VALUE STREAM MAPPING AND RESOURCE OPTIMIZATION FOR A HIGH-RISE BUILDING USING LINE OF BALANCE

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ABSTRACT

VALUE STREAM MAPPING AND RESOURCE OPTIMIZATION FOR A HIGH-RISE BUILDING USING LINE OF BALANCE

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The challenges in project management are to deliver projects faster, better, and cheaper. One of the major problems in construction that affects the success of the project is the delays. Unprecise project schedule and inefficient resource management can lead to project delays and cost overruns very easy. Another problem in construction is an excessive amount of waste. The Line of Balance (LOB) method is advantageous over other scheduling techniques in repetitive projects because it maintains work continuity and minimizes working team idle time. Value Stream Mapping (VSM) is a lean construction tool, which visualizes and optimizes the processes in the projects by eliminating waste and producing continuous flow. Although both tools LOB and VSM are proved to be powerful tools, limited research was focused on combining the features of the tools. The objective of this study is to create a model to optimize the project duration scheduled with the LOB technique with the help of VSM. The model is tested in a high-rise building project built-in Ankara. VSM future state was used to optimize the occurred delay in the project and to eliminate the non-value-adding activities in the concrete operations. The future state of the schedule was proposed by utilizing the data provided by the experts and showed faster delivery times. Since LOB is a resource-driven technique, the remaining activities were optimized using resource optimization method. A resource optimization model for resource-leveling and allocation that guarantees the optimal solution was presented. The model used in this study could help construction professionals in reducing waste by implementing lean concepts for a better sustainable future.

Keywords: Value Stream Mapping, Line of Balance, Learning Effect, Resource Optimization, Lean Construction

ÖZ

DENGE ÇİZGİSİ KULLANARAK YÜKSEK KATLI BİR BİNA PROJESİ İÇİN DEĞER AKIŞI HARİTALAMA VE KAYNAK OPTIMIZASYONU

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Proje yönetimindeki zorluklar daha hızlı, daha iyi ve daha ucuz proje teslim etmektir. İnşaatın projenin başarısını etkileyen en büyük sorunlarından biri proje gecikmeleridir. Proje takviminin belirli olmaması ve verimsiz kaynak yönetimi, proje gecikmelerine ve maliyet aşımlarına çok kolay bir şekilde yol açabilir. İnşaat sektöründeki başka sorunlardan biri de, fazla miktarda atık oluşmasıdır. Denge Çizgisi (DÇ) metodu diğer planlama tekniklerine göre avantajlıdır, çünkü iş sürekliliğini korur ve çalışma ekibinin boşta kalma sürelerini en aza indirir. Değer Akışı Haritalaması (DAH), atıkları ortadan kaldırarak ve üretimi sürekli hale getirerek, projelerdeki süreçleri görselleştiren ve optimize eden, bir yalın inşaat uygulamasıdır. Hem DÇ hem de DAH'nin güçlü uygulama yöntemleri olduğu kanıtlanmış olmakla birlikte, kısıtlı sayıdaki araştırmalar iki yöntemin de özelliklerini birleştirmek üzerine odaklanmıştır. Bu çalışmanın amacı, Değer Akışı Haritalaması yardımıyla birlikte Denge Çizgisi metodu ile planlanan proje süresini optimize etmek için bir model oluşturmaktır. Model Ankara'da yerleşik yüksek katlı bir bina projesinde test edilmiştir. Projedeki meydana gelen gecikmeyi optimize etmek ve projedeki katma değeri olmayan betonarme faaliyetleri ortadan kaldırmak için DAH yönteminin gelecekteki durumu kullanılmıştır. Uygulamanın gelecekteki durumu, uzmanlar tarafından sağlanan verilerden yararlanılarak önerilmektedir ve daha hızlı teslimat süreleri göstermiştir. DÇ, kaynak odaklı bir teknik olduğu için, kalan faaliyetler kaynak optimizasyon yöntemi kullanılarak optimize edilmiştir. Kaynak seviyelendirme ve paylaştırma için en uygun çözümü garanti eden bir kaynak optimizasyon modeli sunulmuştur. Bu çalışma, daha iyi bir sürdürülebilir gelecek için yalın kavramlar kulanılarak inşaat profesyonellerinin atıkları azaltmalarına yardımcı olabilir.

Anahtar Kelimeler: Değer Akışı Haritalama, Denge Çizgisi, Öğrenme Etkisi, Kaynak Optimizasyonu, Yalın İnşaat

To My Beloved Family…

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ABBREVIATIONS

CPM	Critical Path Method
LOB	Line of Balance
TCTO	Time Cost Trade-Off
VSM	Value Stream Mapping
PMBOK	Project Management Body of Knowledge
PERT	Program Evaluation and Review Technique
LSM	Linear Scheduling Method
RASP	Repetitive Activity Scheduling Procedure
API	Activity Performance Index
RSM	Repetitive Scheduling Method
HLOB	Heuristic Line of Balance
SHLOB	Search-based Heuristic Line of Balance
GA	Genetic Algorithm
SYRUS	System for Repetitive Unit Scheduling
RUSS	Repetitive Unit Scheduling System
CHRISS	Computerized High-rise Integrated Scheduling System
ALISS	Advanced Linear Scheduling System
TPS	Toyota Production System
JIT	Just-in-Time
VA	Value Adding
NVA	Non-Value-Adding

LIST OF SYMBOLS

SYMBOLS

w	Weekly Working Days
PHU	Person-Hour per Unit
PR_{target}	Target Production Rate
PR_{actual}	Actual Production Rate
$TS_{optimum}$	Optimum Team Size per Unit
$TS_{theoretical}$	Theoretical Team Size per Unit
TS_{actual}	Actual Team Size per Unit
$D_{activity}$	Duration of Activity per Unit
PHU_n	Cumulative Person-hour at the nth Unit
PHU_1	Person-hour at the First Unit
St_{n+1}	Successors Start Time
$St_{corrected}$	Corrected Start Time
Bt	Buffer Time
Bt_{min}	Minimum Buffer Time
TS_{number}	The Available Team Number per Activity
CT	Cycle Time
LT	Lead Time
W	Waste Percentage
UPH	Unit-Person Hour

CHAPTER 1

INTRODUCTION

Project owners always look for solutions for delivering projects faster, better in quality, and cheaper. With other words, methods that can reduce waste and at the same time, increase the added-value portion in construction activities and processes.

Some of the responsibilities of the project managers are to deliver the project on the predefined time, quality, and within budget. These factors make project planning and scheduling one of the essential disciplines in the construction industry. According to the PMBOK, a project is a temporary (with a defined start and end) effort taken to create a unique project or service. Every project is unique because every project is designed and constructed distinctively (*PMBOK Guide,* 2004).

Many projects fail to meet the scheduled delivery dates. Factors such as lousy scheduling, resource limitations, weather conditions, and wrong managerial actions can affect the project delivery date. Delays are any imposed or obligated expand or increase in duration between the finish of the activity and the start of the following operation (Riad, Arditi, and Mohammadi, 1991). Any delay in a project can cause disagreement and conflicts among project stakeholders. One of the most important facts is that delays also may cause penalties which affects the project cost and lead to cost overruns.

It is well known that the success of the project depends on the planning schedule (Liu et al. 1995). The most popular scheduling technique in the construction industry is the Critical Path Method (CPM) (Nageeb and Johnson, 2007). In the 1990s, CPM was used among 93% of the firms in ENR Top 400 Contractors (Tavokoli and Riachi, 1990) and, CPM provided benefits like improved scheduling, better planning to start the work, and project control. On the other side, CPM has been criticized because of the disadvantages like a high amount of time to create a schedule, ineffective communication (between contractors and sub-contractors, and managers and workers), and constant updating requirement. One of the significant criticized issues is the network size of the charts. In repetitive projects, the network method becomes complicated and difficult to handle. The reason for this is, that the prepared schedule for one unit has to be repeated several times (n-times) through the project, and the activities of the units have to be connected according to their preceding relationship. Bar charts, which are simple to produce and understand, however don't show activity dependencies. Considering all facts, CPM proves that it is an excellent tool for scheduling and controlling the process; however, it is not suited for projects with repetitive nature.

Projects like a high-rise building, housing projects, pipeline, tunnels, and highway projects are called a project with repetitive nature, where several activities are repeated throughout all the parts/sections/units of the projects. A unit can be a representation of a floor in a high-rise building, a house in a housing project, meters or kilometers in highway projects and station in pipeline projects. El-Rayes and Moselhi (1998) categorized activities in repetitive projects as typical and atypical. In the first group, the activities in all units in the projects are assumed to have the same duration. The atypical activity type is the category of activities that do not have the same duration. This can be explained as some activities in some units may have variation in the work quantity or/and crew productivity.

Several authors that worked on scheduling repetitive projects proved that Line of Balance is a better-suited scheduling tool. The Line of Balance was first developed for manufacturing and production control in the early 1950s by the U.S. Navy. The objective of LOB was to evaluate the rate of flow of the products in a product line (Al Sarraj, 1990; Rowings and Rahbar, 1992).

In construction, the Line of Balance is a linear scheduling method used for scheduling projects with repetitive nature. There are different models of Linear scheduling methods; however, the basics in methodology are similar. The linear scheduling methodologies work by plotting the unit progress versus time, which means that any amount of work can be controlled at any time and location.

In the literature, different names are used for linear scheduling like Line of Balance (LOB), Vertical Production Method (VPM), Linear Programming (LP), Combined PERT/LOB, and Time Spaced Diagram (Rowings and Rahbar, 1992). The difference between LOB and linear scheduling method may be a question of emphasis, though the main difference is the following: LOB is used to schedule the cumulative person-hour of the activity, and linear scheduling methodology, schedule or record the progress of the activities that are moving continuously through the project duration (Johnston, 1981).

LOB scheduling allows for balancing the operations in the project and providing continuous resources utility, which are primary issues for repetitive projects. In comparison with scheduling methods like CPM, LOB provides a better graphical interface which enables users to interpret the relationships between the activities better and identify other project characteristics like production rate and activity duration easily (Tokdemir, Erol, and Dikmen, 2018). LOB tends to provide better results as activities may have different production rates in repetitive projects (Arditi, Tokdemir, and Suh, 2002b). Other advantages of LOB are marked by (Pai, Verguese, and Rai, 2013): LOB allows managers to see if it is possible to meet the schedule according to the work productivity, prevents hiring and procurement problems, ensures smooth procession of crews with minimal or no conflicts from unit to unit, and decreases idle time for workers and equipment.

The learning effect in repetitive projects is an essential issue since repetitive activities offer opportunities to achieve higher productivity. The practice has shown that labor productivity rates improve when working through repeating activities. With other words, the duration of activities will decrease throughout the units in the project, which is called the learning effect (Arditi, Tokdemir, and Suh, 2001a).

One of the aims of the construction management discipline is to plan, schedule, and control a project at the predefined objectives (defined time, given cost, desired quality, and the available resources). The project objectives are connected; in other words, if changes occur in one of the objectives, the others are affected.

The efficient management of resources and its allocation to different project activities are essential in construction projects. Resource allocations that are not adequate can lead to an increase in idle time, which consequently affects the project schedule and budget. Resources are in the form of money, material, workforce, and machines; which are also known as "4m" (Ammar, 2019). Selecting a suited resource scheduling tool is essential in construction projects. As a resource-driven technique, LOB methodology's objective is to provide a balanced resource usage and synchronization of the work in the project schedule (Ammar, 2013).

Akpan (1997) classified the resource optimization problem into three groups:

- The time-cost trade-off (TCTO),
- Unlimited (Unconstrained) resource optimization, and
- Limited (constrained) resource optimization

All these optimization techniques have different approaches; however, they have the cost feature in common. The process of trading between cost and time is called the time-cost trade-off. The objective of time cost trade-off is to find solutions to minimize the project cost while finishing it on time or solutions for reducing project duration and project cost simultaneously. The limited resource problem occurs when there is a limitation on the resource amount. In this case, the objective is to provide a project schedule where the project duration is extended as little as possible with the minimum amount of resources. This problem is also known as the resource leveling problem (Easa, 1989).

On the other hand, the unlimited resource problem occurs when the projects need to be finished at a predefined deadline, and the resource amount is unlimited. Here, the objective is to finish the project at the desired date by using all available resources. This problem is also called the resource allocation problem.

In general, resource optimization techniques can be categorized into three groups: analytical methods, heuristic methods, and meta-heuristic methods. Analytical methods use optimization techniques where the problem is formulated mathematically. The optimal solution is obtained by using integer, linear, non-linear dynamic programming, etc. The main disadvantage of this method is that the formulation of the problem's objective functions, variables, and constraints are time-consuming. Heuristic models are easy to apply and simple to understand (Hegazy, 1999). The general idea in heuristic methods is to shift the activities according to resource priority rules. Heuristic methods provide local optimal solutions, which may be a right solution but not the optimal in the whole process. Meta-heuristic and Evolutionary methods provide the optimal global solution for the problem (Ammar, 2013; Xiong and Kuang 2008; Liu, Burns, and Feng, 1995).

The literature has shown that the learning effect in LOB technique is accurate and provide high person-hour estimation efficiency. Also, integrating LOB scheduling technique features with Lean tools like Value Stream Mapping can decrease lead time, project duration, and reduce project cost (Gunduz and Naser, 2017).

VSM is a lean tool created by Toyota Motor Company used to depict current state and the create an ideal state (future state) in the process by implementing lean principles. VSM is also called as "Material and Information Flow Mapping" (Rother and Shook, 1999); because it allows creating maps that visualize material and information flow in the processes. As a visualizing tool, VSM helps to visualize work that is non-visible too. Also, it helps to locate waste and find the source of it, which enables eliminating the waste permanently. The primary goal of VSM is to, identify work that does not add value in the process and remove waste. As waste is eliminated the capacity is increased, the value-added portion to the customer is improved, and work can be delivered faster (Martin and Osterling, 2014). VSM is beneficial in creating connections with the customer, which, helps the organization to focus on the client and add more value to him. VSM also simplifies the work process at the macro level. In other words, VSM shows the process from a customer's order through all the process until delivery. VSM can be beneficial in orienting newcomers and help them adapt to the organization.

Despite all the benefits mentioned above, VSM application to construction is minimal. A few research was conducted using VSM in different areas of the construction industry (Arbulu and Tommelein, 2002; Arbulu, Tommelein, Walsh, and Hershauer, 2003; Fontanini and Picchi, n.d.; Gunduz and Naser, 2017; Pasqualini and Zawislak, 2005; Rosenbaum, Mauricio, and Gonzales, 2014; Shen, Tam, Tam, and Drew, 2004; Yu, Al-Hussein, Al-Jibouri, and Telyas, 2013; Yu, Tweed, Al-Hussein, and Nasseri, 2009).

In light of this information, the objective of this study is to create a model to optimize the project duration scheduled with the Line of Balance (LOB) technique with the help of Value Stream Mapping (VSM). The concepts of Line of Balance with the learning effect and the optimization process of the lean tool Value Stream Mapping were introduced. A high-rise building composed of twenty floors, as a case study. The LOB schedule was prepared, and the reinforced concrete activities duration was optimized using VSM tool. Later, the project schedule was optimized using a resource optimization method in LOB schedule. The method can solve both resource allocation and resource leveling problem. The method was based on Ammar (2019) and optimized in the LINGO software. This thesis presents a unique framework of using both methods LOB and VSM simultaneously and a resource allocation model in LOB scheduling. In this study, the implication of lean concepts to a traditional construction firm was shown. The study showed that the optimized future state of VSM provides a future state in LOB schedule which is an Ideal LOB schedule. This study can help construction professionals in reducing waste by implementing lean strategies and create leaner construction facilities for a more sustainable future.

The thesis structure is organized as follows. The literature review for Line of Balance and Value Stream Mapping is presented in CHAPTER 2. Next, in CHAPTER 3, the methodologies for proposed methods are given. The thesis continues with the study case given in CHAPTER 4, followed with CHAPTER 5 where the comments of results are given. The thesis ends with the conclusion part.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

This chapter includes the background of Line of Balance (LOB) technique. A literature review for LOB , and an overview of the current practice of planning techniques in the construction industry were given. After a short introduction for lean philosophy and the types of waste were presented. The chapter continues with a literature review of Value Stream Mapping application in construction industry.

2.2. Line of Balance

2.2.1. Background of Line of Balance

The Line of Balance was developed in the early 1940s by the Goodyear Company, later in 1952 the US Navy started using LOB and refined the tool further until 1958 where it was elaborated to the US Army. The first application of LOB was in housing projects handled by the National Building Agency in the 1960s (Yang and Ioannou, 2004). Firstly, LOB was developed for manufacturing projects until Lumsden (1968) modified the LOB technique and applied it to a house construct scheduling. Kristy (1970) applied LOB version for manufacturing project into a construction production and supply of precast concrete beams project (Al Sarraj, 1990).

In industrial manufacturing, LOB was applied to record the progress of activities against time. The idea of plotting production lines later was adopted to other graphical methods. The typical LOB production lines were plotted on time versus the progress status that contains the cumulative number of the finished equivalent units plot (two-dimensional plot) (Yang and Ioannou, 2004). The primary objective of LOB was to obtain the flow rate of the product in a production line (Al Sarraj, 1990). The main difference between using LOB in manufacturing projects and construction projects is that in manufacturing, the product is transferred from station to station (stationary labor and equipment), while in construction it is the labor and equipment that is moved from unit to unit.

Researchers made several attempts to modify or to create modified versions of Line of balance technique. For example, Roech (1972) created velocity diagram method, Peer and Selinger (1973) developed vertical production method (VPM), Johnston (1981) developed linear scheduling method (LSM), Stradal and Cacha (1982) created the time-space scheduling method (TSSM), and Harris and Ioannou (1998) established the repetitive scheduling method (RSM).

The LOB is a tool used for scheduling and controlling repetitive projects, where the activities that are performed continuously are repeated through the units in the project. LOB provides work and resource continuity in repetitive units in a way that the working crews avoid idle time. The basis of LOB consists of achieving the desired output rate in a way that the resources work without interfering (Harris and McCaffer, 2013).

