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ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL & ENVIRONMENTAL ENGINEERING

ENHANCING LABOR PRODUCTIVITY OF SELECTED BUILDING CONSTRUCTION OPERATIONS USING VALUE STREAM MAPPING INTEGRATED WITH DISCRETE EVENT SIMULATION

By

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A Thesis Submitted to The School of Graduate Studies of Addis Ababa Institute of Technology in Partial Fulfillment of The Requirements for The Master of Science Degree in Civil Engineering in Construction Technology and Management

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DECLARATION

I certify that this research work titled "*Enhancing Labor Productivity of Selected Building Construction Operations Using Value Stream Mapping Integrated with Discrete Event Simulation*" is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources, it has been properly acknowledged/referred.

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ABSTRACT

As a consequence of traditional managerial concepts, construction is characterized by a high share of non-value-adding activities (NVAA) and resultant low productivity. Labor productivity growth in the construction industry has averaged only 1% per year in the past 20 to 30 years. Likewise, the labor productivity of the Ethiopian construction industry is at the lowest level. This research offsets with the objective of measuring the level of NVAA and identifying their root causes using value stream mapping (VSM). Then it strives to enhance labor productivity by the application of lean concepts and principles using VSM integrated with discrete event simulation (DES).

Two case studies', slab rebar and HCB operations, were selected and data were collected by observing the elapsed time of each sub-process and interviewing the manpower involved in the project. The developed VSM were used to analyze and measure the NVAA in the operations and propose the relevant lean concepts and principles. Subsequently, it was used to produce DES models in a detailed manner for the current state maps and exploration of different optimization scenarios.

The research outcome has revealed that 99.96 % and 99.7% of the slab rebar and HCB operations are constituted by NVAA, respectively. Moreover, from the current state VSM, the existence of a vicious circle of wastes has been witnessed and root causes related to the perspective of material and methods comprised the huge share. Workplace organization/ standardization (WOS), production scheduling (PS), and optimization of labor resources were found to be the most pertinent principles for both operations. The assessment of the scenarios using DES showed that labor productivity could be enhanced by 36.3 % and 34.6% for slab rebar and HCB operations, respectively. Correspondingly, the lead time improved by 95.9% and 49% for slab rebar and HCB operations. Finally, this research principally recommends project participants to give due attention to the flow dimension of construction and to identify and eliminate NVAA using VSM. Moreover, to adopt WOS, PS, and optimization of labor resources principles to enhance labor productivity and to integrate DES to comprehend the efficacy of the applied concepts and principles.

Keywords: labor productivity, value stream mapping, lean concepts and principles, discrete event simulation, Simphony CYCLONE

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ABBREVIATIONS

CPM	Critical Path Method
CS	Current State
CSM	Current State Mapping/Map
CT	Cycle Time
DES	Discrete Event Simulation
FS	Future State
FSM	Future State Mapping/Map
GDP	Growth Domestic Product
JIT	Just-In-Time
LPS	Last Planner System
LT	Lead Time
MGI	McKinsey Global Institute
NVAA	Non-Value-Adding Activities
PDAC	Plan-Do-Act-Check
PS	Production Scheduling
TPS	Toyota Production System
TQM	Total Quality Management
VAA	Value-Adding Activities
VSM	Value Stream Mapping
WOS	Workplace Organization and Standardization

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1. INTRODUCTION

Construction industry is one of the largest industries which support the economy of a country. It has a major strategic importance and its level of productivity has a significant effect on national economic growth. According to International Monetary Fund (2017), Ethiopia with a rapidly growing GDP, the percentage contribution of the industry has increased from 3.8 percent in the 2008/09 to 7.9 percent in 2014/15. This increase is due to the significant rise in both private and government expenditures in the industry. In a broader setting, construction has a major influence on many other industries. Thus, reducing waste in construction and enhancing productivity can go a long way in helping the economy of the country.

1.1. Background Study

Notwithstanding its salient role, the construction industry of Ethiopia like other construction industries in developing countries is facing numerous challenges in performing and implementing projects. The performance of the industry is characterized as poor in complying with project requirements such as cost, time and quality (Robinson, Carrillo, Al-Ghassani, & Anumba, 2002). A recent study by Zewdu (2016) indicated that the existence of mismanagement is one of the main causes for the delay of construction projects. Also, Yimam (2011) addressed that the construction project management (PM) process and practice maturity of the contractors was proved to be at a lower level. The study showed on average that the contractors PM process maturity is at a non-formal level and their PM practice maturity is at a low level. In contrast to developed countries, the construction project management in Ethiopia is traditional (Alemu, 2006). In accord, Forsberg and Saukkoriipi (2007); Howell (1999); Koskela (1992) as result of traditional managerial concepts, construction is characterized by a high share of wasteful activities and resultant poor productivity.

There has been an increasing focus on the application of lean principles on construction since the 1990s (Ballard & Howell, 1994). It has been researched that how lean principles complement to construction industries for various stages and different types of constructions. The contribution of the new production philosophy in terms of productivity, quality and other indicators have been witnessed in practice to ensure a rapid diffusion of the new principles (Koskela, 1992). Lean construction has three main focuses that distinguish it from traditional construction management. The primary focus is on waste and its reduction; the second focus is on productivity and how it can be enhanced to its full potential by managing flows; the third one is maximizing value (Ballard & Howell, 1994).

Lean construction categorizes production activities as either a value-adding or non-value-adding (NVAA) activity (Koskela, 2000). The existence of significant number of wastes in the construction has depleted the overall productivity of the industry and serious measures have to be taken to remedy the current situation. While innovations in manufacturing have propelled the sector to new productivity heights, construction has been unable to keep up its most productive state (MGI, 2017). Specifically, the reduction of non-value-adding activities has been identified by Koskela (1992) as a fundamental driver for enhanced productivity.

There are various lean tools which can be used to improve construction process and its performance. Value stream mapping (VSM) is one those tools that are being used. It is an iterative method used to map and analyze value streams, and its objective is to evaluate and communicate the production process aspects such as material and information flows (Lasa et al., 2008, as cited in Aziz, Qasim, & Wajdi, 2017). Integrating simulation with VSM has been found to be an ideal way to get exhaustive output of lean improvement in a complex and dynamic environment (Aziz et al.). Thanh (2017) simulation is one of the powerful techniques for supporting the decision-making process for construction management by examining the feasibility and capability of improvement opportunities. As amplified by him, simulation model aid in analyzing causes for the reduction of productivity during construction operations. One of the most common simulation used to model construction process is discrete event simulation (DES). DES has been proven as an effective technique in predicting and evaluating the behaviors of systems (Banks, Carson, Nelson, & Nicol, 2010). To articulate, these issues associated with management should be apprehended. And endeavors towards developing solutions by adopting advanced concepts, principles and decision-making tools is necessary.

1.2. Statement of the Problem

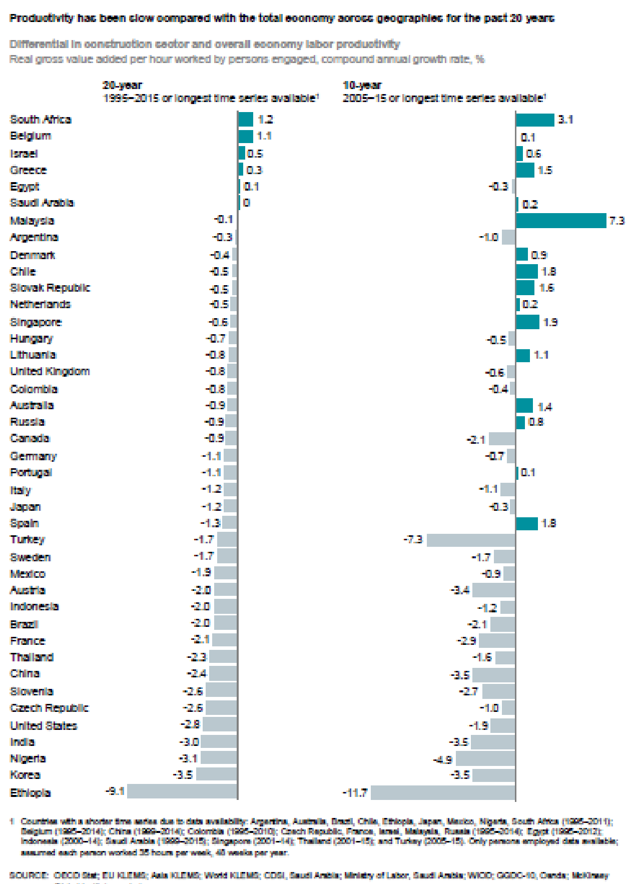
Like other countries, the construction industry in Ethiopia has a significant role in the development of other industries. Accordingly, the improvement of the growth of the construction industry contributes for the growth of many other sectors. Improvement of construction labor productivity is therefore critical. Researches show that the construction project management in Ethiopia is at a lower level. In line with this, as it was confirmed in various studies, the performance of most construction projects was not satisfying. McKinsey Global Institute [MGI] (2017) over the past 20 years, worldwide labor-productivity growth in the construction industry has averaged only 1 percent a year, compared to a rate of 2.8 percent in the case of the total economy and 3.6 percent in manufacturing. Similarly, Koskenvesa, Koskela, Tolonen, and Sahlstedt (2010) labor productivity has only improved from the mid 70´s approximately by 1 % per year: and it has been the industry's great concern (Zhao & Chua, 2003). Correspondingly, productivity in the Ethiopian construction industry is an evident issue that needs to be addressed. As illustrated by several indicators, not only productivity is low by international standards, it is also declining. According to the study conducted by Chia, Skitmore, Runeson, and Bridge (2010) Ethiopian construction labor productivity ranks 77th among the 79 selected economies. Also, an assessment on 25 countries including Ethiopia in this regard showed that only 25 % of construction firms matched the productivity growth achieved by the overall economies of their respective countries and indicated that the construction sector has been continued to be a drag on overall productivity (MGI, 2017). Corroborating their case, Alemu (2006); Amanuel (2016) unveiled the inexistence of measuring performances and it is immensely affected by poor labor productivity. As a construction is a labor-intensive industry, where labor costs account for between 30 and 50 percent of the total cost of a construction project (MGI, 2017; Patel & Vyas, 2011, as cited in Abou Dargham, Assaf, Faour and Hamzeh, 2019), the low labor productivity of the construction industry is an important issue.

The manufacturing industry has dramatically improved productivity through the adoption of a new production philosophy which has led to the lean production system (Koskela, 1992; MGI, 2017). In construction, this new philosophy is little known, especially in Ethiopia, it is even unheard-of by most construction professionals. However, the construction process consists of countless activities that add no value to the product, which are called wastes (Sahlu, 2017; Ayalew, Dakhli,

& Lafhaj, 2018). The construction industry must improve its productivity by integrating modern advances to deal with the growing demand (Koladiya, 2017). Specifically, Koskela (1992) the reduction of non-value-adding activities has been identified as a fundamental driver for enhanced productivity. Accordingly, lean construction is one of those innovations developed to reduce the antecedent of lower productivity, inspired from lean production success (Ballard & Howell, 1994). In the main, a very high level of waste exists in construction. Eliminating or reducing waste could yield great cost savings to society by enhancing the labor productivity of projects. Consequently, this thesis aims in identifying these wastes and enhancing labor productivity by the adoption of lean construction concepts and principles using VSM integrated with DES.

Figure 1

Differential in Construction Sector and Overall Economy Labor Productivity[1]



[1] (MGI, 2017, p.24)

1.3. Objective of the Study

1.3.1. General Objectives

The general objective of the research is to enhance the labor productivity of selected building construction operations by the application of lean concepts and principles using lean tool, value stream mapping, integrated with discrete event simulation.

1.3.2. Specific Objectives

1. To determine the share of wastes or non-value-adding activities in the selected building construction operations:
2. To identify the root causes of non-value-adding activities.
3. To measure the improvement in labor productivity by the application of lean concepts and principles using VSM integrated with DES.

1.4. Research Question

This thesis will answer the following questions derived from the objectives

1. What are VAA and NVAA (waste) activities?
2. Why do these wastes exist (root causes for waste)?
3. How are these wastes could be identified by using value stream mapping?
4. How can construction wastes affect labor productivity?
5. Which lean concepts and principles are antidotes for these wastes?
6. How would the integration of VSM and DES aid in improving construction labor productivity?

