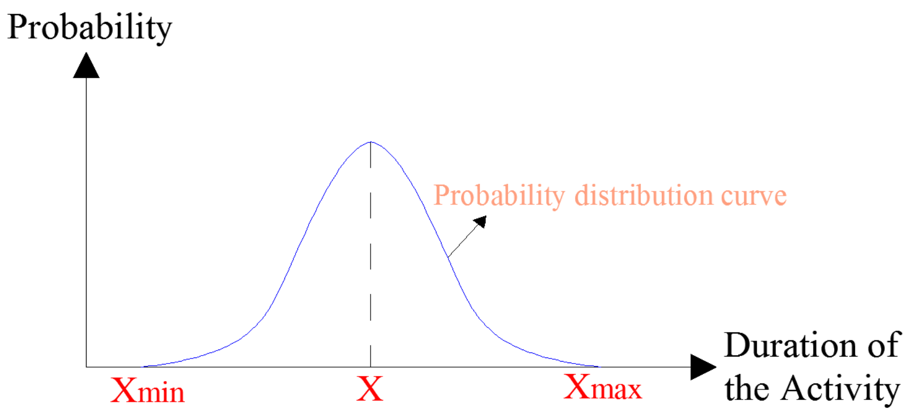
Example:

ID	Lean Construction Principle	Explanation of the Principle	How frequently the principle can be used in practice	Impact of the principle on project duration when it is used
P13	4-D Scheduling and Simulation	Building Information Modelling (BIM) software is used for 4-D scheduling, which allows shared geometry in a single model. Animation of construction workflow is prepared to detect problems in work processes and to identify conflicts between civil, mechanical, and electrical projects before execution of activities.	3	4

ID	Lean Construction Principle	Explanation of the Principle	How frequently the principle can be used in practice	Impact of the principle on project duration when it is used
P1	Training Activities	Regular training activities are carried out in order to improve existing knowledge and capabilities of the employees. Training activities are evaluated by the participants and they are modified based on feedback of the employees.		
P2	Long-term Employee Relationships	Most of the employees of the current project worked in similar projects of the company. They know the work environment and culture of the company. Additionally, there is statistical data about productivity rates of employees.		
P3	Using Multi-skilled Workforce	Workforce utilized in the project have skill of performing more than one operations. They can shift to other works in case of labor shortage in different activities.		
P4	Improving Process Transparency	Visual tools, 3D models, documents, and pictures are utilized in construction site to inform all employees about work progress. They are aware of project targets and milestones.		
P5	Clean Construction Principles	Some people are employed to keep the construction site clean. Plenty of time is spared to prevent dirtiness on the site. Materials, devices, and equipment are placed in fixed positions when their utilization is finished. Their fixed positions are known by everybody.		
P6	Minimum Material Storage	Materials are not stored on the construction site. They are delivered to the site before the related activity starts.		
P7	Optimum Site Conditions	Construction site access is improved and materials are placed to the closest location of their use when they arrive to the construction site.		
P8	Long-term Supplier Relationships	Selected suppliers worked with the company in previous projects. Both parties are aware of working principles of each other. Suppliers are reliable in terms of delivering the material orders on time.		

ID	Lean Construction Principle	Explanation of the Principle	How frequently the principle can be used in practice	Impact of the principle on project duration when it is used
P9	Consensus-based Decision-making	Work planning is decided by participation of all parties related to the project. Representatives of the owner, main contractor, sub-contractors, consultants, inspectors, suppliers, and workforce come together and project plan is determined by considering all opinions.		
P10	Cooperation between Different Departments	Schedules are updated by coordination of mechanical, electrical, and civil departments. They share incomplete information with each other during execution of activities.		
P11	Regular Meetings	Project participants hold regular meetings, which include subjects of constraint analysis, production planning, evaluation of completed works, identification of reasons for non-completed works, and lessons learned. During these meetings downstream players are encouraged to be involved in upstream decisions.		
P12	Using Time Buffers	Time buffers are placed between activities to compensate uncertainties in activity durations. Instead of calculating the activity durations for the shortest time possible, buffers are utilized to prevent delays caused by variations and uncertainties. For this reason, optimum time buffers are placed for each activity.		
P13	4-D Scheduling and Simulation	Building Information Modelling (BIM) software is used for 4-D scheduling, which allows shared geometry in a single model. Animation of construction workflow is prepared to detect problems in work processes and identify conflicts between civil, mechanical, and electrical projects before execution of activities.		
P14	Risk Management	Risk factors associated with the activities are identified and risk reduction strategies are prepared for each activity during the planning and execution phases.		

PART III: At this part, participants are expected to determine durations of the given activities for two scenarios: 1) when none of the lean construction principles described in the Part II are implemented and; 2) when all of the lean construction principles described in the Part II are successfully implemented in the site. Planners usually prefer to use the most likely durations while they are preparing schedules. However, because of unintentional changes, the actual duration of the activity can be different than the most likely duration. Sometimes, decision makers use probabilistic techniques like PERT, Monte Carlo Simulation etc. to take into account of optimistic and pessimistic scenarios as well as the most likely scenario. Assume that the duration of the activity is shown by the below probability distribution function where X_{min}, X, and X_{max} show the optimistic, most likely, and pessimistic scenarios respectively.



Consider residential building projects. Activities given in the following table are carried out. They are simplified from a case study project, which will be used to examine effects of lean construction principles. The project includes construction works of two 8-storey and three 5-storey residential buildings. Finishing works are not included to project. Land purchasing and design activities are completed. Conventional formwork systems are used for concrete operations. Based on this information, please determine your suggested optimistic and pessimistic durations as a function of given most likely duration for both non-lean and lean scenarios by considering, what may go wrong in practice, and possible changes.

Example:

Activities	Durations Based on 3 Scenario (When none of the Lean Construction Principles are Implemented)			Durations Based on 3 Scenario (When all of the Lean Construction Principles are Successfully Implemented)		
	Xmin	X	Xmax	Xmin	X	Xmax
Excavation	As a function of t_1 (E.g.: 0.95 t_1)	t_1	As a function of t_1 (E.g.: 1.50 t_1)	As a function of t_1 (E.g.: 0.90 t_1)	As a function of t_1 (E.g.: 0.95 t_1)	As a function of t_1 (E.g.: 1.30 t_1)
Reinforcement	As a function of t_2 (E.g.: 0.90 t_2)	t_2	As a function of t_2 (E.g.: 1.40 t_2)	As a function of t_2 (E.g.: 0.90 t_2)	As a function of t_2 (E.g.: 1.00 t_2)	As a function of t_2 (E.g.: 1.20 t_2)

ID	Activities	Durations Based on 3 Scenario (When none of the Lean Construction Principles are Implemented)			Durations Based on 3 Scenario (When all of the Lean Construction Principles are Successfully Implemented)		
		Xmin	X	Xmax	Xmin	X	Xmax
A1	Excavation		t_1				
A2	Reinforcement		t_2				
A3	Formwork		t_3				
A4	Concrete		t_4				
A5	Backfill		t_5				
A6	Walls		t_6				
A7	Electrical Installation		t_7				
A8	Mechanical Installation		t_8				
A9	Plastering		t_9				

The questionnaire is completed.