2.2.2. Current Practice Review

Different planning and scheduling techniques are used in construction. Among them, the most comprehensive and most commonly used methods are the bar chart, network analysis, and PERT; the information about the scheduling techniques is based on Harris and McCaffer (2013) book “Modern Construction Management.”

2.2.2.1. Bar Chart Method

Bar charts are the most widely and most straightforward technique used for planning. The bar chart is created as follows; a list of activities with their start and finish dates are plotted to a timescale. The bars length is from the beginning (the start date) of the activity to its end (the finish date). The duration of the activity can be presented in days, weeks or months. The finished activities are marked with another bar on the lower section of the main bar, which also shows the progress for each activity.

Figure 2.1., presents an example of a project bar chart model. The project is composed of seven activities. The timeline indicates that the construction is at the 7th week. First and fifth activities have finished, and the second activity is in the process in the fourth week.

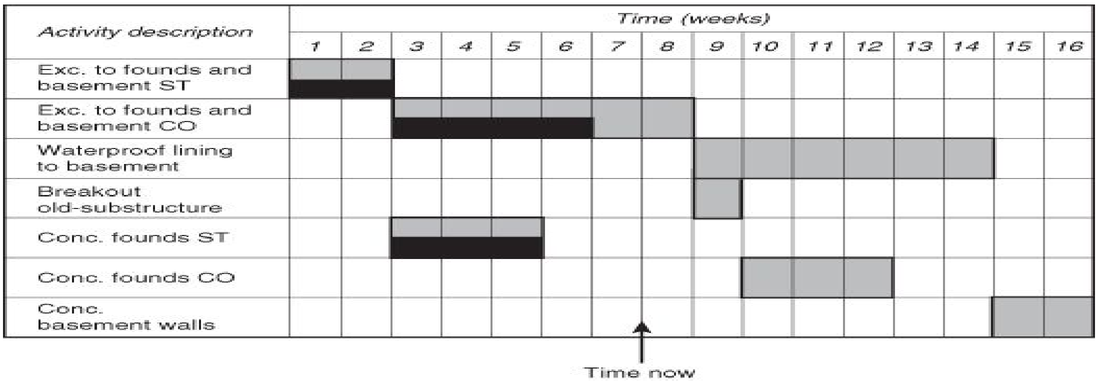


Figure 2.1. Bar Chart Example (Harris and McCaffer 2013)

The main advantages of bar charts are simplicity, easy to understand, and clearness. Bar charts are successful in achieving the schedule because progress can be recorded, and schedules can be followed and extracted by its order. On the other side, bar charts have its shortcoming. The projects are difficult to schedule, and updates and/or changes and manipulation in bar charts are almost impossible.

2.2.2.2. Network Analysis Method

Compared with bar charts method, the network analysis model is more advantageous because it gives the user the ability to manipulate the data. Here, the data is the planning data of the network which is linked according to the activity's relationship (finish-start, finish-finish, start-finish, and start-start). The scheduler can make changes in the duration of the activity, activity resource. Also changes in logical relationships can be made too. Two forms of network analysis are available, the activity on the node which is more popular and activity on the arrow. An example of a network schedule is presented in Figure 2.2.

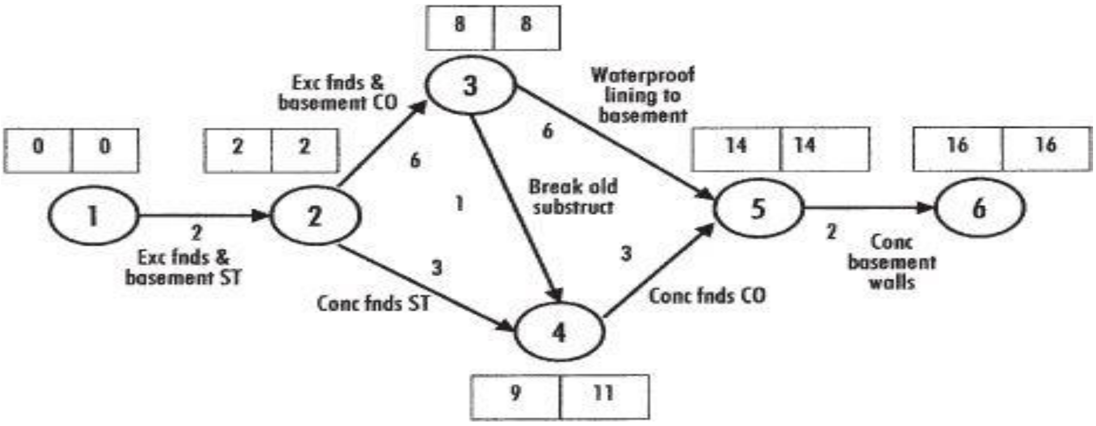


Figure 2.2. Network Chart Example (Harris and McCaffer 2013)

Here the length of the arrow is not essential. Some activities may be connected with dummies. Dummies show the logical relationship between the activities. The duration and resources are assigned to each activity. According to the relationship, the early start and finish dates and late start and finish dates are calculated. The early start dates are calculated in the forward process, and the dates are written in the left box as it can be seen in Figure 2.2. Later, the reverse process is applied, from the finish dates, the late start dates are calculated and written in the right box. The activities that have the same early start and early finish dates are known as critical activities. The difference between the early and late finish dates shows that the activity has a float. Activity float indicates that the activity can finish earlier or later without affecting the total project duration.

Critical Path Method (CPM) is an example of network models. CPM is utilized in projects in which activity parameters are deterministic. CPM is beneficial in illustrating the logical sequence of activities. On the other side, when working on complex projects, CPM network schedule becomes over detailed, which may cause difficulties in understanding the schedule.

2.2.2.3. Program Evaluation and Review Technique (PERT)

The network analysis method assumes that the information of the data (durations, resource) is reasonable and accurate. However, cost overruns and project delays, are very common among construction projects due to uncertainty. PERT method addresses this uncertainty issue by calculating the expected duration with the values of optimistic duration (Od), most likely duration (Md), and pessimistic duration (Pd). The technique is probabilistic and assumes that the probability exceeding md is 1% and od is 99%. After the calculations of the expected duration, standard deviation, and variance with the equations shown below, a network is created according to the network analysis method, and the total project duration is estimated.

Expected duration: $Ed = (Od+4Md+ Pd)/6$

Standard deviation: $sde = (Pd-Od) /6$

Variance: $vde= (sde)^2$

After the project delivery date is estimated, an extra time (contingency) is added for uncertainties that might occur during the execution phase. Later the probability of the estimated project duration to finish in time is calculated. The probability values are checked on the normal distribution curve according to the standard deviation. The variance represents the degree of spread associated with any distribution.

Z= (target duration-expected project duration)/standard variance

The target duration is the duration considering contingencies, where the expected project duration is the sum of the activities expected durations. The variance is the sum of activities variance. A short example is provided in the following to show the computation of the PERT method.

A project of three activities with finish to start relationship is taken to consideration. In Table 2.1. the duration, their relationship and the required calculations are presented. The total project duration is 14 days. Considering contingencies that might arise during the execution of the project; an extra time of 3 days float is assumed. The project duration considering risk association is assumed to be 17 days (target duration). The sum of the variances is estimated to be 0.92. So, Z= (17-14)/ $\sqrt{0.92}$ = 2.88

Table 2.1. Pert Example Calculations

Activity	Preceding activity	Od (day)	Md (day)	Pd (day)	Ed (day)	νde
A	-	2	3	4	3	0.11
B	A	5	7	10	7	0.69
C	B	3	4	5	4	0.11

The probability is read from the Normal Probability Distribution Table in the Appendix A, P(Z=2.88) = 0.998. This implies that the project will be delivered on time within 17 days with the probability of 99.8%.

2.3. Line of Balance Literature Review

Since in the 1980s, the majority of the massive construction firms claimed that, planning and scheduling were essentials for project delivery, and that planning needed improvement (Arditi and Albulak, 1986).

According to the literature, LOB is the most suited tool for scheduling and projects with repetitive nature (Al Sarraj, 1990; Arditi and Albulak, 1986; Harris and Ioannou, 1998; Rowings and Rahbar, 1992). The literature review has shown that in the very beginning of using LOB in construction, the researchers were focused on creating a LOB methodology that was suitable for construction projects. Later the research was focused on issues like resource leveling, deadline satisfaction problem, multi-objective resource optimizations using algorithms, the effect of learning on activity duration and labor productivity and creating digital LOB tools.

Researchers were mainly attempting to apply LOB into construction projects and explaining the method. The authors also discussed why the technique is better suited for projects with repetitive nature giving examples of construction projects. For example, Building Research Station (1971), applied LOB to present progress for housing project, O'Brian (1975), applied it to a high-rise project, Dressler (1980), tunnel excavation project, Johnston (1981) and Arditi and Albulak (1986) applied LOB in a highway project, Stradal and Cacha (1982) railway bridge, Rowings and Rahbar (1992) to a reconstruction highway project (Al Sarraj, 1990; Arditi and Albulak, 1986; Rowings and Rahbar, 1992; Yang and Ioannou, 2004).

Rowings and Rahbar (1992) developed an approach for scheduling linear transportation projects called the repetitive activity scheduling procedure (RASP). RASP contains information at the same level as CPM. The approach allows planning and controlling linking linear projects with critical production rates. The model depicted time and space in a graph containing bar charts too. Hamerling (1995) developed a model to provide a level of analytical capability in the linear scheduling process in conjunction with an AUTOCAD based program called the linear scheduling method (LSM). The author focused on the computerization of linear scheduling and introduced to solutions for identifying the controlling activities path (Hamerlinnk and Rowings, 1998). Hamerlinnk and Rowings (1998) continued the work of Hamerling (1995) and developed a model that can detect and control the activity path in a linear schedule. This method allows determining float for noncontrolling activities, which are the critical activities. The method used a similar technique used in CPM called the upward and downward pass. Hassanein and Moselhi (2005) proposed a method to accelerate the delivery dates of linear projects with a minimum cost, ensuring crew works continuously. The methods identify the controlling activity and select a strategy (working overtime, working on weekends, and double shifts) to reduce the activity duration and makes a project reschedule obtaining the most cost-efficient schedule. The method is implemented to a Windows operating software, providing a user-friendly interface.

Duffy et al. (2010) proposed a linear scheduling method with varying production rates (LSM_{VPR}), which objectives are, to create a framework to apply changes in the production rate and to illustrate the construction phase on a time-space graph. The method allows to create a project schedule with minimum information and analyzes the impact of starting the activities at a different time on the project duration. The feature activity performance index (API) is used to visualize obstacles with different colors and indicates the variance in the predicted production rate from the desired one.

According to the LOB methodology, several units can be done simultaneously by hiring teams besides, where the crews are allocated to perform sequential units without any interruption. Zou et al. (2018) created a mixed integer linear programming model that deals with minimizing the level of workers while validating the prespecified deadline. The method is performing a time-cost trade-off analysis and finds the optimum solution for a large-scale project.

Harris and Ioannou (1998), presented the repetitive scheduling method (RSM) which could be used in multiunit scheduling. The repeated activities in the RSM were showed in production lines in an x-y plot, where each line represented a repeated activity. This method introduced two new concepts, control point for positioning successive production lines and control sequence of activity used for determining the project duration. Maravas and Pantouvakis (2011), continued the work of Harris and Ioannou (1998) and proposed a new methodology for RSM which deals with repeating activities with uncertain or imprecise unit production rates, called fuzzy repetitive scheduling method (F-RSM). F-RSM deals with variation between the units and variation in work performance of crews. The method scheduled the activities in two- or three-dimensional graph and uses the concept of control sequence and control segment to determine the critical activities and enables to estimate the activity float in non-controlling activities.

Arditi et al. (2001a) presented the learning effect approach and the mathematical models for calculating learning in the line of balance schedule. The authors obtained the learning rates by modifying the historical construction activity production rate and incorporating the impacts of different factors. The author presented the required LOB calculation for estimating the worker-hours and activity duration of each unit according to the learning rate.

Zhang et al. (2014) created a model that can replace the log-linear learning curve called the improved learning curve (LC). The model prior considers labor experience and machinery. The model is integrated into the LOB schedule with learning effect to minimize resource usage and meet the deadline satisfaction of a project.

Suhail and Neale (1995) created an integrated CPM/LOB method using the previous research and field knowledge. The technique was created using the advantages of both methods achieving goals in productivity and reduced cost by calculating the required crew size. The technique uses CPM analytical methodology to determine resource leveling and float duration and integrates it into LOB methodology to schedule repetitive projects. Later, Ammar (2013) attempted to improve the model and proposed a nongraphical LOB and CPM integrated method. The method considers resource continuity and logic dependency. The duration of the unit is modeled by considering the overlapping activities and logic relationships. The methods steps are estimating the basic LOB calculations, next the calculation is performed to all repetitive units, the third step is to model the following activities, and the last step is to perform the CPM time analysis.

Dolabi et al. (2014) proposed a methodology for improving the deadline constraint satisfaction issue in CPM/LOB scheduling method. The author presented a heuristic line of balance (HLOB), and an improved version of HLOB the SHLOB (searched-based heuristic line of balance), which are used to determine the required crew size that satisfies the deadline of the repetitive project. The CPM/LOB scheduling is done in six steps (scheduling a standard unit using CPM, estimating the production rate, estimating actual production rate, activity duration, overlapping activity relationship, and final scheduling). Also, a mixed integer nonlinear programming (MINLP) for LOB scheduling is used for validating the results obtained by HLOB and SHLOB.

2.3.1.1. Multi-Objective LOB Research

The literature review showed that a lot of research were focusing on developing algorithms that can optimize from one to multiple objectives. Arditi et al. (2002b) discussed the challenges of the line of balance and developed an algorithm that handles multiple objectives of LOB (resource and milestone constraints, accurate and efficient project acceleration, nonlinear and discrete activities, the effect of learning, reduce the project duration, cost optimization, and visual interface). The authors presented a new term in LOB scheduling the "criticalness," the learning curve, and developed strategies to reduce the project duration by increasing the production rate.

Senouci and Al-Derham (2008) created a multi-objective optimization model using a genetic algorithm for scheduling linear projects. The model is capable of generating an optimal to near-optimal time and cost optimization and visualizes the time cost trade-off. The optimization is done in three modules; the scheduling module for development of linear project schedule, the cost module calculates the cost of the project, and the multi-objective module for obtaining an optimal and near-optimal time cost trade-off. Agrama (2014) developed an algorithm that enables multi-objective optimization for a multi-story project. The model is able to create a LOB schedule and develops easy to use spreadsheets considering the lag time and finish-to-start relationship between the activities. The model utilizes a tool used for determining the repeating activities at repeating floors.

Limited research was obtained considering probabilistic scheduling in projects with repetitive nature. Ioannou and Srisuwanrat (2006) presented the sequence step algorithm (SQS-AL) for scheduling projects with repetitive nature with probabilistic duration while keeping the resources continuously. SQS-AL is designed to determine the delays in activity for achieving the projects minimum duration and keeping the work continuous. Later, Srisuwanrat and Ioannou (2007) continued working on probabilistic scheduling methodology and developed the complete unit algorithm (CU-AL). The algorithm is developed in Stroboscope and "ChaStrobeGA" performs the project profit and idle time trade-off. The performed optimization showed that reducing resources idle time may increase the project duration and indirect cost. To obtain an optimal solution (maximizing the project cost), continuity constraints must be employed.

Tokdemir et al. (2018) proposed a delay risk assessment method for repetitive projects using LOB schedule. The schedule is done considering the targeted delivery rate and risk scenarios are quantified according to the sources of uncertainty and vulnerability of the activities. Monte Carlo simulation is used for quantifying the delay risk of the project using probability distributions of required labor-hours and learning rates. The method may help decision maker in estimating the delay risk and formulate risk strategies.

Different researchers dealt with resource leveling in LOB scheduling. Damci et al. (2013) developed a model using a genetic algorithm that deals with multi-resource leveling for LOB scheduling. The model proposes that the activity with the most extended duration controls the production rate and duration of other activities. The principles of optimum crew size are used for resource leveling. The model provides smooth resource utilization while keeping the optimal productivity rate. Damci et al. (2016) investigated resource leveling in LOB schedules using different (ten) objective functions, and proposed a genetic algorithm-based model that is able to consider those objective functions. The model is based on the principles of "optimum crew size" and "natural rhythm," assuming that the production rate can be increased when multiple crews of optimum crew size perform the activity. All the objective functions obtained the same resource histogram and LOB schedule. Reasons for this are the fact that LOB contains a limited number of non-critical activities that the resource leveling can be applied and the float used in the non-critical activities is done considering the principle of "natural rhythm" that does not allow idle time to occur for any crew.

Zhang et al. (2017) developed an algorithm for resource leveling in LOB using the backward controlling activity. Accordingly, the project duration can be decreased by prolonging backward controlling activity, which gives advantages in resource allocation for the controlling activity and reduction in project delivery. The author created an algorithm for resource leveling that allows reducing the crew size in backward controlling activities. This method is helpful in resource leveling and reducing the project duration without any resource increase.

Gouda et al. (2017) proposed a model for optimizing resource allocation in linear scheduling by using a hybrid approach. The crews in this model are assumed to be skilled workers with multitasking ability. The model showed a decrease in total project duration when hiring this group of workers.

2.3.1.2. Computerized LOB Tools

Psarros (1987) made one of the first attempts to create a digital tool for scheduling linear projects in the construction industry, creating the System for Repetitive Unit Scheduling (SYRUS). The tool is a software driven program that combines linear scheduling and network methodologies. The software works this way; after the data for the repeating activities is defined, the program analyzes the network and produces a LOB diagram for the critical activities.

Arditi et al. (2001b) developed an algorithm that could handle the LOB scheduling methodology. The authors created a computer program called repetitive unit scheduling system (RUSS), where a learning effect is presented, and its objective was to optimize resource allocation and maximize productivity in all activities. The program is menu driven and written in "C" language. After obtaining the inputs of the project (person-hour, crew size, resource, cost information, and activity relationship), the program analyzes the inputs and calculates the productivity rates of each activity. A table containing start and finish times of activities for all or the first and last unit is created. The program generates optimized schedule plotted in a LOB graph for each path separately, cost reports, and timetables.