1.5. Significance of the Study

Manufacturing industry have impelled the sector to new productivity level by adopting lean production, although construction has been unable to keep up its most productive state. The aim of lean construction is maximizing performance for the customer; designs concurrently product and process; and employs production control throughout the life of project (Howell, 1999). Koskela (1992) lean construction is aimed at improving construction performance by eliminating wastes that do not add value to the customer. Through the application of lean construction, the NVAA or waste elements will be identified so that if these could be strategically eliminated, project performance will be improved .Thus, efforts should be made to identify wastes in Ethiopian construction projects and in determining its root causes, which have prompted poor labor productivity from the perspective of flow related issues. This is indispensable since the management of the industry is at a low level and projects are overwhelmed by delay.

The fundamental reasons to study about waste and productivity are the same, which is to get more information about the current state so that improvements can be achieved. Therefore, considering the levels of waste and productivity can be both useful, as the construction industry has been criticized for its low labor productivity (Alemu 2006; Amanuel, 2016) and high level of waste (Sahlu, 2017; Ayalew et al., 2018). Construction companies can significantly abate construction cost and amplify their profit by eliminating construction wastes. As contractors are one of the key players in the industry and the makers of the final product, any development and improvement initiatives in the industry must consider ways of improving the capacity and capability of the contractors (Yimam, 2011). Adopting lean technology provides a significant competitive advantage for the participants (Ballard & Howell, 1994). Implementing lean construction will be able to assist the industry to move away from the traditional construction method of doing things, propel the industry towards a more synergistic and sustainable future (Ballard & Howell). Eliminating waste in both material and time would improve project performance, namely enhancing value for individual customers, and would also have a positive impact on the national economy (Polat and Ballard, 2004).

1.6. Research Scope and Limitations

Construction productivity is a complex problem. Almost all the factors involved in a project will take effect on the productivity performance. As construction is a labor-intensive industry, this paper focuses on labor productivity in the construction industry. This study considers the current issues relevant to this subject and have the limitations listed hereafter.

1. Accordingly, this research focus on the loss of the productivity by non- values adding activities' occurring on the site. The non-value-adding activities are the product of the work conditions, which could be traced to project related factors.

2. This research will only focus on building project and specifically in the proposed production stages of building construction.
3. The research doesn't include analyzing all the production steps in building construction, but only the selected production steps based on criterion the researcher identified.
4. The research doesn't include works that precede and succeed the proposed production stages, which might affect the performance of the project.
5. The research doesn't include implementation plan and improvement in the cost of operation.

1.7. Research Organization

- This chapter - Introduction: it represented the initial background of the subject, from the performance of the construction industry, lean production and its adoption by construction industry to VSM, and its integration with DES for improving construction labor productivity. Then, the problem statement; general objective and three specific objectives to be achieved; six research questions to be answered; significance of the study for the construction industry and its stakeholder; and scope and limitation of the research are discussed meticulously.

- Chapter two - Literature reviews: it discusses the theoretical background of lean philosophy and its origin from TPS, and lean construction evolvement. Then, it will introduce various types of lean principles and tools; NVAA and their root causes; simulation, its types and role in construction, and its integration with VSM.

- Chapter three - Research methods: the research strategies, purpose and approach that are adopted for the study and its pertinence to the research problem is discussed. It will highlight the relevancy of adopting VSM and DES, and criterion are presented for the selection of the production stages. It will present a framework adapted for VSM & DES, and discuss each step accordingly.

- Chapter four - Current state map: in this chapter the current state map and analysis of each case studies is presented. Moreover, the current state maps of each operations are presented.

- Chapter five - Future state map: the future state map that would improve operations' labor productivity based on the adopted principles is presented. Furthermore, the applied lean concepts and principles significances are summarized and presented in a table format.

- Chapter six - Modelling and simulation: the Simphony CYCLONE models constructed based on the current state maps, the input modelling, verification and validations, and the output analysis is discussed in a detailed manner. Finally, the scenarios modelled by the application of lean concepts and principles and comparison with current state model are presented.

- Chapter seven – Conclusion and recommendations: finally, three conclusions are presented based on the research outcome, and five possible courses of actions and three research areas are recommended.

2. LITERATURE REVIEW

2.1. Introduction

Major construction industry review reports and recent initiatives have identified lack of performance improvement as a key issue in the industry (Robinson et al., 2002). The concept of lean construction has been witnessed as a useful means of performance improvement by improving productivity, workflow reliability, planning and control, particularly in developed countries (Koskela, 1992). Lean technology reduces all forms of NVAA and improves project performance, which provides a significant competitive advantage for the participants (Ballard & Howell, 1994). In the past two decades, great performance improvements have been obtained in the manufacturing industry by means of increasing productivity (MGI, 2017). As stated, the major factor in this achievement was the implementation of the new production philosophy called, lean production, which provides a continuous improvement in the production process by removing various types of waste.

While manufacturing attained great results, the construction industry still encounters severe problems resulting from huge amounts of waste (NVAA) (Senaratne and Wijesiri, 2008). Waste in a construction is a problem not only for the construction industry, but also influences the state of the overall economy of the country, as it has a major impact on many other industries by both purchasing the inputs from other industries and providing products to other industries. Performance enhancement opportunities can be addressed by adopting waste identification and waste reduction strategies parallel to value adding strategies (Alarcón, 1995). Waste measurement is important since it is an effective way of assessing performance and allows areas of potential improvement to be pointed out (Formoso, Isatto, & Hirota, 1999). However, the greatest obstacle to wastes removal in general is a failure to recognize it. This is prevalent in the construction industry because it is not well understood by construction personnel. Ayalew et al. (2016) have identified that lack of knowledge, lack of industry support, lack of sufficient support among project teams, employee's resistance and lack of standards as the most influential barriers that will hinder the implementation of lean construction in Ethiopian construction industry. Bolstering his case Sahlu (2017) indicated that most project managers in case studies conducted, understand construction wastes in physical terms.

2.2. Lean Production

The ideas of the new production philosophy first arose in Japan in the 1950's and the most prominent application was the Toyota Production System (TPS) (Koskela, 1992). The fundamental idea in the TPS was the elimination of inventories and other waste through small lot production, reduced set-up times, semiautonomous machines, collaboration with suppliers, and other techniques (Monden, 1983; Ohno, 1988; Shingo, 1984; Shingo, 1988, as cited in Koskela). It was developed by Toyota led engineer Taiichi Ohno (Howell, 1999). Later the term “lean” was formed by researchers working on international auto production to ponder both the waste reduction nature of the TPS and to contrast it with mass production (Womack et al., 1991, as cited in Howell, 1999). Lean principles were developed to make a paradigm shift in the way the company was managed (Howell). The principle was considered to be an innovation that transforms the company into practical problem-solving way of management (Koskela). In the subsequent years, the principle was adopted by the manufacturing industry and a significant increase in productivity and product quality were recorded. Japanese companies have doubled factory productivity rates by practicing lean principles for over a period of five-years (Stalk & Hout, 1989, as cited in Koskela).

Lean theory is a flow process of material and information, which are controlled for minimal variation in a cycle time, enhancing continuously regarding waste and value and periodically for efficiency by implementing new technologies (Plossl, 1991, as cited in Koskela, 1992). Lean is a philosophy that requires a continuous improvement effort which is focused on a value stream (Koskela, 1992). Hence, it is indispensable to pay attention to the stream and challenge each step whether it is necessary or not, to identify the product’s value chain. Lean production is based on value generation, which is gained by reducing NVAA in manufacturing process. The whole production system is managed in such a way that it gives a value to end user and its fundamental idea is producing only what the client perceives as “value” (Womack, 1999, as cited in Pasqualini & Zawislak, 2005). Koskela (1992) lean philosophy essence is that there are two kinds of phenomena in all production systems, which are called conversions and flows. While every activity expend cost and consume time, only conversion activities add value. Thus, the improvement of flow activities should primarily be focused on reducing or eliminating them, whereas conversion activities should be made more efficient.

Liker (2004, as cited in Kolidaya, 2016) TPS system is categorized in four main categories namely: 1) long term philosophy, which includes one principle of long term thinking; 2) the right process will produce the right results, which includes seven principles; 3) add value to the organization by developing your people, which consists of three principles; and 4) continuously solving root problems drives organizational learning, which consists of three principles. However, Womack and Jones (1996, as cited in, Bertelsen & Koskela 2004; Koskela, 2000; Pasqualini and Zawislak 2005; Picchi, 2000) moved from the automotive industry to look at manufacturing in general and established the five principles for lean production. They called this theoretical foundation, “lean thinking”, viz:

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

Bertelsen and Koskela (2004) the principles have also proved to be valuable in increasing productivity in several western manufacturing industries. The three middle principles focus directly on value, whereas the first and the fifth can be seen as general objectives. The principles are thus derived from an ordered situation with a well-known product and customer base, a production process that is precisely defined and a well-established supply chain (Bertelsen and Koskela).

2.3. Lean Construction

Construction is essentially the design and assembly of objects in a fixed place. Consequently, it possesses the characteristics of site production, unique product, and temporary teams (Koskela, 1992). He stated a distinguished characteristic of construction as “one-of-a-kind”, site production, and temporary multiorganization. Also, Bertelsen and Koskela (2004) amplified the nature of construction from a production point of view as, it is a complex production of a one-of-a-kind product undertaken mainly at the delivery point by cooperation within a multi-skilled ad-hoc team. Construction industry has used the traditional “transformation” concept to manage production.

Traditional project management is based on an activity centered approach, which aims to optimize the project activities and define the assignment and objectives of project participants by assuming customer value is already identified in a design phase (Howell, 1999). This concept views production as pure transformation of inputs into outputs. It suggests breaking down the total transformation hierarchically into smaller transformations and reducing the cost of each independently.

Bodkhe, Waghamare, & Patil (2017) lean construction is the term used to define the application of lean thinking principles to the construction environment. The development and incorporation of lean principles in construction is generally tied to Koskela's groundbreaking work on the development of the TFV theory of production. Bodkhe et al. (2017) it is to overcome the failure of traditional construction management delivery methods to achieve time, cost and quality objectives**.** Lean construction is a management philosophy, which is conceptualized in three complementary dimensions: transformation, flow and value (Koskela, 1992). In this approach, T refers to the transformation of materials into a completed facility, F refers to the flow of the material through the construction process and V refers to value generation and creation, which comes primarily through the elimination of loss and waste in the process.

According to Koskela (1992) all activities can be divided into conversions and flows. Conversion activities produce tangible outputs or add value, because they take material, information or other input and transform into a product whilst flow activities bind such conversion activities during the delivery process of the outputs. Although all activities expend cost and consume time, lean construction argues that only conversion activities add value and these should be made more efficient, whereas, non-value-adding flow activities need to be reduced (Koskela). As amplified by Tommelein (1997) flow means a change in location of the entity as is and conversion means a change in state of an entity possibly because of the entity being combined with others, going through a physical or chemical transformation (or being altered in terms of information contents). Koskela (1992) traditional thinking of construction focuses on conversion activities and ignores flow and value considerations.

Koskela, Bølviken, & Rooke (2013) believed that construction is mainly managed based on transformation concept, and principles related to the flow and value generation concepts are largely neglected. Howell (1999) the focus on activities hides the waste generated between continuing activities by the unpredictable release of work and the arrival of needed resources. In accord Koskela (1992) these managerial principles violate principles of flow process design and improvement, and thus lead to non-optimal flows and an expansion of NVAA. CPM, network planning requires the division of tasks into specific activities, which are then arranged into a sequence providing for the shortest duration. An activity is usually a part of the overall workflow of a team or it is a complete workflow in itself. Koskela (1992) when an activity is a part of an overall workflow, it is strongly affected by the preceding activity and CPM networks do not generally model issues. When an activity is a complete workflow (eg. installation of an elevator), the network method just determines the starting time, but does not plan the flow itself. To recapitulate, lean thinking views the entire project in production system terms as a project is one large operation (Ballard & Howell, 1994; Koskela, 1992). Lean thinking focusses on how value is generated instead of how any activity is managed (Ballard & Howell, 1994).