Later, Arditi et al. (2002b) stated that, the larger a repetitive project gets the more extensive its network becomes, which may cause difficulties in managing the network and may lead to miscommunication between the occupant in the project. The authors discussed essential concepts for scheduling high-rise projects: flexible and multi-level and coded them into a scheduling module called "lobplan." Also, the authors developed a tool called computerized high-rise integrated scheduling system (CHRISS), which incorporates LOB principles and Gant Chart. The program consists of five modules (construction knowledge input, project information input, expert system, the construction planning, and LOB scheduling) which are embedded in the expert system called LOBEX (knowledge source for activity relation).

Tokdemir et al. (2006) created a web-based and standalone software tool named ALISS (Advanced Linear Scheduling System) that handles various problems in LOB scheduling and overcomes the shortcomings of the previous computerized LOB tool SYRUS, RUSS and CHRISS. ALISS is developed using Visual Basic and Visual Basic Script language programs and utilizes MS access and SQL server as a data repository. ALISS calculations for the project parameters (early start and finish, late start and finish dates, float, and criticality) for each unit are done in five modules (input module, constrain module, milestone module, criticality module, and cost module).

ALISS works as follows; first, it creates a LOB schedule, where in each activity, only one crew is assigned. The program checks for the deadline satisfaction and if it is satisfied the program stops, if not it continuous. Next, ALISS looks for activities with more crew availability, according to the duration, it sorts the activities by descending order. The first activity on the list is selected, and an additional crew is assigned to the activity. After this action the program runs the LOB analysis to see if the duration is reduced. If the deadline constraint is satisfied the program updates the schedule and stops. If not, it selects the next activity on the list and repeats this step. This step continues until the deadline constraint satisfaction is met (Tokdemir, 2003).

Yang and Ioannou (2004) created a computerized implementation of the RSM methodology called Repetitive Project Planner (RP2). RP2 is a stand-alone program and consists of two 32-bit Windows application. One has a menu-driven interface providing facilities for editing, saving, retrieving and entering; and the other performs the scheduling calculations and presents the diagrams. The program needs the project information like (activity and relationship type) so that RSM based algorithm calculates the start time of each activity, and the program estimates the minimum project duration. RP2 can generate RSM diagrams and tabular report that contain information about each activity and are useful in performing crew utilization strategies and what-if analysis. Later, Ioannou and Yang (2016), continued the work on repetitive scheduling method, where the authors classified projects as vertical (discrete) and horizontal or linear (continuous). If the progress of the project was measured using counting scales or dominant attribute scales the authors classified projects as uniform and nonuniform projects. The RP2 was updated with the new RSM approach that includes three types of activity and ten activity relationships types. RSM methodology unifies all types of projects with a clearer distinction between units and location. The program is sufficient for developing tabular report and production diagrams for a four-story apartment building containing detail to serve for testing similar project and research.

2.3.2. Resource Leveling

Easa (1989) presented a resource leveling model using integer-linear optimization. The model guarantees optimal leveling for single resource and continuous activities. The proposed model's objective function provides a minimum absolute deviation of resource requirements. Also, the objective function provided a uniform resource level. The required input data for the model are the scheduling results obtained from the CPM. An interface program is used to establish automatically the model’s constraints and objective function. The model was able to solve small to medium-sized projects, and it is applicable to network scheduling techniques.

Harris (1990) developed a heuristic method for resource-leveling that is based on the critical path method (CPM). to measure the level of resources, a resource histogram is used. The objective of the method was to assign the activities in the project to specific days. This can enable the resource histogram to form a rectangle, where its moment is at a minimum. The obtained histogram represented a plan with minimum resource usage during the lifecycle of the project. The proposed approach gave similar results to heuristic approaches. Another advantage of the model is that the concepts are logical and clear and the leveling can be done by computer or manually. The author presented an example of the proposed method.

Chan et al. (1996) presented a resource leveling approach using a genetic algorithm (GA). The GA features to selection and recombination tasks give the ability to learn the domain of project network. Following the objective functions, the GA provides evolved schedules. The model can provide limited resource allocation and resource-leveling. The authors demonstrated the proposed method with standard test problems and compared the proposed method with heuristic methods.

Akpan (1997) presented a heuristic method to provide an optimum resource level which is used at the execution period of the project. Also, the model provided a sensitivity analysis to increase the number of resources to the maximum, so that the project is completed on time. The optimal solutions for these problems are done using the constraining index and resource utilization.

El-Rayes and Moselhi (1998), presented an algorithm for optimizing the resources in projects with repeating activities that satisfy the precedence relationship, crew work continuity, and crew availability constraints. The author applied the model in two stages. In the first stage the precedence relationship and crew availability constraints are satisfied, while in the second stage the crew work continuity is provided. The proposed method is tested in a highway project.

Mattila and Abraham (1998) presented a method to level the resources in projects that are planned and scheduled using linear scheduling method. The authors used the integer linear programming, that uses the concepts of activity float and rate float. According to the authors, the production rate can decrease with respect to the activities float rate. Also, the production rate of any activity depends on the number of resources used. Rate float can be used in activities that have common resources to achieve resource utilization.

Hegazy (1999) proposed some improvement for resource-leveling and allocation heuristics, and a model using a genetic algorithm to search for near-optimal solutions for both aspects of resource optimization. The heuristic methods are improved by introducing random priorities in selecting tasks. After, the GA approach searches for solutions that provide the shortest duration and leveled resource profiles. The proposed approach is advantageous in its application to commercial scheduling and managing software. Also, the GA improved the performance in the software. The GA procedure is automated in a macro program. The multi-objective benefits are shown in a case study and several experiments.

Jaeho and Skibniewski (1999) developed a model for finding the solution for resource-leveling by combining two models: local optimizer and a hybrid model. The combined methods use simulated annealing. The local optimizer is developed with four independent algorithms. The algorithms use different combinations of schemes for shifting activities. The authors stated that the metaheuristic model produced a good and reasonable solution. The simulated annealing hybrid model is designed to help the local optimizer to escape local optimal solutions. The proposed method is tested, and the results indicated that the method can find a solution, that is close to global optimal solutions. Also, the method is viable for projects with complex networks.

Senouci and Eldin (2004) presented a model for resource scheduling using an augmented Lagrangian Genetic Algorithm. compared to the previous models, this model can consider all precedence relationship, minimize project cost, perform time-cost trade-off, and perform multiple crew strategies. Also, the model can perform resource-constrained scheduling and resource leveling simultaneously. The resource-constrained problem is addressed to the quadratic penalty function which transforms it to an unconstrained one. The performance of the method is tested with an illustrative example.

Hariga and El-Sayegh (2011) presented a method for resource-leveling that uses the activity splitting approach. The splitting of activities, in general, adds the cost of the activity, however, the proposed method can split the activity and minimize the cost. The objective of the model is to provide a resource leveling using the trade-off between the extra cost of activity splitting and releasing resources. The model is illustrated with an example problem.

2.4. Lean Philosophy

The new production philosophy is developed in the 1950s in Japan by the Toyota Production System (TPS) called "lean production." It is based on eliminating waste in everything that does not add value to the customer, providing a continuous flow of the products, and perusing perfection.

Many authors illustrated the TPS as a “house.” A healthy and robust house will not collapse if it has a solid foundation, columns, and roof. The roof represents the goals of TPS (quality, delivery time, and cost). The columns are the principles: Just-In-Time and Built-in Quality. At last but not least, the TPS house has to sit on a reliable and stable foundation. In the center of the house are people who continuously improve the TPS (Marchwinski, 2009). A typical TPS house is presented in Figure 2.3.

The basement of the TPS house is about creating production smoothing, standardized work, and kaizen which provide stability. Production smoothing (“Heijunka” the Japanese term) consists of reducing the variations in production, from day to day, by volume levelling and mix of items. “Heijunka” starts with eliminating unevenness, overburden people and unbalanced work. The next step is creating standardized work, which provides more straightforward, cheaper, and faster managing. Also, it ensures production flow and pull flow. Waste is eliminated by using the 5s rule (sort, straighten, shine, standardize, and sustain). Kaizen is the Japanese word for gradual improvement, and its goal is to achieve perfection.

The first column (from left to right) is about Just-in-Time (JIT) philosophy, which indicates that only the necessary parts that are within the necessary time, cost and quantity should be produced and delivered. The objective of JIT is to minimize the inventory and work in progress. The first column also promotes teamwork and problems solving across boundaries. Accordingly, the ideal state for production is created when people, machines, and facilities work together without creating waste. Continuous flow process is the process of achieving a sequential flow by eliminating the wastes in the parts within a process, or between the process (Marchwinski, 2009).

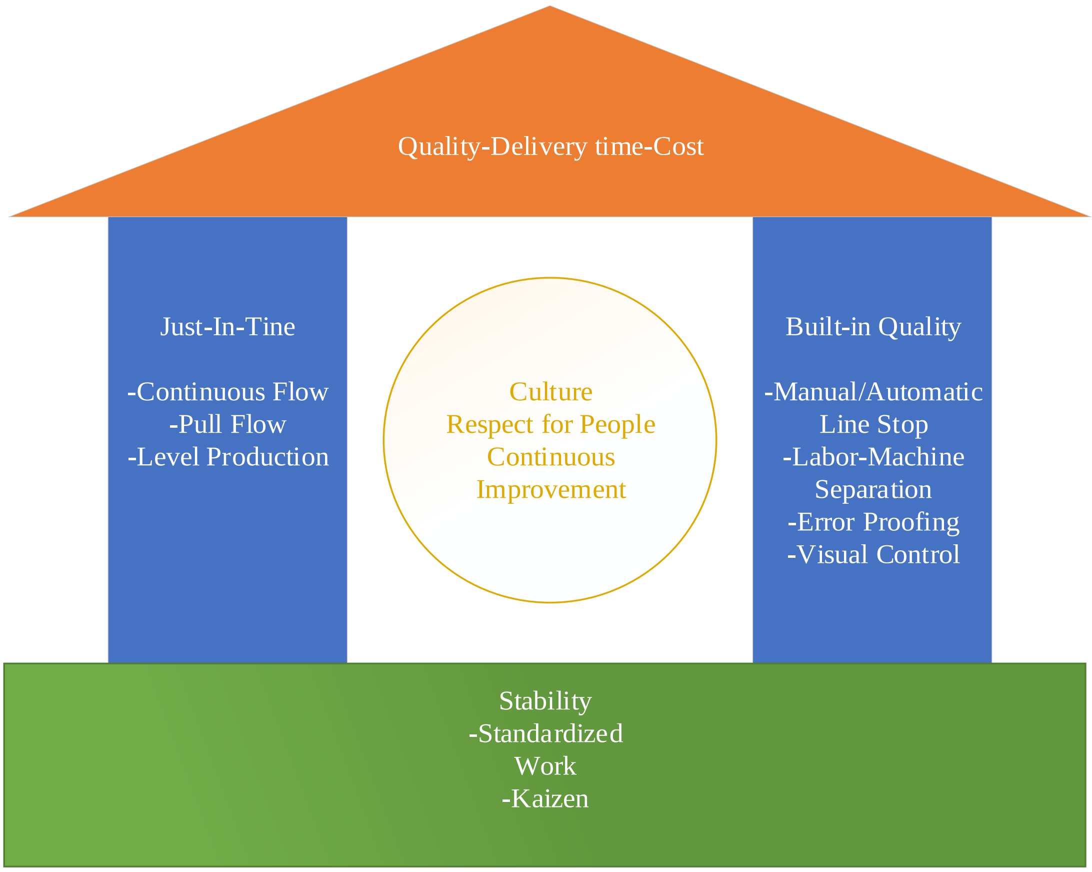


Figure 2.3. House of Toyota Production System - modified from (Marchwinski, 2009)

The column on the right is about creating the separation between people and machines. Creating machines that do not need the assistance and monitoring of people, which relive the people and create free space to continue with the value-added work. Jidoka concept describes the required controlling techniques to make the problem visual and stops the work (machine). Jidoka is about deep bounding to respect the commitment, sharing information, and hearing out each other perspective, so the right conditions or every employee are created to succeed at their job through a mutual trust (Marchwinski, 2009).

The practice of kaizen and standardized work, rest on the determination that every employee should be engaged in their development and should actively participate in the design and running of their workplace. Another method is providing error proofing tools, also known as "Poka-yoke" in Japanese. They are used for controlling and warning.

Monden (1993) sorted the operation into three categories (Hines and Rich, 1997):

- value-adding

- non-value adding

- necessary but non-value adding

According to lean manufacturing, non-value adding activities or "waste" is anything that does not add to the product in the form of time and cost, or it does not add value to the product for the customer (Hines and Rich, 1997; Liker and Lamb, 2000). Here the customer is in the first place, and the customer defines what and how the value-adding activities transform the product. The third type of operations, the necessary but non-value adding activities are wasteful. However, the activity is necessary under the current procedure.

Based on TPS methodology, to achieve the goals, all the non-value adding activities have to be eliminated. Ohno (1988), in his book "Toyota Production System-Beyond Large-Scale Production," defined seven waste types:

- overproduction,
- transportation,
- waiting,

- unnecessary movement,
- over processing,
- defects,
- inventory

Overproduction: this kind of waste occurs when products that are not needed at the moment are produced. Overproduction may lead to productivity and quality loss. Also, it may cause other wastes like excess inventory, cost of transportation and storage, and overstaffing.

- Transportation: is the waste that occurs when the products are unnecessary transported to another place (short or long-distances).

- Waiting: is the waste when the time is ineffectively used. It occurs when the workflow is stopped because of (processing delay, stockout, capacity bottleneck, equipment), which cause time loss and inefficiency.

- Unnecessary movement: are the movements that can be avoided by the workers. Unnecessary movement can cause a decrease in production and quality.

- Over-processing (improper processing): this waste occurs when instead of simple solutions, the product is produced in over complex solutions. Creating too many steps in producing a product may cause this waste. Incorrect processes may be caused by some designs' mistakes.

- Defects: are the type of waste that is not tolerated, which means that the product needs to be produced again. Defects affect the direct cost, and extra time is spent on reproduction.

- Inventory: this type of waste can increase the lead time. A bigger inventory space increases the identification problem. This problem is avoided by only keeping necessary inventories. Also, unnecessary inventories create extra storage costs.

The implementation process of Lean Production consists of three phases. The first one is about strategic change function. The second phase is to introduce the principles of Lean Production. Finally, the last step is to prepare for the physical changes (Pasqualini and Zawislak, 2005). The best tool that can be used is the Value Stream Map. VSM is used for analyzing and designing the flow of information and material, that are required to create a product or service and bring to the customer (Rother and Shook, 1999)

The Seven Value Stream Mapping Tools

The seven VSM tools are created by the TPS to prevent the seven waste types. The tools provide continuous flow and analyze the system providing a “kaizen-system” in the firm. Hines and Rich (1997) presented the seven VSM, and according to the effectiveness in eliminating the seven wastes and the usefulness, the authors graded the VSM tool. The seven tools are listed below:

Process activity mapping

Supply chain response matrix

Production variety funnel

Quality filter mapping

Demand amplification mapping

Decision point analysis

Physical structure

Table 2.2. The Seven Value Stream Mapping Tools (Hines and Rich, 1997)

Tool/ Waste	Overproduction	Waiting	Transport	Inappropriate processing	Inventory	Unnecessary Motion	Defects	Overall
Process activity mapping	L	H	H	H	M	H	L	L
Supply chain response matrix	M	H			H	L		L
Production variety funnel		L		M	M			M
Quality filter mapping	L			L			H	L
Demand amplification mapping	M	M			H			H
Decision point analysis	M	M		L	M			M
Physical structure		L			L			H

Note: the correlation and usefulness are graded with H= high, M= medium, and L= low

2.5. Value Stream Mapping Literature Review

The very first steps on implementing lean methodologies in the construction industry are made by Koskela (1992), where he criticized the traditional way and introduced a new philosophy, lean principles. The literature review showed that the research of VSM was done in many sectors starting from manufacturing, where it originates to the other sectors like healthcare, construction, production development, and service (Shou et al., 2017). Shou et al. made cross-sector research on VSM usage. According to the authors, until the year 2016, the VSM research distribution among the sectors is as following: manufacturing leads with 69%, healthcare 15%, construction 8%, product development 6%, and service 2%. As it can be understood, a limited number of researches using VSM in different areas of construction has been done.

Arbulu and Tommelein (2002) applied VSM in a construction supply chains pipeline project to illustrate the waste causes. The authors showed the flow through the design, procurement, and fabrication phases of pipeline supports and the causes of waste were shown using VSM. The authors collected the data through interviews, where the value-adding and non-value adding activities were evaluated, and batch sizes and lead times for the configurations of the supply chain were also estimated. Their study provided significant improvement in the supply chain performance and reduced total lead time by eliminating the waste in the supply chain processes.

Arbulu et al. (2003) presented a study case for construction pipe support supply chain used in power plants. The authors used VSM to analyze the inefficiencies between the processes and disciplines in the re-engineering pipe support supply chain. The current state helped the authors to determine the value adding and non-value adding times and lead times. The improved processes are illustrated in the future state map by applying supply chain management strategies.

Other studies in the construction supply chain have been done by Fontanini and Picchi (n.d.) and Dallasega et al. (n.d.). Fontanini and Picchi, presented a new framework of VSM, converging several value streams into an environment called the Value Stream

Macro Mapping (VSSM). The authors applied VSSM in an aluminum window supply chain (design, planning, drawing, installing, aluminum manufactures) to identified wastes. The proposed possible problem-solving in interfaces is among processes and agents.

Dallasega et al. (n.d.) provided a standardized methodology for supply chain window installation in construction sites. According to the authors, profane material on site is the major problem in the supply chain, which causes quality loss. The authors analyzed the current state and presented a VSM future state for the window supply chain.

Mastroianni and Abdelhamid (2003), in response to the challenge from Ford Motor Company, presented a lean tool for reducing construction project delivery time. The authors presented lean tools like Value Stream Mapping, Logistic Planning, Visual Management, the 5S process, and Last Planner.

Pasqualini and Zawislak (2005) applied VSM in a Brazilian construction company. According to the authors, modification in VSM was necessary since construction and manufacturing differ. In the study case, the authors applied VSM in one productive stage, in masonry work. The authors stated that through VSM's application, several problems in the traditional construction application were detected and actions were taken to improve productivity and increase the flow.

Yu et al. (2009) developed a VSM approach for the house construction industry, in collaboration with home builders. The study aimed to develop a lean production model and to analyze the traditional practice. According to the authors, the model has four features (production leveling at pacemaker, first-in, first-out lane-based flow, work restructuring, and improved operation reliability). The authors stated that changes in the traditional methodology of VSM were made to apply the VSM tool in the house construction site. The authors presented a future state of the project, which showed improvement in overall performance and reduced total delivery time of housing projects.

In another study, Yu et al. (2013) developed and implemented the production system for the application of lean tools like 5s, takt time planning, value stream mapping, standardized work, and variation management in a building prefabricate fabric. Even though the modular prefabricate works are built in a closed environment (factory), the methods used for construction are the same as the one used in the site. Intending to get support from the middle managers, the authors started a pilot project by applying the lean tools into only one production line for six months. The implication of the lean tools increased productivity from 0.91 to 1.73 and won the support of the middle managers to expand the lean practice in the company.

Vilasini and Gamage (2010) implemented the VSM methodology to a precast concrete yard which supplies a bridge construction site. The authors used VSM since it contains a correlation to the actual waste in the construction sites. The authors tested the effectiveness of the method on the site. The proposed methodology helped in improving the quality and reducing cycle time.

Fontanini et al. (2013) presented the application of lean principles and the lean tool value stream map to Brazilian Companies. The objective of the paper was to present lean construction optimization features. The authors presented a study case in concrete slab works. According to the authors using VSM, the waste is the structural element where processes can be observed and detected. The authors considered "pushed" processes to be the ones that are not connected to the next process which creates queue and increases the lead time; and "pulled" processes to be the ones where continuous flow is present and pace is established.

Matt et al. (2013) presented a methodology for a customized and integrated value stream map for the construction industry. The authors aimed to provide a VSM methodology that processes flow within companies and partners, and that can be designed in an efficient way and customer oriented. The proposed approach was developed in the frames of the project "build4future."

Gunduz and Naser (2017) presented a new framework of VSM by adopting the cost implementation. This framework was applied to a pipeline project. The current state for each stage of the pipeline project was built based on the data collected by observation (cycle time, value-added, and non-value added). To create the future state of VSM, the authors used the Line of Balance technique to balance the resources. The paper presents an integration of the cost based on VSM with LOB technique, providing a sustainable tool and increasing productivity, reducing cost, and optimizing the resource allocation.

Later, Gunduz and Naser (2018) continued the research on the framework of implementing the design of VSM that is supported by the LOB principles. The framework considered the cost perspective of the project. The objective of this framework was to reduce the cost in the future state of the project and improve productivity. In this study, the authors gave instructions for the implementation of future state strategies.

CHAPTER 3

RESEARCH METHODOLOGY

3.1. Introduction

In this chapter, the theory for LOB technique, the learning rate features, and learning models were presented. Later, the methodology for LOB with a learning effect was shown. The chapter continues with the methodology for resource optimization. Finally, the methodology for VSM is given. The methodology flowchart proposed for this thesis is given in Figure 3.2.

3.2. Theory of LOB

The LOB method was first developed for improving production control and planning in the manufactory. Later, LOB methodology started to be used in construction projects with repetitive nature such as high-rise buildings, housing projects, highway, and tunnels.

The theory of lob is based on finding the required production rate to meet the delivery of the project (Lumsden, 1968). In other words, it requires the number of units that need to be finished at a certain amount of time, so the project completes on time. According to Lumsden (1968), since the production rate "m" is constant, the relationship between time "t" and the quantity "q" is assumed to be linear. The graphical interpretation is shown in Figure 3.1., and mathematical expression in *Equation 3.1.* is shown below:

$$q = mt + c \tag{3.1.}$$

where c determines the intercept on the vertical (Q) axis. The equation can be expressed as the following two equations.

$$q_2 = m(t_2 - t_1) + q_1 \quad (3.2.)$$

and

$$t_2 = (q_2 - q_1)/m + t_1 \quad (3.3.)$$

Based on Harris and McCaffer (2013) the following steps are done for creating a Line of Balance schedule

1. Create a logic diagram for the activities
2. Estimate the required person-hour for each activity
3. Define the buffer time
4. Calculate the required production rate
5. Estimate the necessary calculation for LOB
6. Draw the schedule
7. Check the schedule for alternative solutions

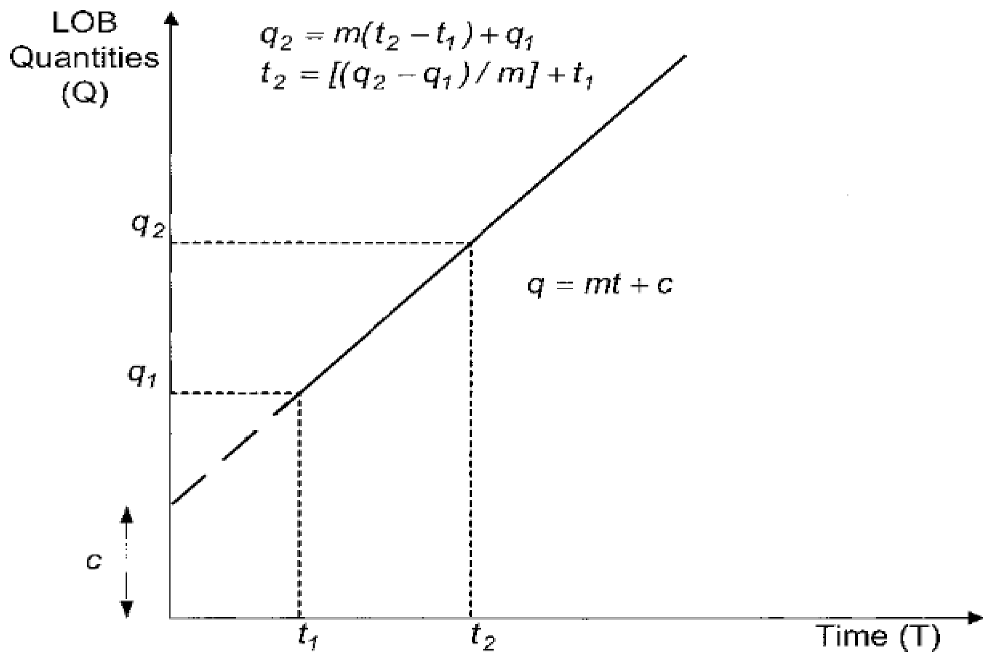


Figure 3.1. Relationship Between Time and LOB Quantities (Arditi et al., 2002a)

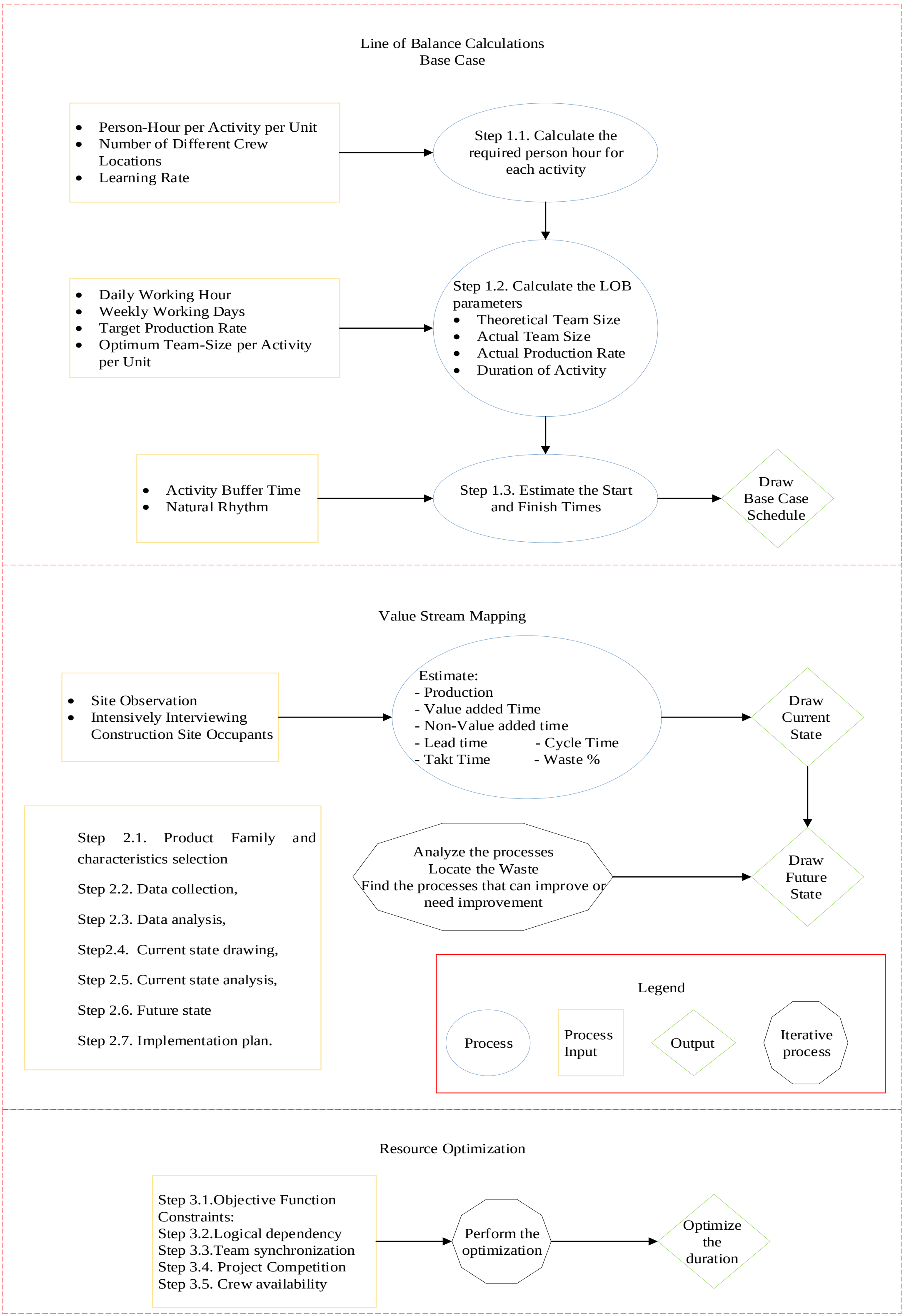


Figure 3.2. Proposed Methodology Flowchart

An example of a logic diagram is given in Figure 3.3. The logic diagram presents the typical activities relationship and the working consequence in a typical unit. In general, the activities have finish to start (FS) relationship. In this kind of relationship, LOB becomes more advantageous compared with CPM because as the repeating activities increase in size, the schedule has to be repeated n times and the network becomes bigger and complicated to manage (Arditi et al., 2002b).

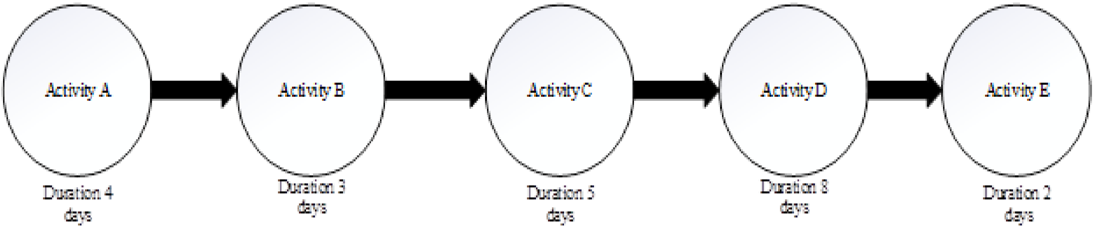


Figure 3.3. Logic Diagram

LOB methodologies basis require to determine the needed resource for each unit or operation so that the target production rate is obtained and the following units or processes are not interfered with (Harris and McCaffer, 2013). In other words, the production rate can be estimated after the crew number of each activity is determined. The next step is to define the buffer times for each activity. Buffer time represents the duration between the finish of the processor activity and the start of the successor activity. The buffer is used to account situations like (concrete curing time, resource mobilization, reserves for the managerial purpose, and time reserved to avoid conflicts between activities) (Tokdemir et al., 2018).

The optimum production rate is achieved when the production rate of any scheduled activity is a multiple of the activity's "natural rhythm". The concept of "natural rhythm" is the optimum production rate that any crew is able to achieve. Difference in activities production rate and the multiple of the "natural rhythm" causes idle time for labor and equipment (Arditi et al., 2002a).

The next step is to make the required calculation for the LOB. The calculations are explained in the methodology section.

After, a diagram for each activity can be drawn. The diagrams are drawn in an x-y plot where the x-axis represents the time, and the y-axis represents the units or quantity. The diagram for an activity is consisting of two inclined and parallel lines, which one of them represents the start time of the activity and the other the finish time. The difference presents the activities unit duration. A typical LOB schedule for a project containing three activities is presented in Figure 3.4.

The last step of creating a LOB schedule is to check for alternative solutions for a more balanced LOB schedule. This can be done by changing the output rate by increasing or decreasing the crew size of the activity. Another step is to overlap some activities and to schedule the activities with the same production rate. This method is called "parallel scheduling" and helps in achieving the goal of the desired output rate by hiring the required amount of resources (Harris and McCaffer, 2013).

3.2.1. Concepts for LOB Scheduling

The request for new concepts in LOB scheduling came when researchers tried to make computerized LOB tool for scheduling high-rise building projects. High-rise projects differ from the other repetitive projects due to physical limitation. These concepts, which were introduced by Arditi et al. (2002b; a) are: "multi-level," "criticalness," and "flexible." Arditi et al. (2002a) presented the concept "multi-level" when scheduling projects with multi-level activities. The construction work is represented in a unit network composed of three levels of activities (main activity, sub-activity, and sub-sub-activity), where the main activity is composed of sub-activities and sub-activities are composed of sub-sub-activities. In general, the duration of sub-sub-activities is minimal (a few hours-2 days maximum) compared with the duration of sub-activity.

A typical example for multi-level activities in high-rise projects is the reinforced-concrete activity which contains (formwork-rebar application-concrete purring) activities. According to “multi-level” concept principle, all the crews need to follow at the same production rate, not higher nor lower. Because otherwise, the scheduler might start the application of formwork at the 5th unit while the concrete for the first unit is not purred yet.

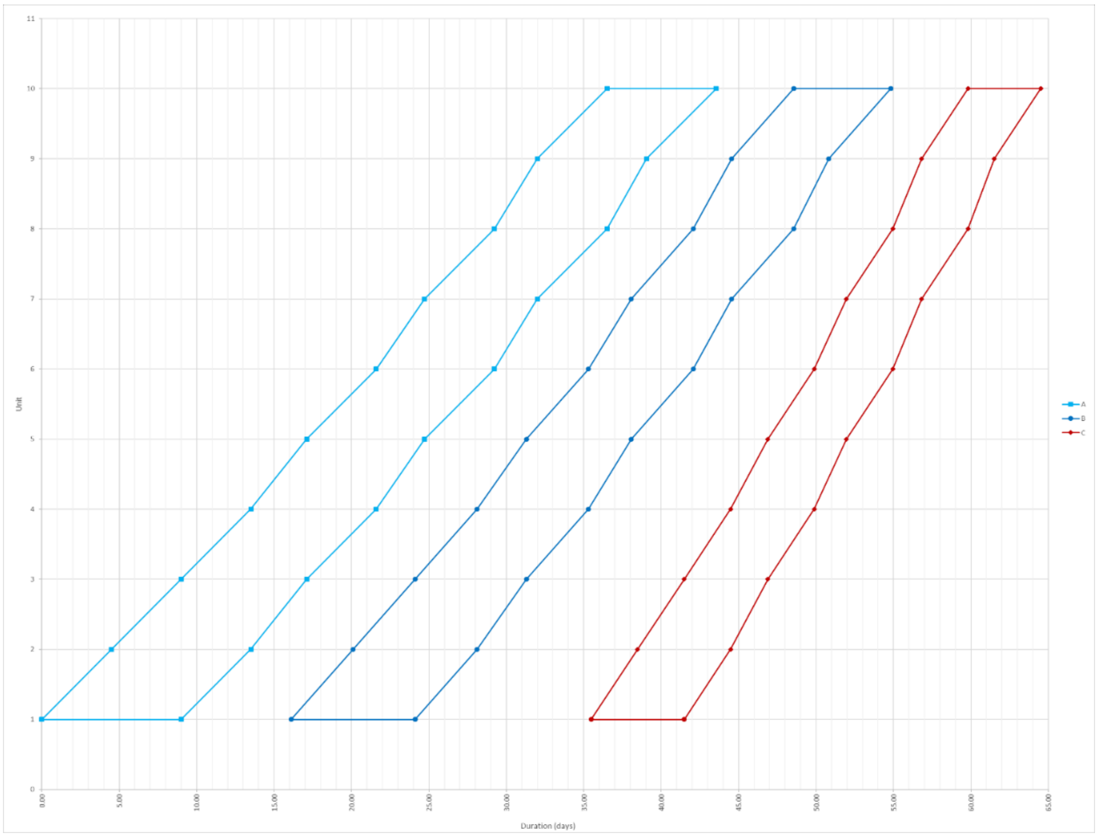


Figure 3.4. Example of LOB Diagram

Activities that have to be carried out after the preceding activity are called dependent activities or time-dependent activities. Space dependent activities, on the other hand, are activities that can be carried out at the same location and after the preceding activity is finished. This type of activities is presented in high-rise building projects. The author presented two alternatives when dealing with multi-level activities in LOB schedule:

1. The main activity and the sub-activity are independent. At this case as long as the activity and sub-activity don't violate the precedence relationship, the production can be different.
2. The main activity is independent, and the sub-activity is dependent. In this case, the production rate of the sub-activities depends on each other and to the production rate of the main activity, so the production rate for all the sub-activities is required to be similar.