Construction productivity could be improved by understanding it as a production, as it is (Bertelsen, 2004). Consequently, enhancing productivity should direct focus in improving flow and value generation, not in improving transformations, which takes ten percent of total construction cost only (Bertelsen). In accord Koskela (1992) the peculiarities of construction (one-of-a-kind projects, site production, temporary organization) often prevent the attainment of flows as efficient as those in stationary manufacturing. Howell (1999, p.4.) "managing construction under lean is different from typical practice, because it has a clear set of objectives for the delivery process, it is aimed at maximizing performance for the customer at the project level, it designs concurrently the product and its process, and applies production control throughout the life cycle of the project." Accordingly, Koskela et al. (2013) construction is project-based production, which is a form of production where a temporary and one-of-a-kind organization, which produces a one-of-a-kind product and we can see the design-production-use process as a chain where the value is created as a potential in design, is embodied in production and is realized in the intended use by the client. Salem and Zimmer (2005) lean construction is stated as the continuous process of reducing waste, meeting all customer requirements, focusing on the entire value stream and pursuing perfection in the execution of a project. Manufacturing has been a source for innovation in construction. Therefore, it is required to re-develop construction as flow by changing the thinking concepts and perception as construction is a sequential transformation (Bertelsen 2004; Howell, 1999; Koskela, 1992).

2.3.1. Lean Construction Concepts and Principles

Koskela (2000) in his approach to production, says there are three layers, viz: concepts, which answers what is production? principles, which describe the relation between concepts, and methodologies, which embody respective concepts and principles and thus convert theory into practical action. “A principle describes the pathway to transform existing reality through the basic idea set by a concept” (Santos, 1999 as cited in, Skaar, 2019, p.393).The foregoing principles introduced by Womack and Jones (1996, as cited in, Bertelsen and Koskela, 2004; Pasqualini and Zawislak, 2005; Picchi, 2000) are stated for all kinds of manufacturing industries. Despite the increase in productivity in several western manufacturing industries by applying the principles, Bertelsen and Koskela (2004) that don’t not at all prove their usefulness for a special kind of production such as construction, because their use should then be argued by showing that construction is a production similar to manufacturing, which is not. They indicated also that the five principles are not only what was comprehended when studying Japanese sources. Lean approach evaluates existing construction flows, guides to identify potential improvements. Koskela (1992) has presented and elaborated lean construction concepts into principles for a flow process design and improvement for construction industry:

1. **Reduce non-value-adding activities:** Reducing the share of non-value-adding activities is a fundamental guideline. The core principles of lean construction are elimination of NVAA, flow, activities and making conversion activities more efficient.

2. **Increase output value through systematic consideration of customer requirements:** value is generated through fulfilling customer requirements, not as an underlying merit of conversion.

3. **Reduce variability:** there are two reasons for reducing process variability. Primarily, from the customer point of view a uniform product is better and secondly, variability increases the volume of non-value-adding activities.

4. **Reduce the cycle time:** the basic improvement in the new production philosophy is to compress the cycle time.

5. **Simplify by minimizing the number of steps and parts:** simplification can be understood as reducing the number of steps in a material or information flow; as eliminating non-value-adding activities from the production process, and reconfiguring value-adding steps.

6. **Increase output flexibility:** increasing flexibility are modularized product design in connection with an aggressive use of the other principles, especially cycle time compression and transparency.

7. **Increase process transparency:** lack of process transparency increases the propensity to errors, reduces the visibility of errors, and diminishes motivation for improvement.

8. **Focus control on complete process:** segmented flow control leads to the risk of sub optimization. Thus, shifting focus on complete processes is necessary.

9. **Build continuous improvement into the process:** the effort to reduce waste and to increase value is an internal, incremental, and iterative activity, that can and must be carried out continuously.

10. **Balance flow improvement with conversion improvement:** in the improvement of productive activities, both conversions and flows have to be addressed. As a rule, the higher the complexity of the production process, the higher the impact of flow improvement as the more wastes inherent in the production process and more profitable is flow improvement in comparison to conversion improvement.

11. **Benchmark:** the best flow processes are not marketed to us; thus, we have to find the world class processes ourselves. Often benchmarking is a useful stimulus to achieve breakthrough improvement through radical reconfiguration of processes.

Koskela (1992) earlier innovation was used as an evaluation of production which is more diverted towards conversions opposite to continuous improvement, where the goal is flow. And all the aforementioned principles are applied for continuous improvement framework for evaluation of production process. To apply lean principles in construction, it should be developed as a set of processes & flows (Koladiya, 2017). Pasqualini and Zawislak (2005) to lean there is always a better way to do any activity, because just like the market changes, a firm must change to adapt itself to these new demands.

Al-Sudairi, Diekmann, Songer, and Brown (1999) applied five principles of lean production to a traditional steel erection process using computer simulation: specify value by a product, rethink your operating methods, focus on actual objects from beginning to completion, release resources for delivery just when needed, and strive for perfection. As a result, cycle time, productivity, utilization and throughput were significantly improved. Similarly, in a research for developing lean model for house construction, Yu et al. (2009) indicated that the home building sector suffers from variability and in order to reduce the variability of the process they recommended: production flow establishing (FIFO lane-based flow) and synchronizing it to takt time; levelling production at pacemaker task; restructuring work; and improving operational reliability with work standardization and TQM. Also, Nikakhtar, Hosseini, Wong, & Zavichi (2015) applied three lean principles: value generation through flow production of processes; pulling and mistake-proofing of processes for a case study research conducted by focusing on reinforcement operations and were able to abate rework time, overproduction and handling time significantly.

Later, Bodkhe et al. (2017) abridged fundamental principles of lean, viz:

- Define value from the customer's perspective
- Understand the value stream of all steps in the process used to create the end product
- Reduce waste
- Ensure a smooth flow of value-added-activities
- Prefabricate and modularize building systems
- Utilize collaborative pull scheduling to provide each internal and external customer what they want, when they request it
- Seek perfection by committing to continual improvement in all areas of the process

According to Germano, Fonsêca, Melo, and Moura (2017) the four accepted lean principles which deserve special attention in concrete work are reduction of NVAA; reduction of process cycle time; increase process transparency and continuous improvements. Also, Melo, Lima, & Melo (2017) proposed the application of the principle of perfection in structural masonry work through an improvement in the construction site's layout, and were able to improve project performance dramatically. Tommelein and Beeche (2001) innovated cladding installation system using the principle of "decoupling linkages". They developed a new technology for handling and installing curtain wall panels on high-rise buildings. Thus, lean principles not only improve project performances but prompt innovations. Decoupling linkages results in work flexibility and schedule acceleration (Tommelein and Beeche).

Koladiya, 2017; Diekmann et al. (n.d, as reviewed by Salem and Zimmer, 2005) the comparable aspects of lean manufacturing and lean construction (agreed principles that apply in construction) are grouped into the five principles:

- Customer focus
- Culture/people
- Workplace organization/ standardization
- Elimination of waste
- Continuous improvement with built-in quality

Koladiya (2017) the aforementioned five principles are the most relevant, fundamental and the most perceived lean principles from all lean construction research works.

2.3.1.1. Customer Focus.

Customer focus is the guiding principle and inherit all the value and value stream principle of lean production presented by Womack and Jones; and increasing output value through systematic consideration of customer requirements by Koskela. Buttressing his case, Bertelsen and Koskela (2004) the five principles of Womack make it obvious that the optimization of the flow of value towards the costumer is the guiding principle, and also the starting point of the application of lean thinking (Picchi &Granja, 2004). Picchi (2000) specifying value and enhancing value for the client needs the understanding of who the direct and the final clients are. Koskela (1992) for each activity there are two types of customers, the next customer and the final customer. Picchi (2000) in construction, the customers or final clients are the users of the facility. Also, Pasqualini and Zawislak (2005) amplified that the different stages of the construction can be interpreted as different orders of the customers (direct customers), since a general schedule of the construction, programming the period of production of each great stage in order to fulfill the contracted deadline. It is the first step to waste recognition, defined as everything that adds no value from the clients' perspective (Womack & Jones 1996, as cited in, Picchi & Granja, 2004).

One of the methods to focus on the customer is mapping the value stream. Howell and Ballard (1999) mapping the value stream shows when the information necessary to meet owner requirements will be available and when it is required. A value stream map is a comprehensive model of the project that reveals issues hidden in current approaches (Howell and Ballard). Value stream maps can be understood as process flow charts that identify what action releases work to the next operation. Mapping brings choices to the surface and raises the possibility of maximizing performance at the project level. Buttressing their notion, Koskela (1992) value is generated through fulfilling customer requirements, not as an inherent merit of conversion and pragmatic approach to this principle is carrying out a systematic flow design, where customers are defined for each stage, and their requirements are analyzed.

Diekmann et al. (n.d, as cited in Koladiya, 2017) have listed the following sub principles:

- meeting the requirements of the customer.
- defining value from the viewpoint of the customer (project).

- using flexible resources and adaptive planning to respond to changing needs and opportunities.
- crossing train crew members to provide flexibility.
- using target costing and value engineering.

2.3.1.2. Culture/People.

Diekmann et al. (n.d, as cited in Koladiya, 2017) have listed the following sub principles: providing training at every level; encouraging employee empowerment; ensuring management commitment; and working with subcontractors and suppliers to regularize processes and supply chains. It is prevalent that, this principle focusses in the implementation of lean and indicates that collaboration of different stake holders in the organization is indispensable.

2.3.1.3. Workplace Organization/Standardization.

Diekmann et al. (n.d, as cited in Koladiya, 2017) have listed the following sub-principles for workplace organization/standardization:

- encouraging workplace organization and use of the 5s.
- implementing error-proofing devices.
- providing visual management devices.
- creating defined work processes for repetitive tasks.
- creating logistic, material movement and storage plans that adapt to changes in workplace configuration.

Yu et al. (2009) applied restructuring work and improving operational reliability with work standardization and were able to improve project performance. Similarly, Esquenazi and Sacks (2006) in a simulation of lean improvement for residential building found that multi-skilling had most effect on improving labor utilization rates because it removed the imbalance in production rates that leads to teams being forced to wait for work to be made ready by preceding teams. Nikakhtar et al. (2015) applied, mistake-proofing of processes concept, and were able to significantly abate numbers of defect and time spent on rework.

2.3.1.4. Waste Elimination.

As stated by Koladiya (2017) waste elimination is further divided into four parts: process optimization through process itself, process optimization through supply chain management, process optimization through production planning and product design optimization through constructability review process.

Table 1

Four Parts of Waste Elimination and its Sub Principles [2]

Waste elimination	Sub-principles
Part I (Process Optimization)	Minimize double handling and worker and equipment movement, Reduce Changeovers Balance crews, synchronize flows Remove material constraints, use kitting, reduce input variation, and reduce scrap
Part II (Supply Chain)	Institute JIT delivery and supply chain management
Part III (Production Scheduling)	Use production planning and detailed crew instructions, predictable task times Implement last planner/reliable production scheduling/short interval production scheduling Practice last responsible moment/pull scheduling Use small-batch sizes, minimize WIP Use decoupling linkages, understand buffer size and location
Part IV (Product Optimization)	Reduce parts count, use standardized parts (Product Optimization) Use pre-assembly and prefabrication Use pre-production engineering and constructability analysis

[2] Dickeman et al. (n.d, as cited in Koladiya, 2017)

2.3.1.5. Continuous Improvement.

- preparing for organizational learning and root and built-in quality cause analysis
- developing and use metrics to measure performance; use stretch targets
- creating a standard response to defects
- encouraging employees to develop a sense of responsibility for quality

Al-Sudairi et al. (1999) implementing lean principles increases volatility of process. A zero buffer (WIP) made the process highly volatile and sensitive to variances in reliability (Al-Sudairi et al). Moving from traditional project management to lean management needs resources of any kind. However, Nikakhtar et al. (2015) costs of modifications will always be significantly lower than the advantages obtained by lean principles.

2.3.2. Lean Construction Tools

Koskela (2000) practical methodologies are based on concepts and principles. There are various lean tools and techniques which can be used to improve construction process and its performance. Kolidaya (2017) some of the common tools are value stream mapping (VSM), Last planner, 5s, Kanban, Work structuring, Hejunka, process mapping, visual management, PDCA and Kaizen. However, discussion of all tools and techniques are not the scope of this research. Thus, the researcher focusses on the discussion of mainly VSM tool and some other useful techniques applied for this research.

2.3.2.1. Value Stream Mapping.

Value stream mapping (VSM) developed from Toyota's material and information flow diagrams and was designed to aid Toyota's suppliers learn the TPS (Rother and Shook, 1999). Rother and Shook defined the VSM as a process improvement technique that has the objective of maximizing value for the final customer. Pasqualini and Zawislak (2005) it is a tool that has been widely used in manufacturing, as a way to initiate a systemic implementation of lean production. It is used to define and analyze the flow of material and information required for the project and can be applied to any value stream. Rother and Shook (1999) "VSM is the simple process of directly observing the flows of information and materials as they now occur, summarizing them visually, and then envisioning a future state with better performance." It identifies wastes in the system, paving the way for a successful lean implementation (Shararah, El-Kilany, & El-Sayed, n.d). It is an iterative method used to map and analyze value streams, with an objective to evaluate production process aspects such as material and information flows, and NVAA (Lasa et al., 2008, as cited in Jarkko, Lu, Lars, & Thomas, 2013; Aziz. et al. 2017). Material and information flow are the two sides of the same coin and should be mapped together (Rother & Shook).

Rother and Shook (1999) VSM is a tool to fight waste and reduce lead time. This unique mapping method aids in visualization of the cycle times, inventory at each stage, human effort and information flow (Xia & Sun, 2013). Shararah et al. (n.d) the purpose of value stream mapping is not only to identify the sources of waste, but also to eliminate them by developing future state value stream that can be implemented. In accord, Wei and Sun (2013); Xia and Sun (2013) VSM doesn't only highlight process inefficiencies, transactional and communication mismatches, but also guides the improvement area. Improvement events create localized improvements, but value stream mapping & analysis strengthens the gains by providing vision, collaborative working and plans that connect all improvement activities by shifting the focus on complete process (Koskela 1992; Rother & Shook). Yu et al. (2009) VSM directs into thinking about flow instead of isolated wastes and to implement lean system instead of individual lean technique. Visualizing the flow creates the opportunity to see where, when, and how both the information and product flows through, and consequently recognize and eliminate the source of waste (Xia & Sun, 2013). Pasqualini and Zawislak (2005) VSM does more than identifying wastes, the systemic visualization shows why wastes exist. In addition, Li and Solís (n,d) VSM could also be used to analyze and aid in re-designing processes. VSM has been used and had shown good results providing significant improvements in efficiency, productivity and service quality, and to bring a reduction in production lead and work in process (Shou et al., 2016, as cited in Etges, 2018). Rother & Shook (1999) it is much more useful than the ubiquitous qualitative tools and layout diagrams that produce tally of NVA steps, lead time, distance traveled, the amount of inventory and so on. Ballard et al. (2003) concluded that VSM is a powerful tool to change the focus into on lead-time reduction, throughput increase and improved productivity.

Rother & Shook (1999); Rother et al. (2003, as cited in Li & Solís, n.d) presented the following benefits of value stream mapping:

- **providing a holistic view of entire flow**: mapping the value stream gives a better understanding of the whole process. The act of connecting separate parts into a more holistic system helps the team to identify both the necessary and unnecessary function. It also aids to discover any information problems that are not easily identified within the production system. It helps to visualize more than just the single-process level. Visualizing information exchanges are important in comprehending how work is accomplished. It interrelates together lean concepts and techniques.

- **identifying waste:** applying VSM to map the current state of the product unveils VA and NVA processes and waste during the production process. What is more, the value stream map can clearly identify the seven most common types of waste. Thus, it maximizes customer value by best possible way to execute process.

- **generating improvement plans**: once wastes are identified in the production process; the team can start developing an improvement plan using lean concepts to eliminate waste and to add value. Consequently, improvement in forecasting and productivity.

According to Solding and Gullander (2009), VSM is a valuable tool for analyzing value flows and cheap, since no special tools or computer programs are needed. Although it can be seen in foregoing discussion of VSM that it has a paramount importance for improving project performance, it has some gaps. The purpose of VSM is to only follow one product or one product group and is mainly for high volume, low variety products (Rother and Shook, 1999). Bolstering their case, Koladiya (2017) VSM needs time and efforts, so it is used to process flows and material for high value project where construction is repetitive although every project is unique. Consequently, VSM does not support analysis of complex systems (Yu et al., 2009). Khaswala et al. (2001, as cited in Björnfot et al., 2011) VSM cannot make a rapid change on a low budget and VSM needs to be a user-friendly. Accordingly, Solding and Gullander (2009) stated the weaknesses of VSM:

- only the flow of one product or product type is analyzed per VSM analysis.
- the VSM gives only a snapshot of the situation on the shop floor at one specific moment.
- the VSM map is a rough simplification of the real situation.

In agreement with Solding and Gullander, Jarkko et al. (2013); Aziz et al (2017, p.296) stated that "VSM cannot provide hard facts for decision making and simply points towards a direction as it lacks the ability to forecast the effects on future performance of a system analytically." VSM has also been criticized for being deterministic since it does not consider fluctuations in demand or process variability (Hampson, Hampson, & Mohamed 2002; Hines, 2004, as cited in Jarkko et al., 2013). It is why integrating simulation with VSM is an ideal way to get exhaustive output of lean improvement in a complex and dynamic environment. Value stream focusses on the total process and not on individual islands. For this reason, a person who knows the entire process is needed (Rother & Shook, 1999).

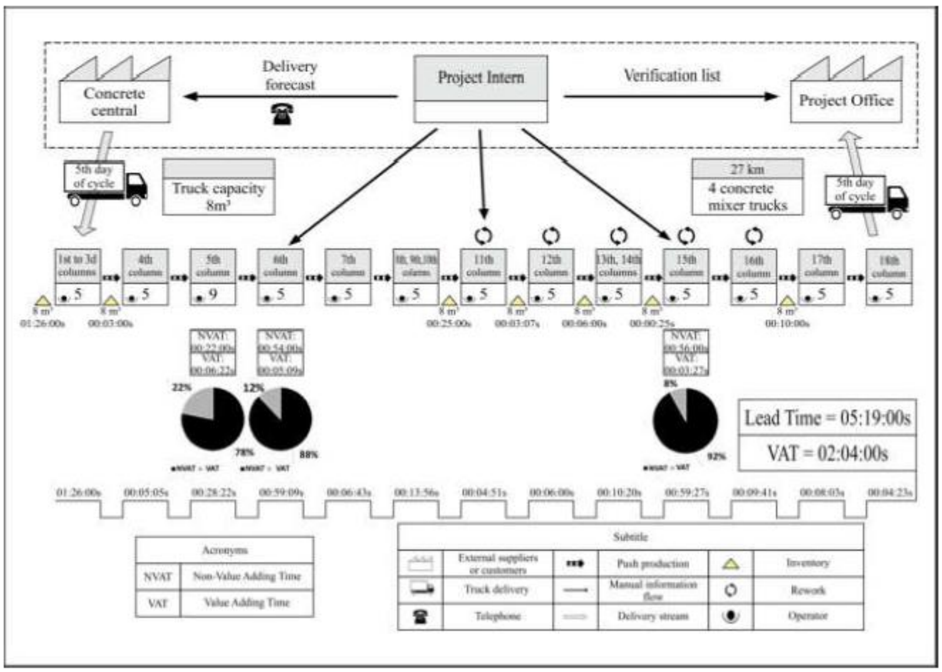
VSM has three components:

1. **Current state map**: it visualizes value-adding and non-value-adding activities in a process. Jarkko et al. (2013) the current state gap presents a visual representation of the value-adding and non-value-adding activities in a process. Solding and Gullander (2009) when a map of the current situation is documented a parallel map is developed within the team which instead describes the ideal future state. Rother and Shook (1999) developing the current and future

state are overlapping effort. Team records all the details from plans and create map based on design teamwork and how it will affect the work of others. The current status is mapped to capture a snapshot of how things are done and where the improvement solutions lie (Xia & Sun, 2013).

Figure 2

Current State Map of Column Concreting [3]



Rother & Shook (1999) pointed out some propositions to serve as guidelines for analysis of the map of the current state and Pasqualini and Zawislak (2005) summarized them. Which are producing according to takt time; producing for expedition or for a supermarket of finished products; developing a continuous flow where possible; using "supermarket" to control production where continuous flow is not possible; sending a customer's programming to a production process only, which is called pulling process, since it controls production rhythms for all preceding processes and finally, uniform distribution of the production of different items in the pulling process period and leveling the product mix along manufacturing.

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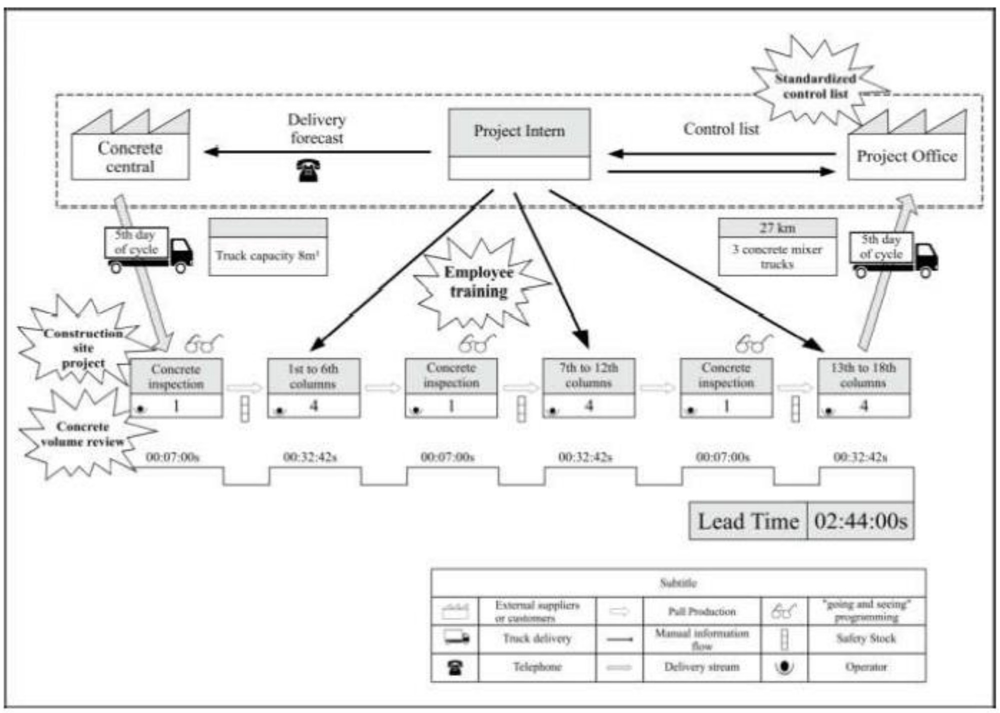
[3] (Germano et al. 2017)

2. **Future state map:** it is a value stream that strives to mitigate the identified problems of current state. Xia and Sun (2013) the future state map is then built to show how things should be done considering potential requirements. In accord, Jarkko et al. (2013) the future state design is a value stream where the identified problems of the current state have been remedied. This future state is used as a base for prioritizing improvement activities, which is called kaizen events (Solding & Gullander, 2009). Yu et al. (2009) an advantage of VSM is that the process improvement efforts become adjunct to the value stream design, so that it can be focused on the improvements that have real impacts on overall process of performance.

Figure 3

Future State Map of Column Concreting [3]



3. **Yearly Value Stream Plan**: it creates an operational plan to reduce the gap between the present and future states (Martin and Osterling, 2014, as cited in Aziz et al., 2017).

2.3.2.2. Just-In-Time.

Koskela (1992) the starting point of the new production philosophy was in industrial engineering-oriented developments. The driving idea in the approach was reduction or elimination of inventories (work in progress). This, in turn, led to other techniques that were forced responses to cope with less inventory: lot size reduction, layout reconfiguration, supplier co-operation, and set-up time reduction. Later, the pull type of production control method, where production is initiated by actual demand from its preceding step rather than by plans based on forecasts, was introduced (Koskela). It is in opposition to "push" production, where each step pushes its finished product on to the next step. Just-In-Time (JIT) strives to deliver the right product at the right time in the right quantity. Reduction of waste through continuous improvement of operations and processes is another foundation of JIT (Koskela, 1992).