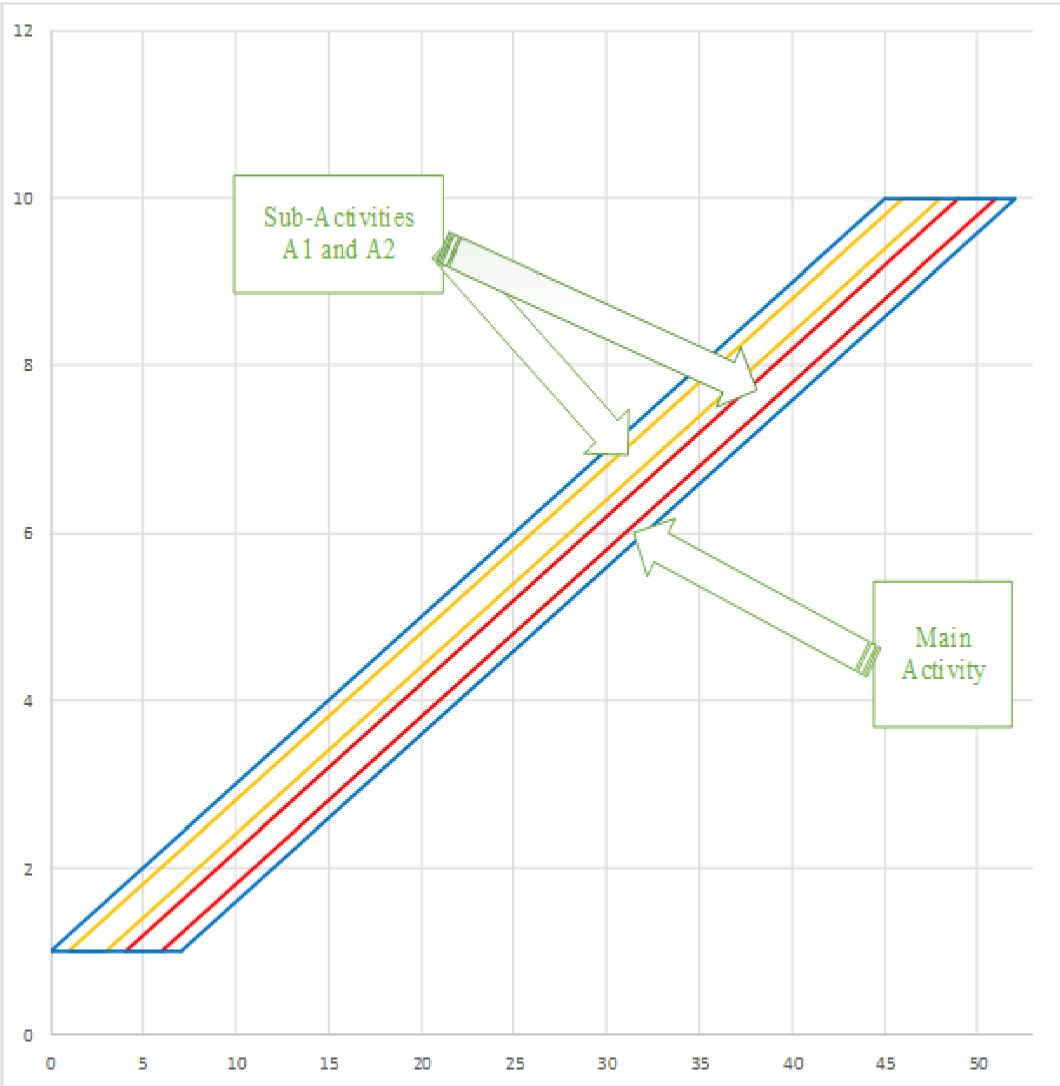


Figure 3.5. Example of Depended Sub-Activities from Arditi et al. (2002b)

Another important concept is "criticalness," which is presented by Arditi et al. (2002b). When scheduling with the unit network, after a specific unit non-critical activity may become critical and disrupt the preceding activities. The term criticalness for LOB scheduling is not the same as in network scheduling. In LOB scheduling the criticalness of an activity is determined by its production rate, and in network scheduling, only its duration is used for defining it. In LOB schedule critical activities are activities that do not contain a float and to achieve efficient performance a continuous use of labor and equipment should be sustained.

The third concept "flexible" defined by Arditi et al. (2002a) describes that activities that have float can be shifted backward or forward without any additional cost and at any time, as they don't violate the precedence relationships. The float can be defined as the maximum time available to finish an activity without causing any delay in the project. Float presence can be beneficial in obtaining a more economical resource use.

3.2.2. Learning Effect

In Line of Balance scheduling methodology, one of the most critical issues is the learning effect. Project with repetitive activities achieves higher productivity rate. Also, labor productivity improves (increase) when working on repeating tasks. In other words, as labor becomes more familiar with the work, less time is spent on performing the same activity (Arditi et al., 2001a). The learning effect is the phenomenon where the time spent in completing an activity decreases as the number of repeating units increases.

According to the learning theory, at every passed unit the unit duration of activity will decrease by a percentage, which is called the learning rate. The lowest learning rate is 100%; this value shows that no learning effect is present. So, the lower the rate becomes, the higher the learning effect gets. A learning rate of 80% indicates that labors are learning at a rate of 20%.

3.2.3. Learning Models

Various mathematical models for calculating the learning effect have been proposed until now. These models describe the change in production as a function of production (produced units). Even though labor productivity improves as they are involved in repeating activities, in construction industry only a limited number of attempts of accounting the learning effect in design and production are done (Arditi et al., 2001a).

Several mathematical models for describing the learning effect are proposed and the most known are:

- Straight-line power model
- Stanford-B model
- Exponential models

In the following models, the "*Y*" parameter presents the cumulative person-hour of a unit, and "*x*" is the cumulative unit number.

3.2.3.1. The Straight-Line Power Models

The straight-line power model or the log-linear model is called so because it forms a straight line when it is plotted on a log-log scale. The learning rate in this model is constant throughout an activity.

$$Y = KX^n \qquad (3.4.)$$

where K is the person-hour required for the first unit, and n is the learning index defined as $n = logS/log2$. S is the learning rate in percentage

3.2.3.2. Stanford-B Models

The Stanford-B model is a modification of the straight-line model that includes the "B-factor" (Arditi et al., 2001a). The B- factor measures the differences in design or management control know-how complexities or to obtain the experience gained from previous learning. The model formula is given below in Equation 3.5.:

$$Y = A(x + B)^n \tag{3.5.}$$

where A is the person-hour of the first unit when a crew has no previous working experience (B=0), n is the learning index, and B is the units working experience available at the commencement of an activity.

3.2.3.3. Exponential Models

Researchers proposed various exponential models as an alternative straight-line power model. Some of the models are explained below.

- Basic Exponential Model:

The Norwegian Building Research Institute proposes this model based on the following rule; the cost of the part of the unit that is reduced by repeating will be halved after a constant number of repeating units. The model Equation 3.6. is:

$$Y = Yu \ + (A - Yu)H/2x \tag{3.6.}$$

where *Yu* is the ultimate person-hour per unit at the end of the routine-acquiring phase, A is the person-hour for the first unit, and H is the halving factor.

- Dejong's Model:

Another version of the exponential model is proposed by Dejong (1957). According to this model, the activities duration is compressible when the work is done manually (labor work) and less compressible when the activity is done mainly by machines (Arditi et al., 2001a). The equation for Dejong's model is given below:

$$Y = a(M + (1 - M)/x^n) \tag{3.7.}$$

where a and n are similar to the power function parameters, and M is the factor of incompressibility.

- S-curve model

The S-curve model is based on the assumption of a gradual startup, where its shape is in the form of a cumulative normal distribution function. The S-curve model shape starts with the gradual start-up function, and it continues with the learning effect function which has the shape of an operating characteristic function. The S-curve models' equation is given below:

$$Y = a(M + (1 - M)(x + B)^n) \qquad (3.8.)$$

where *M* is the incompressibility factor, *B* and a are the equivalent experience unit, and n is the value of the learning index. The equation is solved by making assumptions for pre-selecting the values of *M, B*, and *a*. The values of the unknowns can be given by giving a logical preselection of the independent variables. The values of coefficients can be determined with the help of the "cubic curve", which equation is given below:

$$logY = A + B(logx) + C(logx^2) + D(logx^3) \qquad (3.9.)$$

where *A* is the first units' person-hour, *B* is the first units learning rate, *C* is the quadratic factor, *D* is the cubic factor, and *x* is the cumulative unit number.

3.2.4. Learning Rates

The learning rates for activities that contain labor and machinery differ in the following way; it is expected that operation with a higher degree of labor content have higher learning rates which create sharper learning slopes compared with operations with machine paced (Arditi et al., 2001a).

According to Yelle (1979), empirical study, the learning rates increase as the machine-paced to labor ratio increases. The learning rates for construction work in European countries is estimated to be 90%, and the United Nations provided more specific values of learning rates for construction works from 80% to 95% (Arditi et al., 2001a).

According to Arditi et al.(2001a) these values are taken from very old data, and the values of the learning rates should be higher than the proposed ones. Reasons for this are the facts listed below:

- higher technology
- higher skilled workers
- efficient techniques and working methods

The learning rates are affected by several factors, the most important ones with approximate weight of importance based on Arditi et al.(2001a) are shown below:

- Workers learning (40%)
- Construction method (20%)
- Managerial support (15%)
- Quality of design (15%)
- Other (weather condition, site condition) (10%)

Table 3.1. Learning Rates (Arditi et al., 2001a)

Activity type	Ratio		Learning Rate (%)
	Labor (%)	Machine paced Labor (%)	
Labor intensive	75	25	80
Labor/Machine	50	50	85
Machine intensive	25	75	90

3.3. LOB Calculations

One important step of creating a LOB schedule is to make the calculations of the standard parameters. These parameters require some necessary information like weekly working days (w), daily working hours, person-hour per unit (PHU), target production rate (PR_{target}), and optimum team size per unit ($TS_{optimum}$). The parameters needed for calculation (theoretical team size, actual team size, actual production rate, and duration of activity), its explanation and formulation are shown below:

- Theoretical team size ($TS_{theoretical}$): is the required team size to complete an activity according to the selected production rate of the unit. $TS_{theoretical}$ is estimated in weeks, and it is calculated according to Equation (3.10.):

$$TS_{theoretical=}\frac{PHU * PR_{target}}{w * d} \qquad (3.10.)$$

- In general, the value of the calculated $TS_{theoretical}$ is a non-integer number. The ratio of the number of workers in activity and $TS_{optimum}$ should be an integer. Therefore, the selected or adjusted number of $TS_{theoretical}$ should be a multiple of $TS_{optimum}$. The obtained value, the multiple of $TS_{theroretical}$ is also called as the actual team size (TS_{actual}).
- According to the actual team size and the theoretical team size, a new production rate is calculated which is called the actual production rate (PR_{actual}), and it is calculated according to Equation (3.11.):

$$PR_{actual} = \frac{TS_{actual} * PR_{target}}{TS_{theoretical}} \qquad (3.11.)$$

- Duration of activity ($D_{activity}$), is the time that the team requires to finish the activity in a unit. These activities are repeated to several units. $D_{activity}$ is calculated according to Equation (3.12.):

$$D_{activity} = \frac{PHU}{TS_{optimum} * d} \qquad (3.12.)$$

These formulations are performed to all activities in all units.

Person-hour adjustment according to the learning rate:

According to the Straight-line power model, the learning rate is considered to be constant through the activity duration. Considering the learning effect, the person-hour per unit decreases logarithmically through the units by a rate. The mathematical equation for this model is expressed below (Arditi et al., 2001a):

$$PHU_n = PHU_1 * R^{logS/log2} \quad (3.13.)$$

where, PHU_n is the cumulative person-hour at the nth unit, PHU_1 is the person-hour at the first unit, R is the cumulative repeated unit number, and S is the learning rate. The parameter R is directly connected with the number of teams and shows how many times a crew has repeated a unit. For example, if two teams perform eight units in a project, the first team will work on first, third, fifth and seventh units and the second team will work on second, fourth, sixth and eighth units. The R-value for both of the teams is 4. Also, the learning effect affects the number of TS_{actual}, and it may decrease throughout the activity duration and so is the number of teams.

The start and finish dates of the activities can be calculated by considering the production rate and the buffer times. The production rate is considered to be the actual production rate when no learning effect is present. However, the production rate is not constant when learning is considered; in other words, the production rate changes during the units. Learning may also cause changes in natural rhythm. Therefore, the activities' start and finish dates are calculated considering the actual production rate, natural rhythm, and buffer time. The steps for calculating the start and finish times based on Tokdemir et al. (2018) are shown below:

1. The successors start time (St_{n+1})

$$St_{n+1} = St_n + \frac{w}{PR_{actual_n}} \quad (3.14.)$$

where, St_n is the predecessors start time, PR_{actual_n} is the actual production rate, and w is the weekly working days.

2. Later $St_{n+1}$is controlled according to the natural rhythm, if a loose in natural rhythm is present St_{n+1} is adjusted. The required adjustment is based on the predecessor's finish time and the crew numbers, and it is performed base on the following equation:

$$St_{n+1} = \begin{cases} Ft_n & Number\ of\ crews = 1 \\ Ft_{n-1} & Number\ of\ crews = 2 \\ Ft_{n-x+1} & Number\ of\ crews = x \end{cases} \tag{3.15.}$$

The last step is to check the buffer time. Buffer or the time reserves is the time or duration between the finish of predecessors (activity x_i) and the start of the successor (activity x_{i+1}). Buffer time helps prevent clashes and conflicts between the following activities. Also, it can be used to consider the reserved time for situations like concrete curing and resource mobilization. Another problem is the constraints-based problems. In some cases, the resources are ready to work, however the work can't be started because at the same location the predecessor still is working on the task. In this case the resource has to wait until the predecessor finishes its task. This is also called the idle time. One possible way to eliminate idle time is to set a buffer time (delays) in activity start dates. This can eliminate the idle time of the resource and provide resource continuous utility, however it also may increase the project duration (Srisuwanrat and Ioannou, 2007).

The new start time (St) for all units in the activities is checked according to the buffer time. According to it, the start time is shifted. The corrected start time ($St_{corrected}$) is calculated according to Equation 3.16.:

$$St_{corrected} = St - (Bt_{min} - Bt) \tag{3.16.}$$

where, Bt is the buffer time and Bt_{min} is the minimum buffer time between successive activities. At last, the activities finish dates ($Ft_{corrected}$) are checked.

$$Ft_{corrected} = St_{corrected} + D_{activity} \quad (3.17.)$$

When the standard LOB parameters calculation is repeated for all activities, and the precedence relationships are satisfied, the total project duration can be determined.

3.4. Resource Optimization Method

Two LOB objectives are to “balance” the repetitive activities and to ensure a smooth (even) flow of resources. It is possible to formulate the LOB schedule in a mathematical programming form, so that an optimal solution is met. From the traditional LOB methodology, the project duration, the required number of teams to achieve the project duration, and the natural rhythm of the crews (timing of crews) in repetitive activities are obtained.

According to researchers, it is possible to formulate the traditional LOB methodology to mathematical programming so that an optimum solution can be met. The mathematical programming form requires three basic issues that need attention: decision variables, problem constraints, and objective function (Ammar, 2019). In the traditional LOB, different researchers proposed to optimize the project duration by using the available resources (resource allocation problem), or to achieve the project duration with a minimum amount of resources (resource leveling problem) (Ammar, 2019; Damci et al., 2016; Zhang et al., 2017; Zou et al., 2018).

However, when the learning effect is considered, as the project progresses, the duration of the activities decreases, and the number of teams decreases with time. Another issue is that, when accelerating activity is considered, the production rate needs to be increased. This affects the LOB schedule in the form that the buffer time location changes. In this study, resource optimization is done using the traditional LOB methodology.

For the following methodology, again a project with n- activity types that have m repetitive units, where the relationships between the activities are specified, is considered. The basic information unit-person hour, optimum crew size, and available crew number are defined.

3.4.1. Decision Variable

The problem can be described (formulated) by using several variables. However, it is essential to formulate the problem by using a minimum number of variables. To do this, only the most important and relevant ones should be selected. After the basic variables are defined, other dependent variables can be estimated. According to Ammar (2019), the most relative parameters in LOB scheduling that directly affect the resource profile are the available crew size per activity and the activity schedule start and finish times. These parameters guarantee an optimal solution when they are selected as decision variables.

Based on the methodology proposed by Ammar (2019), in this study two sets of decision variables are selected:

- The available team number per activity denoted as TS_{number} , and

- Activities start time for first and last units, denoted as $St_{i,j}$, where i denote the activity name and j the unit number.

To describe the problem completely, the required number of decision variables is 3*n (number of repeating activities in a project).

3.4.2. Constraints

The mathematical problem can be described by three types of constraints which are:

- Activity Logical Dependency,
- Crew Synchronization, and
- Project Competition.

3.4.2.1. Activity Logical Dependency Constraints

The aim of this constrains is to provide the activities precedence relationship at the repeating units. The relationship between two consecutive activities is expressed in Equation 3.18.:

$$St_{i,j} \geq St_{i+1,j} + D_{activity} + Bt \tag{3.18.}$$

where, St_i is the start time of activity i, St_{i+1} is the start time of the preceding activity, $\sum D$ is the total of all possible durations between the preceding and succeeding activities. $\sum D = D_{activity} + Bt$, where $D_{activity}$ is the activity duration, and Bt is the duration of buffer time.

The logical dependency is completed when the constraints for the first and last units for all activities are defined. The mathematical expression is given in Equation 3.19. and Equation 3.20.:

$$St_{i,1} - St_{i+1,1} \geq \sum D \tag{3.19.}$$

and,

$$St_{i,n} - St_{i+1.n} \geq \sum D \tag{3.20.}$$

3.4.2.2. Crew Synchronization Constraints

As mentioned above, the team for all units in all activities synchronization needs to be maintained, so that the work continuity of the teams working on a project is maintained. The mathematical expression is presented in Equation 3.21.:

$$PR_i = \frac{n-1}{St_{i,n} - St_{i.1}} \tag{3.21}$$

where PR_i is the production rate for activity i, n is the last unit, and $St_{i,n}$ and $St_{i.1}$ are the start time of first and last unit of activity i respectively. The production rate PR_i can be expressed as $TS_{number}/D_{activity}$, and substituting it to Equation 3.21. and after arranging *Equation 3.22.* is represented as follow:

$$\left(St_{i,n} - St_{i+1.n}\right) * TS_{number} \geq (n-1) * \sum D \qquad (3.22.)$$

The number of teams working on an activity should be constrained with the number of units, and the availability of the teams. Also, it is essential that the team does not work in fractions. This means that the team number should have integer values.

$$TS_{number} \leq m \text{ ; Integer} \qquad (3.23)$$

and,

$$TS_{number} \leq TS_{available} \qquad (3.24)$$

3.4.2.3. Project Completion Constraints

The project competition constraint controls that the project duration is satisfied. This constraint is controlled with the competition of the last activity and last unit of the project.

$$St_{n,n} \leq D_{project} - D_{activity} \qquad (3.25.)$$

3.4.3. Objective Function

The equation in methodology provides a model for general resource optimization. In this model, both resources leveling, and resource allocation are addressed

The deadline problem is satisfied with minimizing the project duration by using the available resources. The mathematical expression is presented in *Equation 3.26.*:

$$MIN.Z = D_{project} \tag{3.26.}$$

The resource leveling objective minimizes the resource usage to achieve the predefined project duration. The mathematical formulation is presented in Equation 3.27.:

$$MIN.Z = \sum TS_{number} \tag{3.27.}$$

In the following, a summary of the resource allocation and resource leveling models is presented:

Resource allocation model

Step 1. Objective function:

Minimize: $Z = D_{project}$

Step 2. Logical dependency constraints:

- $St_{i,1} - St_{i+1,1} \geq \sum D$
- $St_{i,n} - St_{i+1.n} \geq \sum D$

Step 3. Team synchronization constraints:

- $\left(St_{i,n} - St_{i+1.n}\right) * TS_{number} \geq (n-1) * \sum D$

Step 4. Project competition constraint

- $St_{n,n} \leq D_{project} - D_{activity}$

Step 5. Team availability constraint:

- $TS_{number} \leq m$; Integer

- $TS_{number} \leq TS_{number}$

Resource allocation model

Step 1. Objective function:

Minimize: $Z = \sum TS_{number}$

Step 2. Logical dependency constraints:

- $St_{i,1} - St_{i+1,1} \geq \sum D$
- $St_{i,n} - St_{i+1.n} \geq \sum D$

Step 3. Team synchronization constraints:

- $\left(St_{i,n} - St_{i+1.n}\right) * TS_{number} \geq (n-1) * \sum D$

Step 4. Project competition constraint

- $St_{n,n} \leq D_{project} - D_{activity}$

Step 5. Team availability constraint:

- $TS_{number} \leq m$; Integer

- $TS_{number} \leq TS_{number}$

The models require the following input data:

- activity data: activity unit duration, predecessors;

- resource data: team sizes and available team sizes for an activity; and

- project data: number of repeating activities (m) and desired project duration.

3.5. Value Stream Mapping Methodology

Value Stream Mapping was first designed for manufacturing. To adopt this tool in construction, some changes need to be done (Pasqualini and Zawislak, 2005). In this study, the proposed VSM methodology was based on Rother and Shook (1999); Yu et al. (2009); Rosenbaum et al. (2014). In the following, the steps for the proposed methodology are showed and described:

1. Product Family and characteristics selection,
2. Data collection,
3. Data analysis,
4. Current state drawing,
5. Current state analysis,
6. Future state, and
7. Implementation plan.

3.5.1. Product Family and Characteristics Selection

Generally, activities that are critical or that do not go in the planned schedule are selected to be the target activities. The target group can be a group of services or products that go through the same steps or a group of processes that need improvement. According to Rother and Shook (1999), it is essential to select only the products that the customer care, however, if the number of the products is limited, all the products can be selected.

VSM parameters like duration, cycle time, lead time, takt time, waste percentage, production rate, unit person hour, value-added and non-value-added time are estimated. Most of these characteristics originate from the traditional (manufacturing) VSM.

3.5.2. Data Collection

Rother and Shook (1999) suggested collecting the data by observation and taking a stopwatch to measure the time while walking along with the processes. This method will better help to understand the process in general. However, when it comes to construction sites, using a stopwatch is not applicable. The labor number and the variability in task performance make it difficult to get reliable data (Yu et al., 2009).

3.5.3. Data Analysis

The VSM parameters are calculated using the collected data. In the following, the explanation of the parameters is given:

- Waste is an amount of cost that is spent additionally in activities (e.g., rework)(Ballard and Howell, 2003), or work that does not help in advancing the project (Alarcon, 1997), in other words, it is a non-value adding activity.
- Tack time: is the target amount of production in order to meet the customer's demand.

$$Takt\ time = \frac{Daiy\ Available\ Time}{Daily\ Production\ Rate} \qquad (3.28)$$

Cycle time (CT): is the amount of time at which activity will be finished (Yu et al., 2009).

$$CT = Finish\ time\ of\ activity - Start\ Time \qquad (3.29.)$$

- Lead Time (LT): is the amount of time, from ending activity 'i' to the start of activity 'i+1'.
- Changeover time: the time that a crew needs to switch working location from one activity to another, including demobilization and mobilization. (Yu et al., 2009)
- The production rate of the activities is calculated as:

$$Productivity = \frac{\sum Person\ Hour}{\sum Work\ Amount\ (ton, m, m^2, m^3)} \qquad (3.30.)$$

- The waste percentage (W) is the amount of waste over the total amount of material.

$$W = \frac{\sum Material\ Waste}{\sum Material} \qquad (3.31)$$

3.5.4. Current State Drawing

The current state illustrates how the work is performed in the construction site. It is drawn by using flow charts (see Table3.2.), where the estimated parameters are shown in the data boxes. The current state shows the connection between the activities. It also helps to analyze and make the basis for the future state of the process. The estimated parameters and obtained current state should be validated with engineers working in the project.

3.5.5. Current State Analysis

Analyzing the processes means finding the ones that need improvement and locating non-value adding activities (wastes). For improvement lean principles like continuous flow, takt time is used. The future state is an improved state compared with the current state (Mastroianni and Abdelhamid 2003). The current state analysis showed several questionable activities that are critical and can be improved.

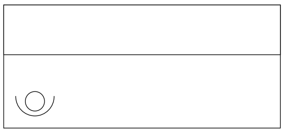
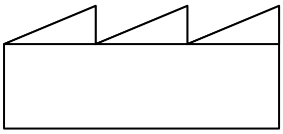
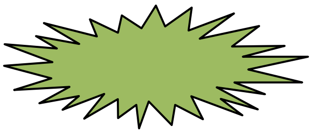
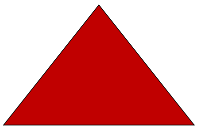
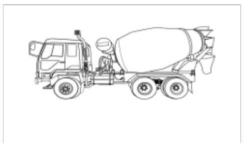
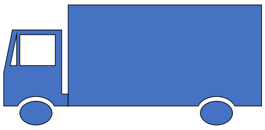
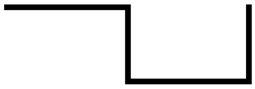
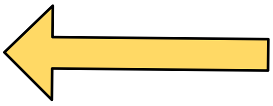
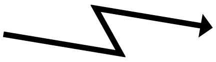
3.5.6. Future State

The objective of the future state is to locate and eliminate the root causes of waste and problems. The future state should be estimated and drawn in a way that it can be achieved. In general, construction sites can be affected by an unpredictable factor (for example weather condition) which can cause a large number of wastes. This fact makes optimizing very difficult. For this study, the future state is presented considering only the observed factors in the construction site.

3.5.7. Implementation Plan

Implementation plans are essential for VSM. Continuous improvement is one of the basics of lean principles. A methodology for it is Plan-Do-Study-Adjust (PDCA) cycle, which shows that perfection is several iterations of improvement. VSM is also an iterative tool, which needs to be updated and consulted very frequently (Martin and Osterling, 2014). The goals in the future state need to have guidance so that the crew can follow to achieve the goals in the future state.

Table 3.2. The Value Stream Mapping Charts

	Process		Production control
	Customer/ Supplier		Data Box
	Kaizen Burst		Inventory
	Mixer		Crane
	Shipment Truck		Timeline Segment
	Push Arrow		Shipment Arrow
	Information Arrow		Electronic Arrow

3.6. Chapter Conclusion

To sum up, the literature has shown that no research has been conducted implicating VSM to improve and optimize the project duration using LOB schedule with learning effect on a high-rise project. In this research, further optimization for LOB scheduling is done using resource optimization, and the VSM future state is used to reduce the waste, increase productivity, and decrease the total project lead time.

CHAPTER 4

CASE STUDY

4.1. Introduction

In this chapter, the case study was presented. The proposed LOB methodology with the learning rate was applied in a real high-rise building project, and the base case schedule was created. After, the actual case from the site and its comparison with the base case were presented. Later, the optimization using VSM was shown. In the end, the resource optimization method was applied to the LOB schedule.

4.2. Case Study

In this thesis, a real high-rise building project was taken as a case study. The project was located in Ankara and composed of three blocks. The construction of the first block (A block) was finished; the construction of the second block (B block) had started, and the third block (C block) had not started yet. In this thesis, the focus point was at B block. B block was composed of 20 floors with a basement. The project was managed traditionally, and no base schedule was prepared before. According to site observation, the construction site depends on the contractor's experience mainly.

For the purpose of this study, the LOB schedule was based on the contractors original finishing plan, and the required information was conducted by interviewing several engineers, who worked on the construction site. The expected finishing date and the delivery rate of the projects were defined according to the information obtained.

In this study, the LOB schedule was prepared considering five groups of repeating activities:

- Concrete works- Activity A,
- Rough finishing works and Façade- Activity B,

- Mechanical works- Activity C,
- Electrical works- Activity D, and
- Final finishing works- Activity E

The following assumptions were done to prepare the base LOB schedule:

- The activities had start-to-finish relationships. In the scope of this study, only labor was considered a resource because it is one of the significant varying resources in construction.
- Production rate= 1 unit per week;
- Weekly working days= 6 days per week;
- Daily working hours= 9 hours per day; and
- The learning rate was based on previous studies (Ammar and Abdel-Maged, 2018; Arditi et al., 2001a; Tokdemir et al., 2018) and assumed to be 90% for all activities

Table 4.1. shows the parameters required and standard LOB parameters calculations, according to which the LOB chart was prepared and shown in *Figure 4.1.* The figure shows the location-based (floors are represented in units) start and finish times, and the expected project duration of 244 days.

Table 4.1. Estimated Values for the LOB Schedule (Base Case)

Unit	MHU (work-hour)	$TS_{optimum}$ (Labor)	$TS_{theoretical}$ (Labor per activity)	TS_{actual} (Labor per activity)	PR_{actual} (units per week)	$D_{activity}$ (day)	B (day)	St (day)	Ft (day)
A	2052	19	38.00	38.00	1.00	12.00	14	0.00	192
B	600	9	11.11	18.00	1.62	7.41	3	117	211
C	135	3	2.50	3.00	1.20	5.00	3	144	217
D	288	8	5.33	8.00	1.50	4.00	3	164	222
E	360	8	6.67	8.00	1.20	5.00	3	171	244

Note: the values for the start and finish dates are rounded-up

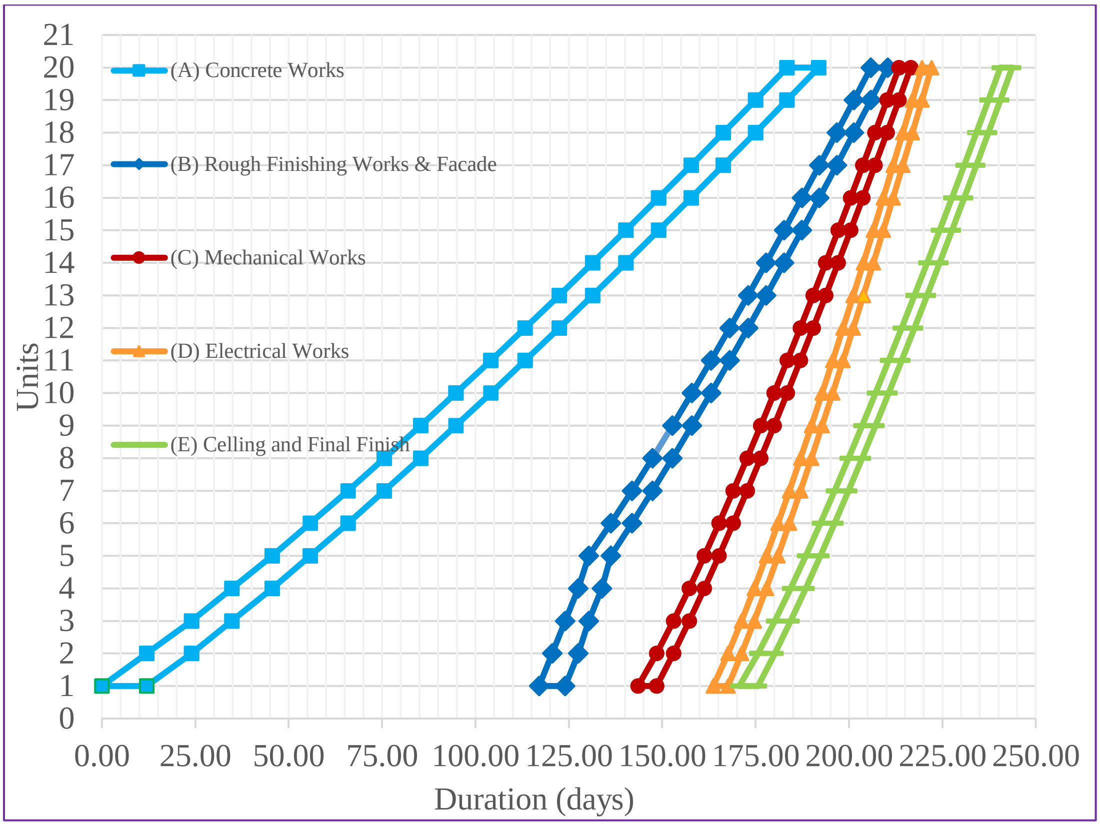


Figure 4.1. LOB Schedule (Base Case)

It was observed that activity-A, the concrete work activity, had a physical constraint. So, the preceding unit cannot start before its succeeding unit was finished. As mentioned in the methodology, the theoretical team size was estimated according to the production rate. Moreover, the number of teams working on a unit the actual team size is a multiple of theoretical team size. For example, in activity B in the beginning, two teams were assigned. However, both teams work together until the fifth unit (at different units), where after the fifth unit only one team continues. As it is shown in Figure 4.1., the slope of activity changed. The break on the slope occurred because of the learning rate as the duration of the units decreases, and the production rate increases. At each unit, the unit duration and required team size were calculated. If the estimated theoretical team size is less than the optimum team size, the team size will be considered as the optimum one.

4.3. Actual Case

After the base schedule was prepared, the project schedule was updated according to the project progress. The updated base schedule is the actual case. The project data was collected when the project was progressing at a slow rate, and the 7th unit was finishing up. According to the site reports the project was moving very slow.

This delay occurred because of several reasons; one of them was the economic crisis during the summer period of 2018. Because of the crisis, the material resources become unavailable for many contractors, which resulted in stopping the works on many construction sites in Turkey. The stagnant cash flow was a significant reason why many firms went bankrupt. Fortunately, the project's contractor did not bankrupt; however, resource unavailability made the work to stop for several. The schedule for the actual case is presented below Figure 4.2.

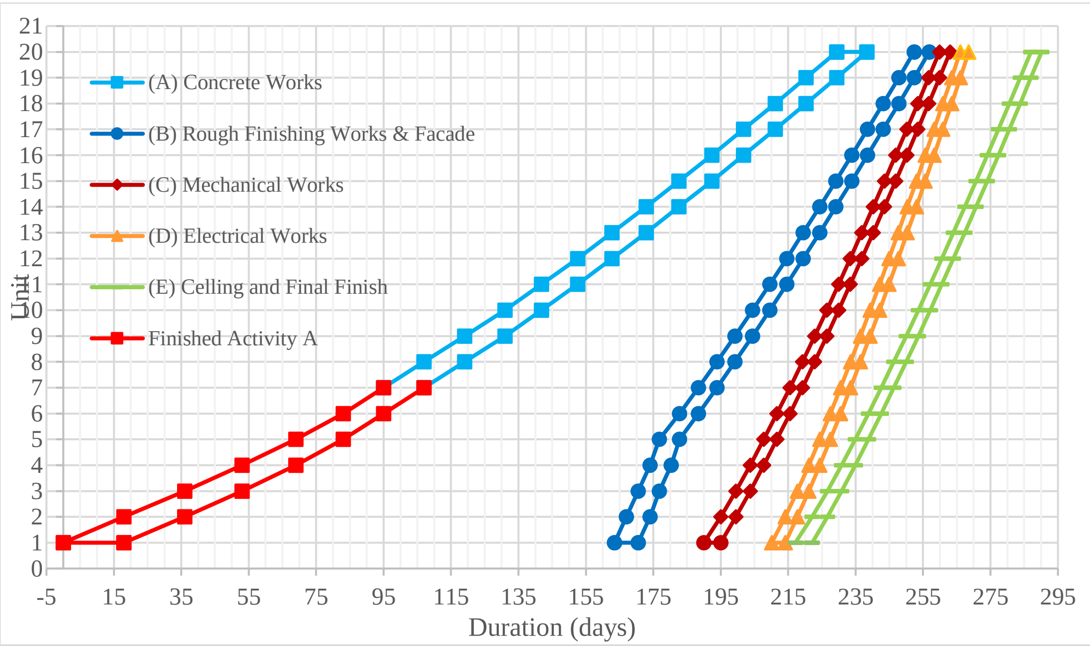


Figure 4.2. The LOB Schedule (Actual Case)

The data obtained from the field revealed that the reinforced concrete works were 31 days behind the base planned schedule. The finished units in the first activity were shown in red lines (see Figure 4.2.). For the remaining 13 units, the learning rate was applied. It is remarked that the first unit finishes in 238.35 days, And the total project duration was estimated to be 290.17 days. Compared with the base case, a total delay of 46.5 days occurred. Value Stream Mapping method was used to optimize the concrete operations first to reduce the duration by eliminating waste.