2.3.2.3. Pull Scheduling.

Push scheduling lead to extremely long lead time because it is a production system in which each process tries to produce the maximum quantity of possible units (demand forecast). Whereas, a production system in which each process produces only what the next one requires (actual demand) is a pull scheduling. Arbulu, Ballard, and Harper (2003) the aim of a pulling system is to produce only what is needed, when it is needed, and in the right quantities. It ensures just-in-time coordination between upstream and downstream tasks. The pull scheduling technique requires working backwards from the date of completion. It is based on the notion that the upstream should not produce until the downstream request for it (Womack & Jones, 1996, as cited in Nikakhtar et al., 2015). This system enforces JIT materials delivery and thus saves on site storage; material holding costs, and idle person and equipment hours (Arbulu et al., 2003). Picchi and Granja (2004) pull and flow lean principles are regarded as the core characteristics of lean thinking and are cornerstones for the elimination of waste. When properly implemented, the benefits are smaller buffers, earlier project completion and increased productivity (Howell 1999; Picchi & Granja, 2004). Lower WIP, tied up less working capital and decrease the cost of design changes during manufacture as only a few pieces are needed to be scrapped or altered. Implementing the concept of pulling (just-in-time delivery of materials) abate overproduction noticeably in reinforcement operations (Nikakhtar et al., 2015).

2.3.2.4. Work Structuring.

Work structuring is a term coined by lean construction institute (LCI) to indicate the development of operation and process design in alignment with product design, the structure of supply chains, the assigning of resources, and possible modularization opportunities (Howell and Ballard, 1999). The goal of work structuring is to make workflow more reliable and quicker, while delivering value to the customer. Total lead time can be abated by reducing the number of handovers (work structuring) and by deploying a multitasking labor (Rother and shook,1999; Yu et al. 2009). One of the eleven Koskela’s principle, simplify by minimizing the number of steps and parts, is in congruous with work structuring. Koskela (1992) simplification can be understood as reducing of the number of steps in a material or information flow. In a research for developing lean model for house construction, Yu et al. were able to save three workdays of lead time by restructuring work and improving operational reliability with work standardization. Corroborating their case, Esquenazi and Sacks (2006) in a simulation of lean improvement for residential building found that multi-skilling had most effect on improving labor utilization rates because it removed the imbalance in production rates that leads to teams being forced to wait for work to be made ready by preceding teams.

2.3.2.5. Kanban.

Kanban is a lean approach developed in the automotive industry as a mechanism to pull materials and parts throughout the value stream on a just-in-time basis. Arbulu et al. (2003) it is developed to manage the replenishment of certain types of made-to stock products from preferred suppliers to site. JIT strategy uses kanbans to pull materials from preferred suppliers to meet site demand. It is often used for ordering raw materials with a cue card that signals the need to place the order. This signaling system can be varied, such as; empty boxes, light signal or a marked item (Arbulu et al.). Two different types of kanbans have been developed: transport kanbans and production kanbans (The Productivity Press Development Team, 2002 as cited in Arbulu et al., 2003). Transport kanbans are used to either signal the need to replenish materials from a preferred supplier (supplier kanbans) or to signal the movement of parts or subassemblies produced within the factory to the production line. The transportation kanbans are similar to the production ones, and contain information such as the quantity of material to be transported, delivery of floor number and eventually, the draw of the material to be transported (Heineck et al., 2009, as cited in, Burgos & Costa, 2012). Similarly, production kanbans are signals to either initiate production (production-ordering kanbans) or to communicate the need for machinery changeovers (signal kanban). Heineck et al. (2009, as cited in, Burgos and Costa, 2012) the production kanbans are made of plastic paper which contains information such as quantity of mortar to be produced, type of mortar, delivery of floor number and delivery time. In the construction industry, the evidence of the use of kanbans of any type is very limited but supplier kanbans relatively common (Yu et al. 2009; Melo et al. 2017).

Arbulu et al. (2003) the kanban strategy has the following goals:

- to give users what they want when they want it by pulling materials from suppliers,
- to support the reduction of material inventories,
- to reduce the paperwork necessary to order new products or to increase stock quantities,
- to facilitate product rationalization,
- to reduce purchasing cycle times,
- to eliminate expediting,
- to contribute to the continuous improvement,
- to act as a catalyst for change in procurement methods, and
- to simplify the site material management processes for acquiring, storing, distributing, and disposing of made-to-stock products by eliminating waste and reducing information processing.

According to Monden (1984, as cited in Burgos and Costa, 2012), the information that are essential and must be contained within the kanban cards:

- the specification of the part to be produced or transported;
- quantity to be produced or transported;
- process responsible for the production and use of the specified part; and
- storage place.

Ohno and Halevi (2001, as cited in Koladiya, 2017) Kanban system's rules are as follows

- the earlier process produces items in the quantity and sequence indicated by the kanban;

- the later process picks up the number of items indicated by the kanban at the earlier process;
- no items are produced or transported without a kanban;
- always attach a kanban to the goods;
- defective products are not sent to the subsequent process, so results can be 100% defect free goods;
- reducing the number of kanban cards increases their sensitivity. This reveals the existing problems and maintains inventory control.

2.3.2.6. 5S Workplace organization.

5S is a basis of lean thinking and continuous improvement. It comes from Japanese words Seiri, Seiso, Seiton, Seiketsu and Shitsuke (Sort, Straighten, Shine, Standardize, and Sustain). Sort the important item to perform the activity and separate it from the non-important items to save time in searching for that when needed. Set a location for each required item to use and keep it safe at single and easily reachable location. Keep the work area clean and organized to maintain standard of workplace and good working order. Set and maintain the standard to achieve productivity at a desired level. Sustain it through training and inspection.

2.3.2.7. Poya-Yoke.

Mistake-proofing of processes in the production industry of Japan, is called Poka-yoke. The objective was to eliminate or minimize the requirement for inspection (which is believed as waste in lean philosophy) by eliminating errors before they occur rather than detecting and mending activities which simply make it fall under category of “rework” (Nikakhtar et al.). Shingo (1988, as cited in Bertelsen and Koskela, 2004) puts emphasis on the involvement of the individual worker in solving process problems and undertaking product inspection. Poka yoke is a means for improving the flow of work. This can be seen as the recognition of the process not being totally ordered and foreseeable and that the approach to this should be cooperation and learning. Nikakhtar et al. (2015) mistake-proofing of processes significantly abate numbers of defect and time spent on rework.

2.3.2.8. Visual management.

Another important concept is visual management. It is an orientation towards visual control in production, quality and workplace organization (Greif, 1991, as cited in, Koskela, 1992). The goal is to render the standard to be applied and a deviation from it immediately recognizable by anybody. It gives information about the planned work, current progress and the problems during the work visually which is easy to check and understand. It is already being used in different forms like fire extinguishers or other hazardous items.

2.3.2.9. Problem solving tools.

These tools are being used as a team approach when there is a need to solve issues or defects which may affect the completion of a program. Issues could be related to cost, quality, safety or productivity and the goal is to find the root and cause of that issue to complete the task by new best way possible.

2.3.2.9.1. Plan-Do-Check-Act.

Plan-Do-Act-Act (PDCA) cycle also named as an improvement cycle. It is a process improvement approach represented as a circle with no ends, which symbolizes the cycle of repetition (O'Connor & Swain, 2013, as cited in Koladiya, 2017). Implementing continuous improvements are often made using the PDCA (Plan-Do-Check-Act) cycle which is a well-known tool for making continuous improvements (Liker and Meier, 2011, as cited in Goodwin & Pantzar, 2017). The tool consists of four steps: Plan, which is identifying the problem and determining a goal for the changes to be made and come up with a method for implementing the change; Do, which is performing the changes according to the method proposed in the previous step; Check, is concerned with the result of the changes that was made. If the goal is reached, continue to the next step, if it isn't reached, go back to Plan; and Act, is standardizing the solution. Koskela (1992) A key idea is to maintain and improve the working standards through small and gradual improvements.

2.3.2.9.2. Fishbone Analysis.

Fishbone analysis is a root cause analysis technique to identify most probable causes for the problem by sorting ideas into useful categories, which is also known as Ishikawa diagram. Root cause analysis is a structured process that aids in identifying underlying causes of an adverse problem. Aziz et al. (2017) it shows many constraints and their causes. In this type of diagram, a standard template of a shape of fish-bone structure is used. At the head of a fish, the problem is written, and the probable causes are written under the title of material, person, method, environment or person. The four W's are "What", it refers to questions related to objects such as materials and machines; "Why", is used to answer questions regarding work conditions such as condition of manpower; "When", it refers to problems related to time sequence in operation; and "Where", is concerned with effects related to the place, production line, area and so on.

A fishbone diagram is a visual way to look at cause and effect. Coccia (2017) it is a more structured approach than some other tools available for brainstorming causes of a problem. Toyota Motor Corporation (2003, as cited in, Card, 2016) 5 Whys' indicate the potential for users to rely on ad-lib deduction, rather than situated observation when developing answers, as well as difficulty in prioritizing causes. Fishbone diagram is used to identify the several causes and a complex interplay of causes for a specific problem or event (Coccia, 2017).

2.3.2.10. Daily Huddle Meetings.

Daily huddle is a discussion based on the weekly work plan. How are we doing? what do we need to maintain the plan as it is in progress? daily huddle discussions must be directly connected to the team's weekly and daily work plan. It is where team members quickly give the status of the previous shift's accomplishments and failures, plus the current shift's plan of work for that day. It ensures rapid response to problems through empowerment of workers. This is where transparency and reliable commitments are measured first and foremost for the last planners themselves to see and interact with directly. It is the heart of LPS, so of utmost importance for the project manager and the team itself to establish and drive healthy daily huddle discipline. It is the quickest means to influence improved workflow reliability and productivity. As part of the improvement cycle, a brief daily start-up meeting should be conducted where team members quickly give the status of what they had been working on since the previous day's meeting, especially if an issue might prevent the completion of an assignment. The daily huddle is not a problem-solving or planning forum, but a powerful means for the team to quickly surface and resolve issues.

2.4. Construction Waste

2.4.1. Definition and Types of Waste

Construction industry has been suffering tremendously from a serious drawback called NVAA (Senaratne & Wijesiri, 2008). According to Ayalew et al. (2018), one of the major problems that challenges Ethiopian construction industry is the existence of waste. Lean construction is aimed at improving construction performance by eliminating wastes that do not add value to the customer. Koskela (1992) defined waste as, an inefficiency that results in the use of equipment, materials, labor or capital in larger quantities than those considered as necessary. A simple way to define waste is, activities, resources and rules that can be avoided while meeting customer requirements. Taiichi Ohno (1988, as cited in Koskela, 1992) determined the seven basic types of waste in production. In this regard Formoso and Hirota (1999, as cited in Ayalew et al., 2018) customized the seven types of waste identified in the Toyota production system from construction perspective.

1. Defects

Defects occur when the products do not satisfy the quality specifications. It can be caused by a numerous reason: poor design and specification, lack of planning and control, poor qualification of the teamwork, and lack of integration between design and production. It happens when the finished or half processed products are not up to the quality requirements. Defects may prompt rework or the use of poor or unnecessary materials to the building. Alemu (2006); Amanuel (2016) have identified rework as a top ten factors affecting labor productivity in Ethiopia. The cost of a product considered as defective is the same as it does for the best one. Other than the losses, there are numerous different costs connected to rejecting, that make this an especially imperative classification of waste to minimize or eliminate.

2. Overproduction

Overproduction is producing more or doing more and sooner than it is needed. Rother and Shook (1999) it isn't only a waste but also a root cause of other wastes such as rework and excess time, because we are using these resources to produce parts that are not yet needed. Ohno sees overproduction as a primary waste driving other wastes in a vicious circle of waste generating waste (Ohno, 1988, as cited in Koskela et al., 2013). However, as construction is usually a produce-to-order process which is in contrast with the situation in mass production, the claim of overproduction as the most important waste of construction cannot be justified (Koskela et al., 2013).

3. Inventory

This is due to excessive or unnecessary inventories. It leads to material waste by deterioration, losses due to insufficient stock conditions on site, and monetary losses due to capital tied up. Organizations often arrange more than needed to satisfy a request and compromise inflation.

4. Unnecessary processing steps

This is related to the nature of processing conversion activity. It occurs in situations where processing or conversion activity does not add value to the product or service from the client's perspective. Abdul Rahman et al. (2012, as cited in Sahlu, 2017) the most evident type of over-processing is rework, which in turn affects productivity adversely.

5. Transportation of materials

Concerned with the internal movement of materials on site with no purpose. It is usually related to poor site layout, and the lack of planning of material flows. Abdul Rahman et al. (2012, as cited in Sahlu, 2017) these wastes include; waste of worker's hours, waste of space on site, waste of energy, and the likelihood of waste of material during transportation.

6. Motion of employees

Motion of employees is a waste with respect to unnecessary or inefficient movements made by workers during their work hours. This might be caused by inadequate equipment, ineffective work methods, or poor site layout arrangement. Unnecessary movements may create or increase the level of injuries, accidents, and their related costs.

7. Waiting

Waiting is related to idle time caused by lack of synchronization and levelling of material flows, and pace of work by different crew or equipment (Sahlu, 2017). This also includes waiting of employees for process equipment to finish its work or for an upstream activity to be complete. As described by (CII 2010; Dozzi and AbouRizk 1993; Gouett et al. 2011, cited in Muralidharan, Krishnankutty, Hwang, Caldas, & Mulva, 2018) waiting is further described in a detailed manner, viz:

- **waiting for permits**: periods of waiting for authorization to proceed, even if workers are attentive to the ongoing work by other craft workers (for instance, waiting for permits, or for task completion sign-off, or to obtain entry to the work area);
- **waiting for instruction**: waiting for instruction from a foreman or for a job allotment;
- **waiting for material**: examples include waiting in line at a storage warehouse, material/parts storage area, or waiting for the return of a concrete bucket;
- **waiting for equipment**: for instance, waiting for a crane to hook and return for the next lift or waiting for another craft worker to finish utilizing tools or equipment;
- **waiting for quality assurance/quality control (QA/QC)**: labor waiting for the QA/QC assessment to be completed; and
- **waiting for an unknown**: crew waiting at the workplace for unknown reasons.

8. Making Do

Koskela (2004) has identified "Making Do" as a common type of wastes in construction. It refers to starting a task before all preconditions are ready (starting without all its standard inputs). He indicated that, it is done for keeping the utilization of capacity high but also for the sake of schedule compliance. Ayalew (2018) this waste is also a major concern for construction industry in developing countries in general and that of Ethiopian construction industry in particular. “In making-do the waiting time of one type of material or other inputs is negative: processing starts before that material has arrived” (Koskela, p.3). Bertelsen (2004) it is a waste from transformation perspective, but acceptable from flow point of view.

In addition, Lee, Diekmann, Songer, and Brown (1999) classified construction waste into eight groups, which are: delay times, quality costs, lack of safety, rework, unnecessary transportation trips, long distances, improper choice or management of methods or equipment, and poor constructability. Garas, Anis, and Gammal (2001) grouped construction waste into two principal components: time wastes, including waiting periods, stoppages, clarifications, variation in information, rework, ineffective work, interaction between various specialists, delays in plan activities, and abnormal wear of equipment; and material wastes, comprising over-ordering, overproduction, wrong handling, wrong storage, manufacturing defects, and theft or vandalism. Similarly, Polat and Ballard (2004) divided waste into material waste and time waste. They found that ordering of materials that do not fulfill specification; imperfect planning of construction and workers' mistake results in material waste. Delays in material supply and waiting for replacement that do not fulfill project requirements are major cause of time waste (Polat & Ballard). Focusing on whether a waste is mitigable or not, Formoso, Isatto, & Hirota (1999) classified waste as unavoidable waste, in which the investment necessary to its reduction is higher than the economy produced, and avoidable waste, in which the cost of waste is higher than the cost to prevent it.

Ayalew et al. (2018) from site observation on randomly selected work item identified that more than 50% of the working hour is wasted in executing NVAA. According to the study conducted by Sahlu (2017) on different case studies in building sites of Addis Ababa, working times spent on NVAA prevail and waiting time takes the biggest share. In contrast, Ayalew et al. (2018) identified that overproduction, over processing waste and transport waste as the most dominating wastes in Ethiopian building construction projects. This shows that different operation exhibits and are dominated by wastes that are different from other operations. Most causes of wastes can be removed by means of implementation of lean construction techniques and only time waste resulting from irregular cash flows cannot be removed by the techniques (Polat and Ballard, 2004).

2.4.2. Causes of Construction Wastes

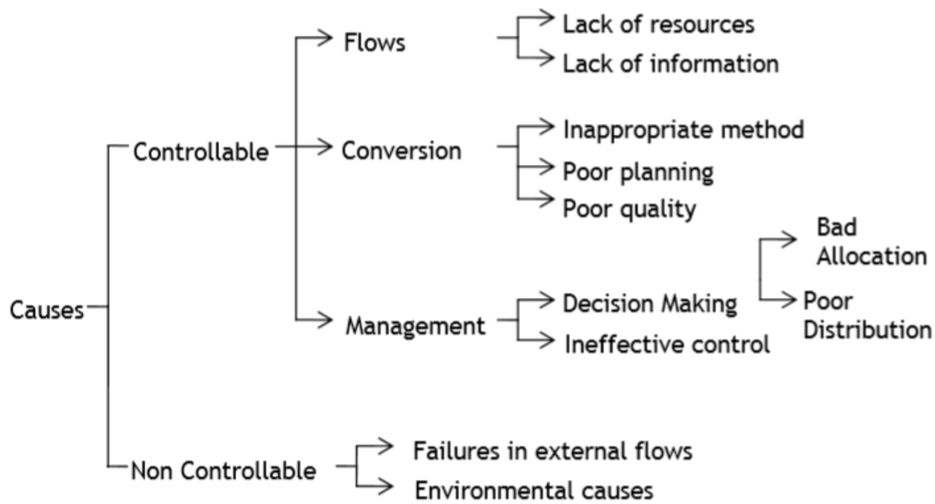
Rother and Shook (1999) while it is good to be aware of waste, future designs need to eliminate the source, or root causes of waste in the value stream. Many lean implementation efforts have been after wastes. According to Ohno (1997, as cited in Burgos and Costa, 2012) the problems should be treated from the root of the cause, as only then can you prevent them from reoccurring. Koskela (1992) argued that NVAA have three root causes: design, ignorance and the inherent nature of production. Tommelein (1997) waste is created when several resources are needed simultaneously for an activity to start, but a missing one causes the others to pile up. Piles create additional work for those keeping track of what is or is not part of them and they occupy space, thus impeding movement and preventing others from using that space. Waste is also created by the lack of detailed planning and communication of progress (Tommelein).

Formoso et al. (1999) stated that waste can also be categorized according to its source; in the stage in which the root causes of waste occur. Waste may result from the processes of the preceding construction, such as materials manufacturing, design, materials supply, planning, and the construction stage (Formoso et al.). Polat and Ballard (2004) identified the main causes of material and time waste in the Turkish construction industry by categorizing the source of waste into fundamental fields of knowledge, viz: design, procurement, material handling, operation, residual and others.

Shahparvari and Daniel Fong (2018) fragmentation and subcontracting were identified as one of the major causes of rework generation in the housing supply chain. Which are based on convenience of lean principles implementation. According to them, fragmentation and subcontracting in housing construction hinder the incentives for project participants to efficiently implement lean towards producing affordable quality housing. Zhao and Chua (2003) rework due to design change is mostly a waste source that has been linked to design issues. On a research conducted by Hampson et al. (2002) lack of design and documentation were the most significant cause of waste in Australia and delays to schedule was found to be the significant waste in Indonesian projects. Serpell et al. (1995, as cited in Senaratne and Wijesiri, 2008) have categorized waste as shown below in the figure.

Figure 4

Causes of Construction Wastes[4]



According to their categorization, apart from external factors, all other prevalent causes are controllable. Later, Dajadian and Koch (2014, as cited in Koladiya, 2017) categorized waste into its origin and respective causes in a detailed manner.

Table 2

Origin and Causes of Waste

Origins of waste	Causes of waste
Contractual	▪ Errors in contract documents ▪ Contract documents incomplete at commencement of construction
Design	▪ Design changes ▪ Design and construction detail errors ▪ Unclear/unsuitable specification

[4] Serpell et al. (1995, as cited in Senaratne and Wijesiri, 2008)

Origins of waste	Causes of waste
Design	▪ Poor coordination and communication (late information, last minute requirements, slow drawing revision and distribution)
Procurement	▪ Ordering errors (i.e., ordering items not in compliance with specification) ▪ Over allowances (i.e., difficulties to order small quantities) ▪ Supplier errors
Transportation	▪ Damage during transportation ▪ Insufficient protection during unloading ▪ Inefficient methods of unloading
On-site management and planning	▪ Lack of on-site waste management plans ▪ Improper planning for required quantities ▪ Lack of on-site material control ▪ Lack of supervision
Material storage	▪ Inappropriate site storage space leading to damage or deterioration ▪ Improper storing methods ▪ Materials stored far away from point of application
Material handling	▪ Materials supplied in loose form ▪ On-site transportation methods from storage to the point of application ▪ Inadequate material handling
Site operation	▪ Accidents due to negligence ▪ Equipment malfunction ▪ Poor craftsmanship ▪ Time pressure
Residual	▪ Waste from application processes (i.e., over-preparation of mortar) Packaging
Other	▪ Weather ▪ Vandalism

Being able to understand this level of waste, promote critical change actions and is a fundamental stage in the performance improvement process and a leaner construction management.

2.4.3. Comparison of Waste and Labor Productivity

Poor productivity is an alarming issue in the construction industry that has been draining the value of projects. Zhao and Chua (2003) low productivity in the construction industry has long been a great concern. The reduction of NVAA is a fundamental driver for enhancing productivity. Koskela (1992) as a consequence of traditional managerial concepts, construction is characterized by a high share of NVAA and resultant low productivity. Koskela (2000) the aim to reach high productivity is strongly correlated to traditional mass production or what is called the transformation concept of production. He indicated that the transformation model is directly associated with the notion of productivity (the ratio of output to the input). A focus solely on productivity would therefore result in producing as much as possible with the given resources. Lean construction first focus is on waste and its minimization; the second focus is on productivity and how it can be improved to its full potential by managing flows; the third one is maximizing value (Ballard & Howell, 1994; Howell, 1999). It is the focus on productivity alone that the literature of lean thinking strongly criticizes since this kind of focus tends to result in huge amounts of waste in the production process (Womack & Jones, 1996, as cited in koskela, 1992). Consequently, the benefits of lean in terms of productivity, quality and other indicators have been tangible enough in practice to ensure a rapid diffusion of the new principles (Koskela). Also, (Bodkhe et al., 2017) lean technology reduces all forms of NVAA and improves its performance and provides a significant competitive advantage for the participants. This would change the contractors' profit margin and would result in less expensive construction cost for a country.

Thomas et al. (1984, as cited in Zhao and Chua, 2003) labor productivity is better as more time is spent in value-adding activities. Therefore, being able to reduce the share of non-value-adding activities is one of the core strategies for construction process improvement, thereby resulting in construction productivity improvement. Forsberg and Saukkoriipi (2007) measurements of productivity and waste can complement each other. The basic reasons to study waste and productivity are the same, which is to comprehend status quo so that improvements can be attained.

Zhao and Chua (2003) when the NVAA are identified and if it could be strategically eliminated, project performance can significantly be improved through a better production flow.

Construction productivity could be improved by understanding it as a production, as it is (Bertelsen, 2004). Consequently, enhancing productivity should direct its focus in improving flow and value generation, not in improving transformations, which takes ten percent of total construction cost only (Bertelsen). To recapitulate, considering the levels of waste and productivity can both be useful to attain a higher level of performance.

2.5. Modelling and Simulation

Modelling is the process of representing a model which includes its construction and working. A model should be a close approximation to the real system and incorporate most of its prominent features (Maria, 1997). Model classifications include deterministic (input and output variables are fixed values) or stochastic (at least one of the input or output variables is probabilistic) and static (time is not considered) or dynamic (time-varying interactions among variables are considered). Typically, simulation models are stochastic and dynamic.