4.4. Value Stream Mapping Optimization

VSM can be applied in activities which already had started and been operating. Because of this fact, in this study, VSM methodology was applied in optimizing the reinforced concrete work-activity (A). The current state was prepared according to the steps in the VSM methodology section.

The reinforced concrete activity was composed of sub-activities (formwork installation, rebar installation, quality control, concrete purring and formwork removal and cleaning). Some of these sub-activities can be decomposed into more sub-activities; however, to make the VSM draft more understandable, the other activities were considered to be sub-sub-activities. It is understood that the impact and duration of the sub-sub-activities were counted in the main sub-activities.

According to the presented VSM methodology, the steps for creating the VSM are shown below:

Data collection: data was collected by site observation in 3 weeks, and several interviews with labors, site engineers and the project manager were conducted. As part of the study, the start and end dates of each activity and their sub-activities were recorded. Also, interviews helped in understanding the problems which the working team was facing. The opinions of labors, site engineers and project managers about possible improvements were noted.

Data analysis: according to the site observations, VSM characteristics were calculated. The estimated parameters and obtained current state were validated with engineers working in the project. Among them, there is the project contractor who was the project manager with 15 years working experience, two site engineers with 4- and 5-year working experience and two supervisors (foreman) with 10- and 12-years' experience.

Current state drawing: According to the obtained data, a current state VSM drawing is presented in Figure 4.3. The monitoring showed that the takt time for the standard units is estimated to be 12 days/unit.

In the center of the map, the production control is located. All information was collected and processed there. The orders were given monthly, and only weekly progress was recorded. The material was transported with cranes to the units. The arrows represent information flow in the form of material information, monitoring, and different types of orders.

In the data box, the measured production, planned unit person-hour, cycle time, and for the activities that the presence of waste was located, were shown. Below the data box, the timeline segment for each activity was presented, where the value-added and non-value-added amounts of times were shown.

Current state analysis: The current state data was analyzed, processes that contain waste and need improvement were located. Monitoring showed problems in the following areas:

- Formwork and rebar installation teams leave the site after finishing their daily task.
- Quality control works inefficiently. The later the control finish, the later the concrete comes.
- Concrete was purred very slow, and the order did not come at the required time.

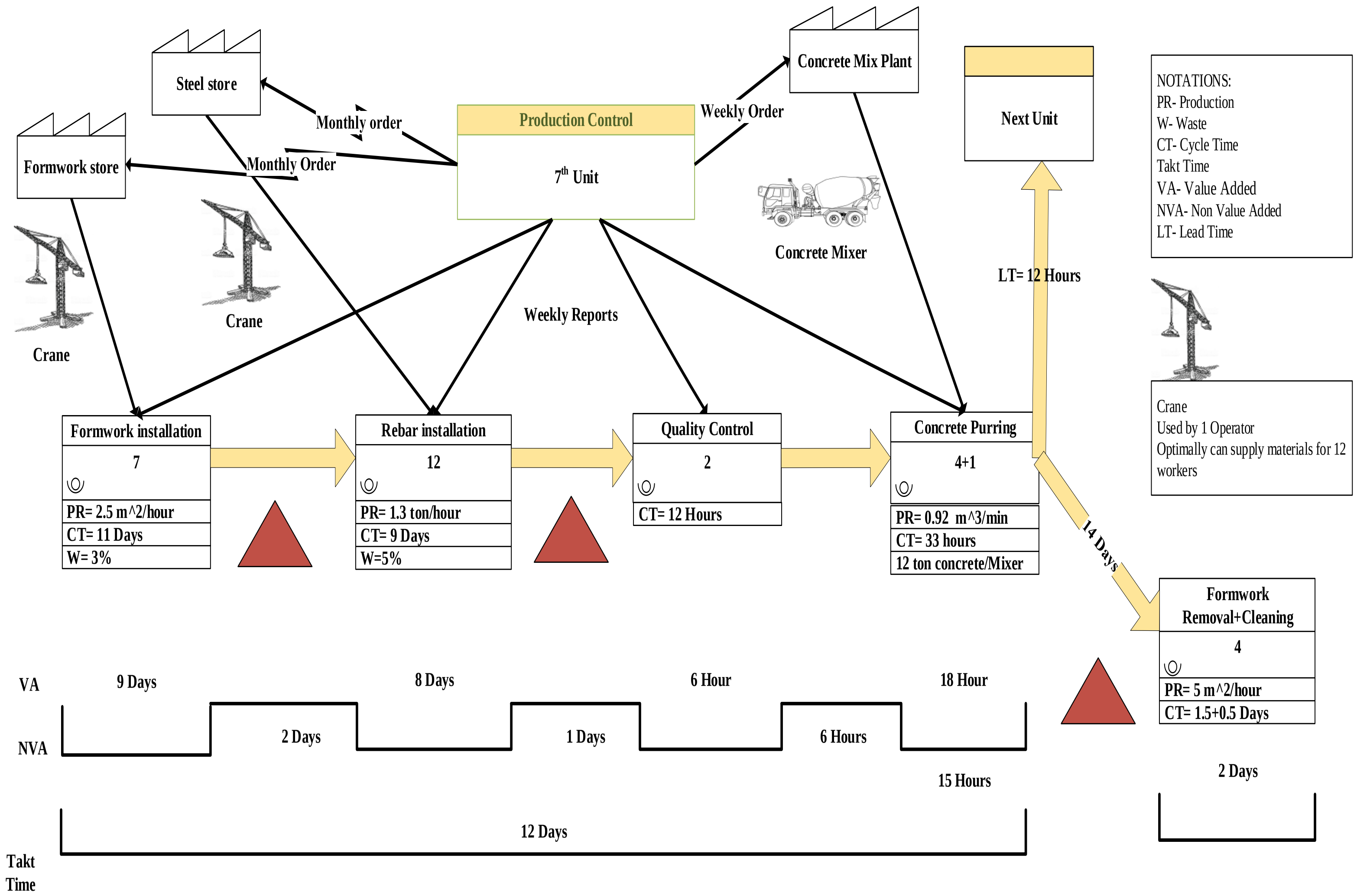


Figure 4.3. Value Stream Map: Future State

- Waste in rebar application was found. Rebars could be used more efficiently.
- The formwork application technique can be changed with a better suited and more efficient formwork technique.

Future state: The problems mentioned above were considered, and a future state was created by using lean approaches to optimize the processes. The future state was presented in Figure 4.4. According to the optimization proposed in the future state, the takt time for 1-unit was estimated to be eight days. This value was updated to the actual LOB schedule. These goals can be achieved if the following changes in the system were done:

- For the future state, daily reports and weekly orders were required. Provide better communication between project occupants.
- All teams are required to work at full-time hours. If the daily tasks were finished, the workers were needed to continue at the next unit.
- Change the concrete supplier.

Due to physical constraints, the first activities total duration was reduced from 238.5 days to 211 days. Only 27.5 days of delay could be optimized using the VSM methodology. The updated schedule was presented in Figure 4.6. The total project duration is estimated to be 262.9 days, where yet compared to the base schedule, a delay of 18.9 days was present. The remaining delay was optimized using the resource allocation method.

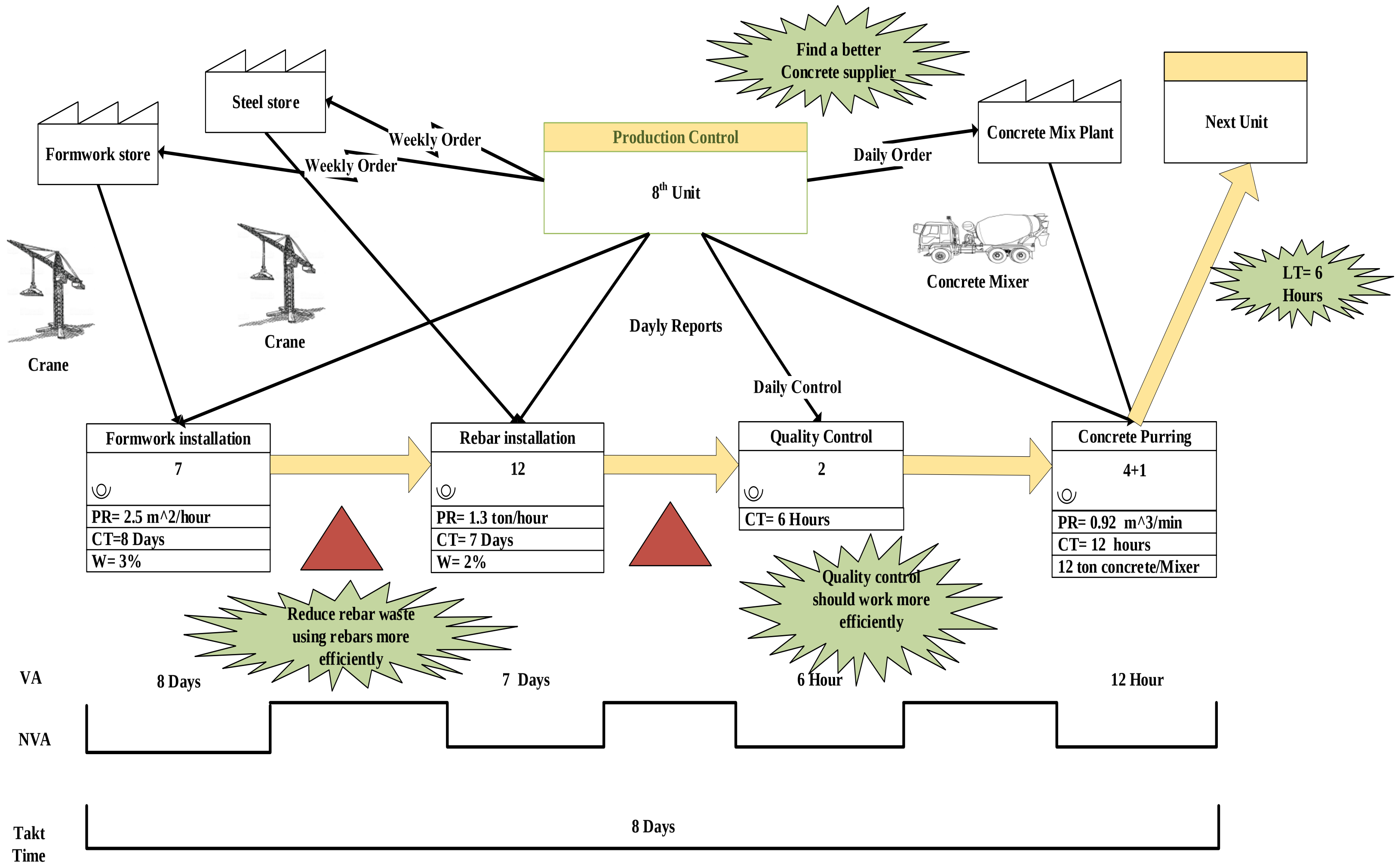


Figure 4.4. Value Stream Map: Future State

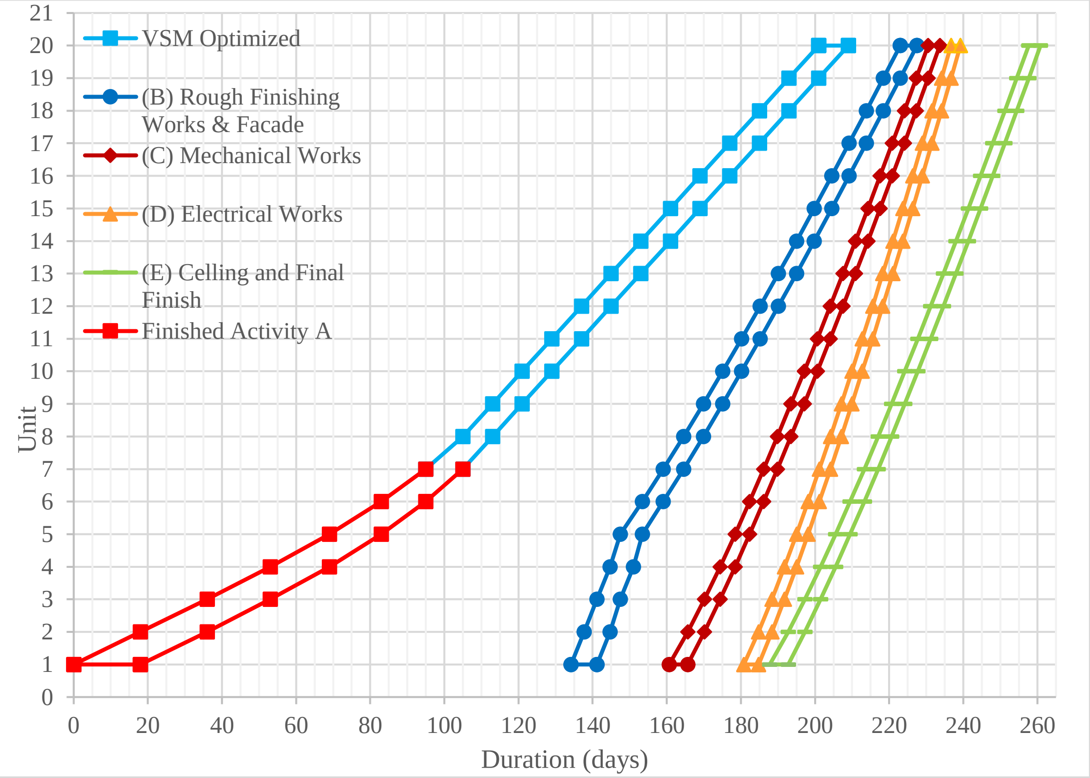


Figure 4.5. LOB Schedule (VSM Optimized)

4.5. Resource Optimization

Since the first activity (Activity A) was optimized using VSM method, only the remaining activities (Activity B, C, D, and E) were optimized using the resource optimizing method. In this case study, there was a deadline scheduling problem, so the resource allocation model was used. The model was formulated and solved in LINGO (2000) software.

LINGO is a powerful tool designed to model and solves different problem types (linear, nonlinear, quadratically constrained, quadratic, etc.) easier, faster, and efficient. The formulated nonlinear model of the project takes an eye blink to analyze and solve the problem under different constraints. First, the necessary calculations were performed in Table 4.2. after, the model was formulated.

Table 4.2. Traditional LOB Calculations for the Resource Optimization Process

Activity	Duration	# of Team	PR_i	$(St_{20} - St_1) * TS_{number} \geq (19) * D$
A	12.00	1	0.083	228.00
B	7.00	2	0.286	133.00
C	5.00	1	0.200	95.00
D	4.00	1	0.250	76.00
E	5.00	2	0.400	95.00

The calculations were based on the traditional LOB methodology, where no learning is present. According to the presented methodology, the duration between the first and last unit has to be fixed. Because of this, the total duration of the activities was increased. The objective function, decision variables, and project constraints of the resource allocation model are presented below:

```
MODEL:
MIN = 80;

! PRECEDENCE CONSTRAINTS;
STC20 - STB20 >= 8;    STC1 - STB1 >= 8;
STD20 - STC20 >= 7;    STD1 - STC1 >= 7;
STE20 - STD20 >= 8;    STE1 - STD1 >= 8;

! CREW SYNCHRONIZATION CONSTRAINTS;
STB20 * CB - STB1 * CB = 133;
STC20 * CC - STC1 * CC = 95;
STD20 * CD - STD1 * CD = 76;
STE20 * CE - STE1 * CE = 95;
```

```
! CREW AVAILABILITY ;
CB <= 20;   @GIN(CB);
CC <= 20;   @GIN(CC);
CD <= 20;   @GIN(CD);
CF <= 20;    @GIN(CE);
CE <= 20;    @GIN(CF);
STE20 <= 75;
END
```

The baseline for the remaining activities was considered to start from 0. According to the obtained results, the real start times were estimated, and the optimized LOB schedule was drawn. The obtained report from LINGO optimization tool was presented in Figure 4.6.

The Lingo software works as follows: initially, it gives an “undetermined” state because the solver has not started to generate a solution. After it starts to solve the problem, the solver gives an “infeasible,” where no solution for the problem is found; and “feasible,” when a solution for the model is found. The solutions can be categorized as “global” and “local” optimum. If the model contains non-linear constraint than the model has a “global optimum” solution, otherwise the local solution is also the global solution too. In non-linear models, the local search mechanism can find an excellent local solution; however, the found solution is not the global solution for the problem set.