Simulation of a system is the operation of a model in terms of time or space, which helps analyze the performance of an existing or a proposed system. In other words, simulation is the process of using a model to study the performance of a system. The Encyclopedia Britannica (2014a, as stated by AbouRizk, Hague, & Ekyalimpa, 2016) defines computer simulation as, the use of a computer to represent the dynamic responses of one system by the behavior of another system modelled after it. Accordingly, Maria (1997) stated simulation in its broadest sense, as a tool to study and evaluate the performance of a system, existing or proposed, under different configurations of interest and over long periods of real time. Simulation is used before an existing system is altered or a new system built, to reduce the chances of failure to meet specifications, to eliminate unforeseen bottlenecks, to prevent under or over-utilization of resources, and to optimize system performance. Simulation is the method of developing and experimenting with computer-based models of operations, such as construction processes, to analyze and evaluate the behaviors of a system (AbouRizk et al., 2016). There are three types of simulation; discrete event, continuous, and Monte Carlo.

1. Discrete event simulation utilizes a mathematical/logical model of a physical system that portrays state changes at precise points in simulated time. Both the nature of the state change and the time at which the change occurs mandate precise description. Customers waiting for service, the management of parts inventory or military combat are typical domains of discrete event simulation.

2. Continuous simulation uses equational models, often of physical systems, which do not portray precise time and state relationships that result in discontinuities (Aziz et al., 2017). The objective of studies using such models does not require the explicit representation of state and time relationships. Examples of such systems are found in ecological modelling, ballistic reentry, or large-scale economic models.

3. Monte Carlo simulation, to reflect its gambling similarity, utilizes models of uncertainty where representation of time is unnecessary. The term originally attributed to a situation in which a difficult non-probabilistic problem is solved through the invention of a stochastic process that satisfies the relations of the deterministic problem (Aziz et al., 2017). A more recent characterization is that Monte Carlo is the method of repetitive trials.

Campbell, Clegg, Perera, Stephenson, and Stevens (1997) reasoned why discrete event simulation is more reliable than continuous simulation. He stated the reason for this is when modelling activities such as ‘build a wall’, it is sufficient to know only the start and finish times, and not what occurs in between and construction sites, due to their complexity, are very difficult to model accurately. Many assumptions have to be made, hence making the results unreliable. Because of the aforementioned reasons, continuous simulation is less suitable for the modelling of most construction processes.

2.5.1. Developing Simulation Models

Simulation models consist of the following components: system entities, input variables, performance measures, and functional relationships. The following are the steps to develop a simulation model.

- **Step 1**: the development process starts with the identification and abstraction of the problem and its overall process from the real world (Aziz et al., 2017). If the problem is not stated precisely or in quantifiable terms and the purpose is unclear, it will lead to time wastage, incorrect analysis, unfitting decisions, and incorrect decision making (Dhebar,1993, as cited in Aziz et al., 2017).

- **Step 2:** conceptual modelling is formalism of the problem domain. This culminates in the production of simulation model assumptions, requirements and specifications. Unequivocal assumptions and specified descriptions in the conceptual model ascertain that the model is developed in accordance with the problem statement (Aziz et al., 2017). The validity of the outcomes directly depends on the inputs in the system. Hence, developing a conceptual model for validation prior to investing resources in a computer-based model is necessary. Yet, it isn't a must to have the model as exactly as the real system, only the essence of the real system is needed (Banks et al., 2010).

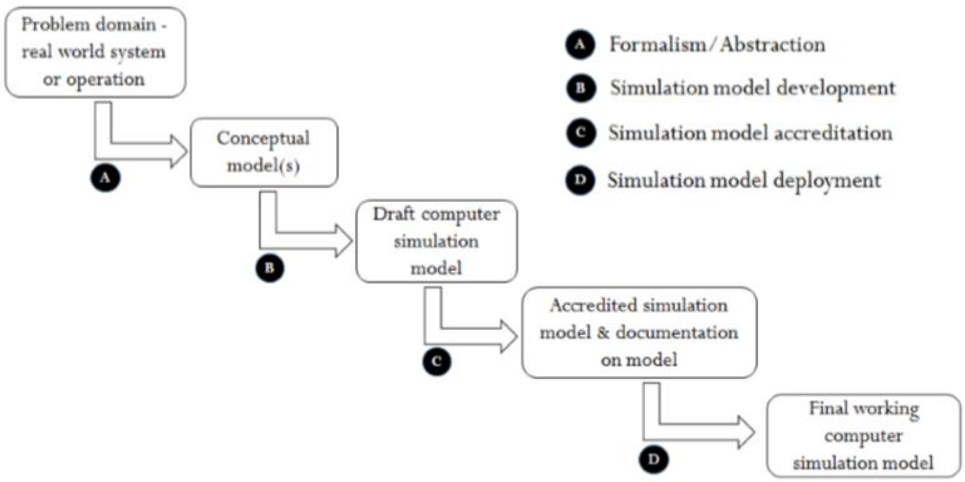
- **Step 3**: the next step in the development process involves translating these concept models into working draft simulation models, such as in Simphony CYCLONE;

- **Step 4**: simulation model accreditation, verification and validation. It can also go hand in hand with documentation of the details of the model; These include model inputs; model implementation and logic; and model verification and validation.

- **Step 5**: finally run the simulation model and observe the result.

Figure 5

A Schematic Layout of a Typical Simulation Model Development Process[5]



The proper analysis of such models requires:

1. application of input modelling techniques,
2. simulating the model multiple times and sampling the required output variable so that we can statistically analyze them, and
3. verification and validation of the results.

Solding and Gullander (2009) simulation is a valuable tool for analyzing complex systems and has many strengths:

- the flow of all products can be included in the model,
- not only a rough simplification,
- can analyses a time span and not only a snapshot,
- dynamic course of events,
    - complex planning/control logic.
    - variations and breakdowns can be included.

[5] AbouRizk et al. (2016)

- advanced analyses, and
    - bottlenecks, utilization etc,
    - mean sizes of buffers, standard deviations.
- possible to experiment with system changes and parameters.

There are also some weaknesses with simulation:

- it demands a large investment in time and money,
- a good knowledge of simulation methods and programs are needed,
- difficulty of getting the right amount of data in the right format, and
- often a simulation expert running a simulation project is not otherwise directly involved in the studied system.

2.5.2. Simulation in Construction

Simulation is one of the powerful techniques for supporting the decision-making process for construction management by examining the feasibility and capability of improvement opportunities. Simulation is widely regarded as an effective tool for analyzing complex process interactions (Halpin, Jen, & Kim, 2003). Construction process are inherently complex with many uncertainties. An accurate modelling of a construction process can help the development of better alternative scenarios and optimization of the involved resources. AbouRizk et al. (2016) defined simulation in construction as, the use of computer software to represent the dynamic responses of a construction system by the behavior of a model made to represent it. A simulation uses mathematical descriptions, graphical constructs and computer algorithms. Newstead (2015) simulation enables construction practitioners to analyze complex construction processes, evaluate different scenarios, and therefore optimize resources for projects. In accord, simulation can offer a better learning environment to demonstrate the impact of decisions on a process (Caňizares & Faur 1997; Walters et al., 1997, as cited in Neeraj et al., 2016). Application of simulation in construction operations has many advantages including estimation of possible delays, productivity determination and improvement, to determine the cost for the production, resource management and optimization (Aziz et al., 2017; Banks, 1998, as cited in Goodwin & Pantzar, 2017; Halpin et al., 2003; Thanh, 2017).

2.5.2.1. Discrete Event Simulation.

Discrete event simulation (DES) is a very advanced simulation technique. Law and Kelton (2000, as cited in Ming Lu et al., 2007) DES is a very powerful method to imitate the behavior of a real-world system by modelling repetitive processes in which durations of operations are stochastic. DES has been proven to be an effective technique in predicting and evaluating the behaviors of systems (Banks et al., 2010). The logic used in DES is that the state of a system modifies immediately at specific times marked by specific actions. These models are processed by advancing the time in discrete segments based on important events that take place in the model (AbouRizk et al., 2016).

The most common simulators are those using a flow diagram approach. It is because most of the systems are an extension of the CYCLONE (CYClic Operations NEtwork). CYCLONE was introduced by Halpin, which simplified simulation modelling for construction practitioners through the use of graphical representation in modelling (Newstead, 2015). Halpin's approach is based on the concept that construction operations can be abstracted in the form of cyclic networks of modelling elements that represent the transition of resources between two states: an active state and an idle state (AbouRizk et al., 2016). CYCLONE models processes based on discrete event simulation. CYCLONE is known for its simplicity and ease of use, as it only uses few modelling elements to enable a complete model of a construction operation (Newstead, 2015).

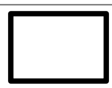
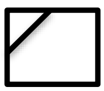
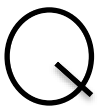
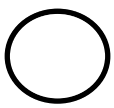
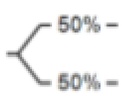
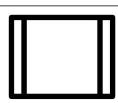
AbouRizk et al. (2016) CYCLONE was amongst the first simulation languages developed for use in construction and it was mainly geared towards modelling construction processes, rather than an entire construction system. In CYCLONE, the construction process is abstracted and represented in the form of operations and processes that are composed of tasks and queues (AbouRizk et al., 2016). Weldeamanuel (2018) using Simphony CYCLONE has experimented and was able optimize maximum production rate of the concrete delivery system. Thanh (2017) used CYCLONE model to conduct the cycle of the micro-tunneling process and studied performance for different soil compositions. CYCLONE is a modelling technique that allows the graphical elements (e.g. queue, normal, and combined nodes in CYCLONE) representation and simulation of discrete systems that deals with deterministic or stochastic variables. There are two basic elements in CYCLONE, a Task element and a Queue element. The Task element represents the active state of a resource and can be of two forms: constrained, requiring a combination of resources prior to allowing resources to flow to the next element (called a Combi), or unconstrained, where resources flow through it unhindered. The Queue element represents the idle state of the resource. That is where resources that cannot proceed to other elements wait.

The actuality of the CYCLONE model will depend on the identification and definition of two common resource flow patterns NORMAL and COMBI together with the associated QUEUE nodes, arrow, and logical relationships. In the CYCLONE system only elements that are logically dependent are the QUEUE node and COMBI processor. A COMBI processor can be preceded only by a QUEUE node and, conversely, the only element that can follow a QUEUE node is a COMBI processor. In Simphony CYCLONE, Simphony is the simulation modelling environment. The elements to regulate the flow of resources in the model:

- Queue element (Queue),
- Combination task (Combi),
- Normal task (Normal),
- Production counter,
- Function, and
- Probabilistic branch (not an original CYCLONE element).

Table 3

CYCLONE System Modelling Elements

Symbol	Function
	Units arriving at Normal will be processed right away without delaying.
	Unit arriving at COMBI will be processed if units are available in all preceding Queue node.
	Queue element is to provide a location in the model for entities to queue while awaiting conditions to be met downstream so they can proceed to the next element, pending COMBI activities.
	Facilitates the consolidation and generation of entities depending on the values assigned to its properties. Consolidate function node performs the consolidate marking.
	Counter measures the modeled system's production rate and to terminate the simulation.
	Arcs show the logic that units flow from element to element.
	It is used to model uncertainty associated with events in systems being modelled
	It can be used to enhance model presentation as it serves as a container for sub models. It does not participate in the simulation

Simulations help bridge the gap in conceptual understanding when paired with readings and cases that provide additional background to the implementation of lean in real construction projects. DES simulation has been mainly used to investigate a wide variety of what-if scenarios about the real-world system and evaluate suggested lean construction techniques to existing systems. The main focus in this research is simulation in lean construction and particularly, integrating VSM with DES.

2.5.3. Simulation in Lean Construction

Simulations have become one of the most important ways to implement lean concepts. Halpin and Kueckmann (2002) process can be efficiently modeled and analyzed from a practical perspective using lean simulation. Therefore, the concepts of lean construction can be validated using simulation as means of testing lean concepts prior to actual field implementation. In order to verify the benefit of changes and assessing the impact of the implementation of lean construction prior to real world application is needed (Shou et al. 2017). In accord (Paul, 2017) simulation is simple, yet easily able to convey the application of lean principles. Halpin and Kueckmann (2002) lean thinking provides a structured format in which processes can be re-designed and simulation offers a methodology for evaluating the benefits to be expected from process re-design.