Table 4.3. Start and Finish Times from Resource Allocation Model

Activity	1^{st} Unit Start	1^{st} Unit End	20^{th} Unit Start	20^{th} Unit End	Max Team
A	0.00	18.0	203.00	211.0	1
B	180.7	187.7	225.0	232.0	3
C	188.7	193.7	236.2	241.2	2
D	205.2	209.2	244.2	248.2	2
E	219.5	224.5	251.2	256.2	3

```
Local optimal solution found.
Objective value:                              80.00000
Objective bound:                              80.00000
Infeasibilities:                             0.6868116E-04
Extended solver steps:                               5
Total solver iterations:                            72
Elapsed runtime seconds:                          0.06

Model Class:                                      MIQP

Total variables:                     13
Nonlinear variables:                 12
Integer variables:                    5

Total constraints:                   17
Nonlinear constraints:                4

Total nonzeros:                      30
Nonlinear nonzeros:                   8


                              Variable           Value        Reduced Cost
                                 STC20        55.49997            0.000000
                                 STB20        44.33333            0.000000
                                  STC1        8.000000            0.000000
                                  STB1        0.000000            0.000000
                                 STD20        62.49997            0.000000
                                  STD1        24.49997            0.000000
                                 STE20        70.49997            0.000000
                                  STE1        38.83330            0.000000
                                    CB        3.000000            0.000000
                                    CC        2.000000            0.000000
                                    CD        2.000000            0.000000
                                    CE        3.000000            0.000000
                                    CF        0.000000            0.000000

                                   Row    Slack or Surplus      Dual Price
                                     1        80.00000           -1.000000
                                     2        3.166632            0.000000
                                     3        0.000000            0.000000
                                     4        0.000000            0.000000
                                     5        9.499966            0.000000
                                     6        0.000000            0.000000
                                     7        6.333333            0.000000
                                     8        0.000000            0.000000
                                     9      -0.6868116E-04        0.000000
                                    10        0.000000            0.000000
                                    11        0.000000            0.000000
                                    12        17.00000            0.000000
                                    13        18.00000            0.000000
                                    14        18.00000            0.000000
                                    15        20.00000            0.000000
                                    16        17.00000            0.000000
                                    17        4.500034            0.000000
```

Figure 4.6. Lingo (2000) Resource Allocation Model Solution Report

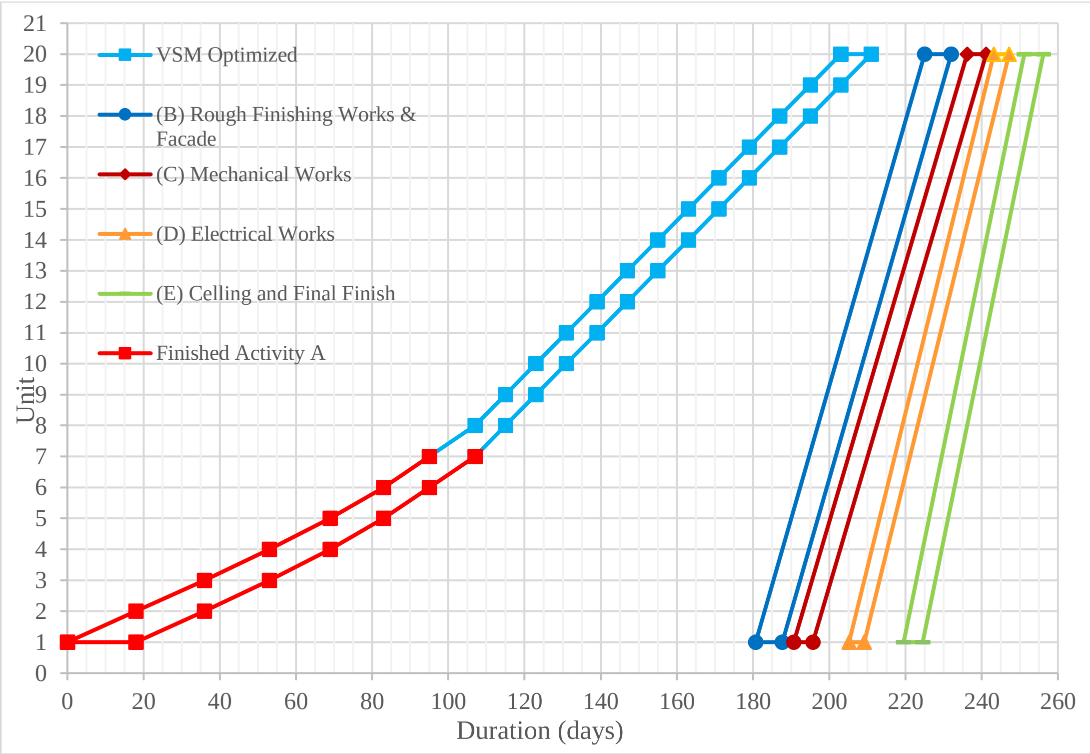


Figure 4.7. LOB Schedule (Resource Allocation Model)

The formulated problem was classified as MIQP (Mixed-Integer Quadratic Program). In the MIQP model class, the variables are linear or quadratic, and some of the variables have integer restrictions. The final optimized duration was estimated to be 256.2 days. The estimated start and end times for the first and last activities and maximum required team numbers were presented in Table 4.3., and the optimized project schedule was presented in Figure 4.7.

CHAPTER 5

DISCUSSION OF RESULTS

The results suggest that the proposed model in this thesis can be used in assisting project occupants in managing project with repeating nature scheduled by LOB technique. It was observed that LOB was a suited, efficient, and effective scheduling tool for scheduling a typical repeating project. Also, it provides better graphical representation, and it is more suited for monitoring the activities. On the other hand, the accuracy of LOB technique on estimating the activity duration at different units and the total project duration depend on the input data. The precision of the person-hour is essential because any wrong estimation can lead to inaccurate project duration.

The learning effect is applied to achieve a better person-hour requirement forecast. It is widely recognized late in repeating projects. Several learning models for estimating the person-hour were presented. In this study, the Straight-Line Power Model was applied, and the learning rate was taken to be 90% for all activities as can be seen in Figure 4.1. and Table 5.1., where the LOB schedule for the base case and its calculations were presented, respectively, the learning effect reduces the unit duration of each activity. The learning effect improves the actual production rate, so the number of workers in the teams decreases. This phenomenon continues until a certain point (unit) where a specific number of teams can be dismissed. In the case of activity B, this happened at the 5th unit where after only one team continues the work. The actual production rate becomes close to the target production rate, and it continues to increase as the project proceeds. Also, this phenomenon can be explained with the theoretical and optimum crew size. At each activity, the theoretical crew size is calculated. If the theoretical crew size is higher than the optimum one, the actual team size becomes a multiple of the optimum team size. As the actual production rate improves, after each completed unit, the theoretical team size is reduced. After a particular unit, the theoretical team size becomes less than the optimum one. It can be seen in Figure 4.1 that the slope of activity B changes after the seventh unit. In the other activities, no breakpoint is present because the estimated theoretical team size is close ore less than the optimum team size; therefore, the actual team size is taken the same as the optimum one.

It is recommended to take special care on the level of details in the LOB technique. If too many activities are considered, the diagrams in the LOB schedule become chaos of oblique lines. Using different line types and colors help in following the activities process. Another issue that needs special care is to overlap the activities that have similar production rate or the events that are connected. In this case, it is the Reinforced Concrete activity which is consisted of several sub-activities.

Last but not least, the lines of the activities cannot overlap other activities. The buffer check is done for each activity to overcome this problem. Which helped to respect the activities buffer times at each unit.

In this study, the application of the lean tool, VSM, to a traditional construction site in Turkey was presented. In this thesis, the implementation of the design of VSM is used to a Reinforced Concrete Works. The obtained results were then combined in the LOB schedule. The main focus was given on locating the non-value-adding activities, eliminating waste, increasing efficiency in the workflow, and reducing total delivery time of a unit.

The site observation and monitoring helped in estimating the VSM parameters (value-adding, non-value adding, cycle time, takt time) which were essential in creating the current state and help to provide a reliable future state map. In different researches, different types of VSM parameters were presented. The type of parameters used depends on the data collected from the site and the objective of the research.

The VSM helps in constructing the workflow and the flow of information and materials as it is in the real construction site. The flow charts used in the mapping process are very straightforward, easy to use, and understandable for all project occupants. After the implication of VSM in the project, waste is located in rebar installation activity. A total of 3% of waste can be decreased if the rebar is used more efficiently. The formwork installation technique is out of date so, a new method, which can reduce the cycle time of the activity to 8 days, was proposed. The implication of the proposed new method will affect the rebar installation process too. The inefficient work of the quality control staff provided further delays. Since, before any approval, no further work can be continued.

Last but not least, one of the major problems was the concrete supplier. The late-arriving of the delivery and slow supply increased the delivery time of each unit. The presented future state proposed a faster delivery and more efficiency in the site. After updating the results from the future state to the LOB schedule, the activity delay duration decreased for a total of 27.5 days. These results prove that VSM is a robust construction lean tool, that helps to analyze the construction activities and helps to improve them. The LOB-VSM integrated model contributes to optimizing the project duration, reducing waste, and reduce the delivery time of the project.

In the last part of this thesis, a resource optimization model is presented. According to the model's objective function, optimal resource usage is provided. Since a deadline problem was present, in this study the resource allocation model was used. For all optimized activities, it is considered that the required amount of the resources can be afforded at the amount that was optimized by the software. The optimization of the project is modeled according to the traditional LOB calculations, where only the first and the last activities were considered as constraints and later drafted. After the model was run, the project duration was satisfying and optimized at the maximum rate. The total number of used teams is 11.

Since the traditional LOB is used, the duration of the project compared to the actual case schedule was varying. The duration of the total project duration in the traditional schedule was longer than when learning was considered. It is noted that the LOB with the learning effect could be used to optimize the project schedule. When the target production rate for the last activity (activity-E) was increased, a new team can be assigned to the activity, and the project will finish at the desired duration. The total team number used was 7, which is less than the number of teams obtained by the resource allocation model. The proposed LOB methodology with the learning effect provides a better and more efficient resource-leveling and resource usage than resource leveling and resource allocation models.

CHAPTER 6

CONCLUSION

The project schedule and resource management are the two most important factors that affect the success of the project. When occurred, delays can affect the projects budget and quality too. Sometimes delays are unavoidable; however, the impact and its duration can be minimized by optimizing the project activities and the resources. In this study, a model to optimize the project duration scheduled with LOB technique using Value Stream Mapping was presented. A base schedule was prepared for the case study project. After, according to the site reports the project was updated. Two methods for optimizing the emerged delay were presented. The first one was, the lean construction tool, Value Stream Mapping, and the second one was a resource optimization technique.

The major findings of the study:

- The implication of the learning effect helps in achieving a better person-hour estimation. After the targeted production rate is satisfied, some teams can be dismissed, as it is presented in Figure 4.1. and Figure 4.2. in activity B.
- As a visualization tool, VSM helped in providing a clear workflow of the construction operations. The method also helped in finding and locating the non-value-adding activities in the following operations:
    - The rebar material usage waste was decreased to 3%,
    - Inefficient work of quality control, and
    - Inefficient work of concrete supply
- A future state of the process was presented, and the total unit delivery time was reduced to 8 days.

- The schedule is updated according to the VSM future state, and a total delay of 27.5 days was optimized.
- The resource optimization model (resource allocation) was used to optimize the rest of the project. The output of the optimization model suggested that the number of teams should be increased for all activities. A delay of 7 days was optimized with the cost of hiring extra five teams.

This thesis developed a better understanding of both techniques LOB and VSM and showed how the VSM could be applied to LOB. It was observed that the research regarding LOB scheduling problems and VSM optimization tool, addressed the problem by creating models and applying them to the pipeline project (Arditi et al., 2002b; Yang and Ioannou, 2004; Senourci and Al-Derham, 2008; Damci et al., 2013; Damci et al., 2016; Zhang et al., 2017; Gouda et al., 2017; Ammar and Abdel-Mageb, 2018, Ammar, 2019). Pipeline projects are very common because several units can be worked at the same time, also in this type of project, there is no physical constraint present. However, in projects with physical constraints, the desired output may not be achieved. In this thesis, the proposed methodology is applied to a real-life high-rise building project. The presented VSM methodology is applied for waste elimination, reducing non-value adding activities, and delivery time optimization. VSM provides excellent visualization for all processes in one map. This helps in locating the waste, finding the inefficient processes, and in decision making.

The realization of the project also depends on resource management. Improper resource management can cause wrong scheduling and planning, which can lead to project delays and cost overruns. A resource allocation model formulated by Ammar (2019) is applied to the high rise project. The proposed model is easy to apply and provides optimal solutions. The optimized schedule is updated to the LOB schedule.

Limitations of the study:

- First, only five major groups of activities are considered in the project schedule. More activities have an impact on the project.

- The learning effect is considered to be 90% for all activities; however, not all activities have the same learning ratios.
- VSM methodology in this study could be applied only in the first activity since the other activities have not started yet. Better integration of LOB and VSM methods could be when both techniques can deal with and/or measure the same activities.
- No implication plan for the VSM future state is given.
- The resource optimization model is limited to the traditional methodology, where no learning effect is considered. Also, the model can handle only projects that have similar activity duration for all units.
- The model can handle only one last unit start time constraint. If more than one constraint is given only one of them is respected.
- The study presents a resource-duration optimization where no cost implication was considered. For all optimized activities, it is considered that the required amount of the resources can be afforded (are available) at the amount that was optimized by the software in the construction site.

Further research can be done in implicating a cost-based VSM and LOB framework. Providing a methodology where both LOB schedule and VSM work simultaneously. Since both tools LOB and VSM have points in common like providing the continuous workflow, visual tools, etc., combining them enables using all features at once. As future research, the future state of VSM can be created using different scenarios with probability features using Monte Carlo simulation.

Regarding the resource optimization model, the model it can be extended to schedules considering the learning effect, where the different duration can be assigned to each unit at the same activity, and different team configurations can be made.

Using VSM and LOB methods provides a continuous flow of information, resources, and materials as well as visualized work, easy monitoring, more efficient construction site, and faster project delivery. The methods can help the user (owner, academics) in optimizing the project duration and in decision making for a better and sustainable future.

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APPENDICES

A. Normal Probability Distribution Table

Z	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
0.0	.5000	.5040	.5080	.5120	.5160	.5199	.5239	.5279	.5319	.5359	4	8	12	16	20	24	28	32	36
0.1	.5398	.5438	.5478	.5517	.5557	.5596	.5636	.5675	.5714	.5753	4	8	12	16	20	24	28	32	35
0.2	.5793	.5832	.5871	.5910	.5948	.5987	.6026	.6064	.6103	.6141	4	8	12	15	19	23	27	31	35
0.3	.6179	.6217	.6255	.6293	.6331	.6368	.6406	.6443	.6480	.6517	4	8	11	15	19	23	26	30	34
0.4	.6554	.6591	.6628	.6664	.6700	.6736	.6772	.6808	.6844	.6879	4	7	11	14	18	22	25	29	32
0.5	.6915	.6950	.6985	.7019	.7054	.7088	.7123	.7157	.7190	.7224	3	7	10	14	17	21	24	27	31
0.6	.7257	.7291	.7324	.7357	.7389	.7422	.7454	.7486	.7517	.7549	3	6	10	13	16	19	23	26	29
0.7	.7580	.7611	.7642	.7673	.7704	.7734	.7764	.7793	.7823	.7852	3	6	9	12	15	18	21	24	27
0.8	.7881	.7910	.7939	.7967	.7995	.8023	.8051	.8078	.8106	.8133	3	6	8	11	14	17	19	22	25
0.9	.8159	.8186	.8212	.8238	.8264	.8289	.8315	.8340	.8365	.8389	3	5	8	10	13	15	18	20	23
1.0	.8413	.8438	.8461	.8485	.8508	.8531	.8554	.8577	.8599	.8621	2	5	7	9	12	14	16	18	21
1.1	.8643	.8665	.8686	.8708	.8729	.8749	.8770	.8790	.8810	.8830	2	4	6	8	10	12	14	16	19
1.2	.8849	.8869	.8888	.8907	.8925	.8944	.8962	.8980	.8997	.9015	2	4	6	7	9	11	13	15	16
1.3	.9032	.9049	.9066	.9082	.9099	.9115	.9131	.9147	.9162	.9177	2	3	5	6	8	10	11	13	14
1.4	.9192	.9207	.9222	.9236	.9251	.9265	.9279	.9292	.9306	.9319	1	3	4	6	7	8	10	11	13
1.5	.9332	.9345	.9357	.9370	.9382	.9394	.9406	.9418	.9429	.9441	1	2	4	5	6	7	8	10	11
1.6	.9452	.9463	.9474	.9484	.9495	.9505	.9515	.9525	.9535	.9545	1	2	3	4	5	6	7	8	9
1.7	.9554	.9564	.9573	.9582	.9591	.9599	.9608	.9616	.9625	.9633	1	2	3	3	4	5	6	7	8
1.8	.9641	.9649	.9656	.9664	.9671	.9678	.9686	.9693	.9699	.9706	1	1	2	3	4	4	5	6	6
1.9	.9713	.9719	.9726	.9732	.9738	.9744	.9750	.9756	.9761	.9767	1	1	2	2	3	4	4	5	5
2.0	.9772	.9778	.9783	.9788	.9793	.9798	.9803	.9808	.9812	.9817	0	1	1	2	2	3	3	4	4
2.1	.9821	.9826	.9830	.9834	.9838	.9842	.9846	.9850	.9854	.9857	0	1	1	2	2	2	3	3	4
2.2	.9861	.9864	.9868	.9871	.9875	.9878	.9881	.9884	.9887	.9890	0	1	1	1	2	2	2	3	3
2.3	.9893	.9896	.9898	.9901	.9904	.9906	.9909	.9911	.9913	.9916	0	1	1	1	1	2	2	2	2
2.4	.9918	.9920	.9922	.9925	.9927	.9929	.9931	.9932	.9934	.9936	0	0	1	1	1	1	1	2	2
2.5	.9938	.9940	.9941	.9943	.9945	.9946	.9948	.9949	.9951	.9952	0	0	0	1	1	1	1	1	1
2.6	.9953	.9955	.9956	.9957	.9959	.9960	.9961	.9962	.9963	.9964		0	0	0	1	1	1	1	1
2.7	.9965	.9966	.9967	.9968	.9969	.9970	.9971	.9972	.9973	.9974	0	0	0	0	0	1	1	1	1
2.8	.9974	.9975	.9976	.9977	.9977	.9978	.9979	.9979	.9980	.9981	0	0	0	0	0	0	0	1	1
2.9	.9981	.9982	.9982	.9983	.9984	.9984	.9985	.9985	.9986	.9986	0	0	0	0	0	0	0	0	0
3.0	.9986	.9987	.9987	.9988	.9988	.9989	.9989	.9989	.9990	.9990	0	0	0	0	0	0	0	0	0
3.1	.9990	.9991	.9991	.9991	.9992	.9992	.9992	.9992	.9993	.9993	0	0	0	0	0	0	0	0	0
3.2	.9993	.9993	.9994	.9994	.9994	.9994	.9994	.9995	.9995	.9995	0	0	0	0	0	0	0	0	0
3.3	.9995	.9995	.9996	.9996	.9996	.9996	.9996	.9996	.9996	.9997	0	0	0	0	0	0	0	0	0
3.4	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9998	0	0	0	0	0	0	0	0	0
3.5	.9998	.9998	.9998	.9998	.9998	.9998	.9998	.9998	.9998	.9998	0	0	0	0	0	0	0	0	0
3.6	.9998	.9998	.9999	.9999	.9999	.9999	.9999	.9999	.9999	.9999	0	0	0	0	0	0	0	0	0
3.7	.9999	.9999	.9999	.9999	.9999	.9999	.9999	.9999	.9999	.9999	0	0	0	0	0	0	0	0	0
3.8	.9999	.9999	.9999	.9999	.9999	.9999	.9999	.9999	.9999	1.000	0	0	0	0	0	0	0	0	0
3.9	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0	0	0	0	0	0	0	0	0