Al-Sudairi et al. (1999) implements five principles of lean production to a traditional steel erection process using Extend® to observe the effect of the proposed principles. Tommelein (1997) used STROBOSCOPE to model pipe-spool process to show how data characteristic of the system as whole can be generated and lead to insights into process waste. Also, Alves, Tommelein, and Ballard (2006) used a simulation model developed using STROBOSCOPE to represent five different scenarios for planning, fabrication, shipping, and installation of sheet metal ductwork in order to illustrate how production system design choices may affect the lead time needed to deliver a project. Hence, lean implementation via simulation models has been a robust strategy to witness the benefits of lean. On a research conducted to survey simulation modelling techniques Shou et al. (2019) identified CYCLONE as second most popular simulation software (next to STROBOSCOPE) used in construction sector. Halpin and Kueckmann (2002) used Micro CYLONE to analyze the process and improve the rate of installation of metal wall frames, due to re-design using lean concepts. Also, Nikakhtar et al. (2015) used ARENA simulation software to model reinforcement process based on lean thinking approach.

2.5.4. Integration of VSM and DES

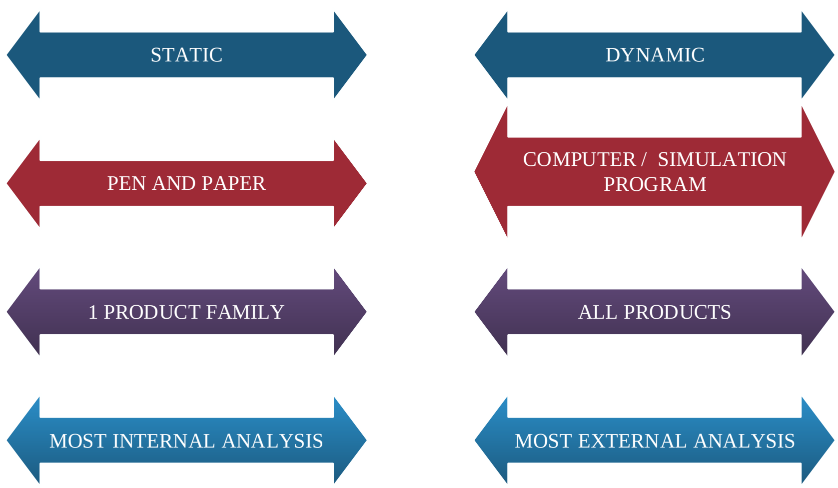
Xia and Sun (2013) VSM gives an illustrative view of the process at any particular instant of time, it may snapshot the wrong representation at that particular instance, which may mislead decision-makers. Donatelli and Harris (2009) VSM and simulation are a natural combination, and each enhances the other's value in the lean manufacturing effort. Using simulation to quantify the benefits that can be expected from implementing system improvements and comparing the actual system with its future performance can assist in making crucial decisions (Abdulmalek & Rajgopal, 2007; Marvel & Standridge, 2009, as cited in Uriarte, Moris, Ng, & Oscarsson, 2015) and avoid failures in the implementation of lean management principles (Anand & Kodali, 2009, as cited in Uriarte et al., 2015). Donatelli and Harris (2009) VSM creates the model and provides the vision, whereas simulation is used to evaluate the model and substantiate the vision. Solding and Gullander (2009) the simulation model can handle several products at the same time and can give more than only a snapshot at one specific time which help eliminate the weaknesses of VSM. Also, Xia and Sun (2013) simulation combined with the VSM offers a viable tool for evaluating the potential level of productivity gains which can be achieved using lean concepts. The vital importance of integrating both is to examine the capability of the lean improvement as simulation model can accurately describe and visualize the dynamics of the process, its performance and the required resources (Aziz et al., 2017).

Yu et al. (2009) are pioneers in integrating DES and VSM in construction. According to them, DES increase understanding of behavior of future design by a VSM. Both DES and VSM provide a holistic assessment of a system, and DES also adds another dimension, time, to VSM (Aziz et al. 2017) and this combination offers insights that may have been missed if VSM alone had been used (Donatelli & Harris, 2009). A simulation model combined with VSM is to examine different scenarios in order to identify the advantages of using VSM (Abdulmalek & Rajgopal, 2007, as cited in Jarkko et al., 2013). Yu et al. (2009) used Simphony CYCLONE to understand the effects of the lean systems proposed on future state map and they were able to observe significant improvement in process reliability. Aziz et al. (2017) investigated the integration of DES, Flexsim, and VSM to enhance the productivity of road surfacing operations by achieving high production rates and minimum road closure times. They indicated that relationship between VSM and DES is a driving innovation in construction processes and a hybrid DES-VSM approach ensures a holistic approach to process optimization.

Donatelli and Harris (2009) simulation makes not only testing ideas easier, cheaper, and quicker, but also gives immediate assessment of proposed changes to the system. In agreement, Implementing lean principles would have been very difficult or impossible without simulation, since errors when implementing an incorrect future state can be costly and result in unnecessary waste and would have made a lean implementation unsustainable (Miller, Pawloski, & Standridge, 2010, as cited in Uriarte et al., 2015).

Figure 6

Some Important Differences Between VSM And Simulation[6]



[6] (Solding and Gullander, 2009)

2.6. Summary of Literature Review and Gap Analysis

It is imperative to enhance project performance as reports and recent initiatives have identified a lack of performance improvement as a key issue in the construction industry. As researches indicate, the status quo of perception of construction as a transformation concept has concealed wastes in the industry. Labor productivity status in Ethiopia has been researched, but flow and value generation theory has been overlooked.

After the innovation of the Toyota Production System by Toyota led Engineer Taiichi Ohno, the automobile industry was able to double productivity over a few years. Then, Womack and others moved from the automotive industry to look at manufacturing in general and established the five principles. Later, the term “lean” was coined by the research team working on international auto production to reflect both the waste reduction nature of the Toyota production system and to contrast it with craft and mass forms of production. After witnessing the improvement in productivity and product quality, Koskela developed the TFV theory of production to overcome the failure of traditional construction management delivery methods, to achieve time, cost, and quality objectives and developed eleven principles. Later, as discussed by Koladiya, Diekmann and others summarized and presented the agreed lean principles that apply in construction, which consists of all Koskela’s eleven principles.

Numerous lean tools are being used in diverse operations worldwide. It is pointed out by researchers that one of the most powerful tools and has been applicable in most industries, from manufacturing to construction is VSM. It is a process improvement technique that has an objective of maximizing value for the final customer. Sahlu and Ayalew observed different operations of building construction and showed the existence of a high share of NVAA in Ethiopia construction. However, the first overlooked the root causes and both researchers didn’t consider the information flow and didn’t analyze the material flow holistically. Similarly, Nikakhtar used a process flow diagram and analyzed rebar operation and identified wastes but failed to identify information flow and related wastes. However, VSM is much more useful than qualitative tools and layout diagrams that produce tally of NVAA steps as indicated by Rother and Shook. Moreover, Pasqualini and Zawislak, and Li and Solís have given insight into the power of VSM in more than identifying wastes and providing information for the redesign of processes. However, it is necessary to adjust

VSM to be used in the construction industry. Pasqualini and Zawislak took the first step and redefined product family to be applicable in the construction industry as a construction stage, based on the concept that each item in the BOQ is what the customer ordered. However, this view of an item as a customer order might lead to stand-alone improvements, which is in contrast with the VSM concept. Which is the focus on overall process performance as discussed by Yu and others. However, the level of VSM adopted by Yu and others has a resemblance to the CPM network diagram as it only focusses on the flow between tasks and overlooks the waste in a single task. This research would be a pioneer in studying the improvement of productivity by identifying NVAA and their causes using VSM and measuring improvements using DES model by the application of lean principles at an operation level of building construction.

Even if VSM is a powerful tool, it has the main drawback of only providing the snapshot of the production process. Consequently, integrating VSM with DES becomes the most efficient technique to attain the utmost benefit of VSM and the application of lean principles outcome. In this regard, Yu and others took the pioneering work and integrated VSM with DES (Simphony Cyclone) in house construction project and stated that the combination of DES and VSM increases the understanding of the behavior of the future design. They not only did that but recommended VSM techniques: incorporating not more than 12 stages of construction tasks, not to map tasks that take more than 2 months of duration, and the level of mapping. Later, Jarkko and others used VSM integrated with DES for analyzing construction component manufacturers and identified that VSM is unable to analytically evaluate the performance of future state design without the help of DES. Recently, Aziz and others worked on improving the productivity of road surfacing operations using VSM and DES and indicated that a hybrid DES-VSM approach ensures an integrated approach to process optimization.

3. RESEARCH METHODS

3.1. Research Methods

After performing an extensive preliminary work reviewing literatures to gain an in-depth understanding and the status quo of the subject matter, a comprehensive research method was designed that could answer research questions and meet objectives.

3.1.1. Research Strategies

Identifying non-value-adding activities and their root causes are the objectives of the study. It requires a meticulous understanding of the production process being performed in order to attain the final objective, which leads to an improvement in productivity. Evaluating the effect of lean concepts and principles for reducing construction process waste needs an actual experiment (Nikakhtar, 2015). Consequently, a case study strategy will be of particular interest. The case study strategy will be of a particular interest to gain a rich understanding of the context of the research and the processes being enacted (Morris and Wood, 1991, as cited in Saunders, Lewis, & Thornhill, 2009). Since a case study strategy is employed in the study, it is likely to need to use and triangulate multiple sources of data to corroborate research findings within a study. Triangulation is the use of two or more independent sources of data or data collection methods in order to ascertain that the data are telling what is being perceived (Saunders et al., 2009).

3.1.2. Research Purpose and Approach

The aim of the research is to integrate VSM with DES to identify the potential of lean construction principles in improving construction labor productivity and very few studies have been conducted in this area. Consequently, not much is known about the situation at hand. Thus, the purpose of the research is exploratory, since exploratory study is undertaken when not much is known about the situation at hand. Exploratory study is particularly useful when there is a wish to clarify an understanding of a problem and uncertainty of the precise nature of the problem (Saunders et al., 2009).

For simulation, there is a high requirement for quantitative data, and for VSM, there is high requirement qualitative data. Thus, it is necessary to adopt mixed methods approach at the same time.

3.1.3. Sampling Technique

Non-probability purposive typical case sampling is used for selecting a project, since the purposive or judgmental sampling enables the use of judgment to select project that will enable best to answer the research questions and to meet the desired objectives (Saunders et al., 2009). As a result, projects with the following characteristics were selected:

1. a project with the proposed production step under execution.
2. a company which is a tier one and a good management strength in applying traditional scheduling (CPM) so that it will give a good improvement indication of applying lean construction using VSM integrated with DES.

3.1.4. Data Collection Methods

This is an exploratory study where quantitative and some qualitative data will be used. To achieve the objective of the study in a comprehensive manner it is necessary to use both primary and secondary data. Consequently, construct validity will be addressed through data triangulation from different sources such as direct observation, interviews, and documents. Internal validity will be addressed through simulation output and external validity is related to analytical generalization.

1. Primary Data.

Primary data is collected from two sources: direct observation and unstructured interview.

a. Direct observation: it is the quantitative source of data for this research. The data that was collected through the observation technique is reliable as the data is recorded by observation from the sampled site in a continuous working time of the production stage. High variability in task durations as well as queuing times and complexity in the construction process make it impossible for the researcher to collect data of a long process through site observations. Thus, a production stage data process times were measured over days and collected in a way that the researcher can have the whole process within a naked eye view. The researcher observed and collected data, viz:

- value-adding time
- non-value-adding time, such as
  - ✓ over-processing times
  - ✓ waiting times
  - ✓ inventories generated
  - ✓ unnecessary transportation times
  - ✓ defects occurred
  - ✓ overproductions
  - ✓ reworks
- cycle time
- lead time
- material flows
- information flows
- employees involved

b. Interview: observation alone seldom yields sufficient understanding of the system. Thus, people familiar with the system should be questioned (Banks et al., 2010). And as a result, interviews were employed:

- ✓ in order to get the interviewees to share their knowledge as the research aims to identify the construction wastes from their root causes as much as their types;
- ✓ so that the interviews were performed with personnel that are part of production stages, to get their opinion regarding the information and material flow. Special focus will be on personnel who are related to the observed cause of construction waste, which has resulted in low productivity such as laborers, foremen, site and office engineers, construction engineers, project manager and resident engineers;
- ✓ for triangulation purpose.

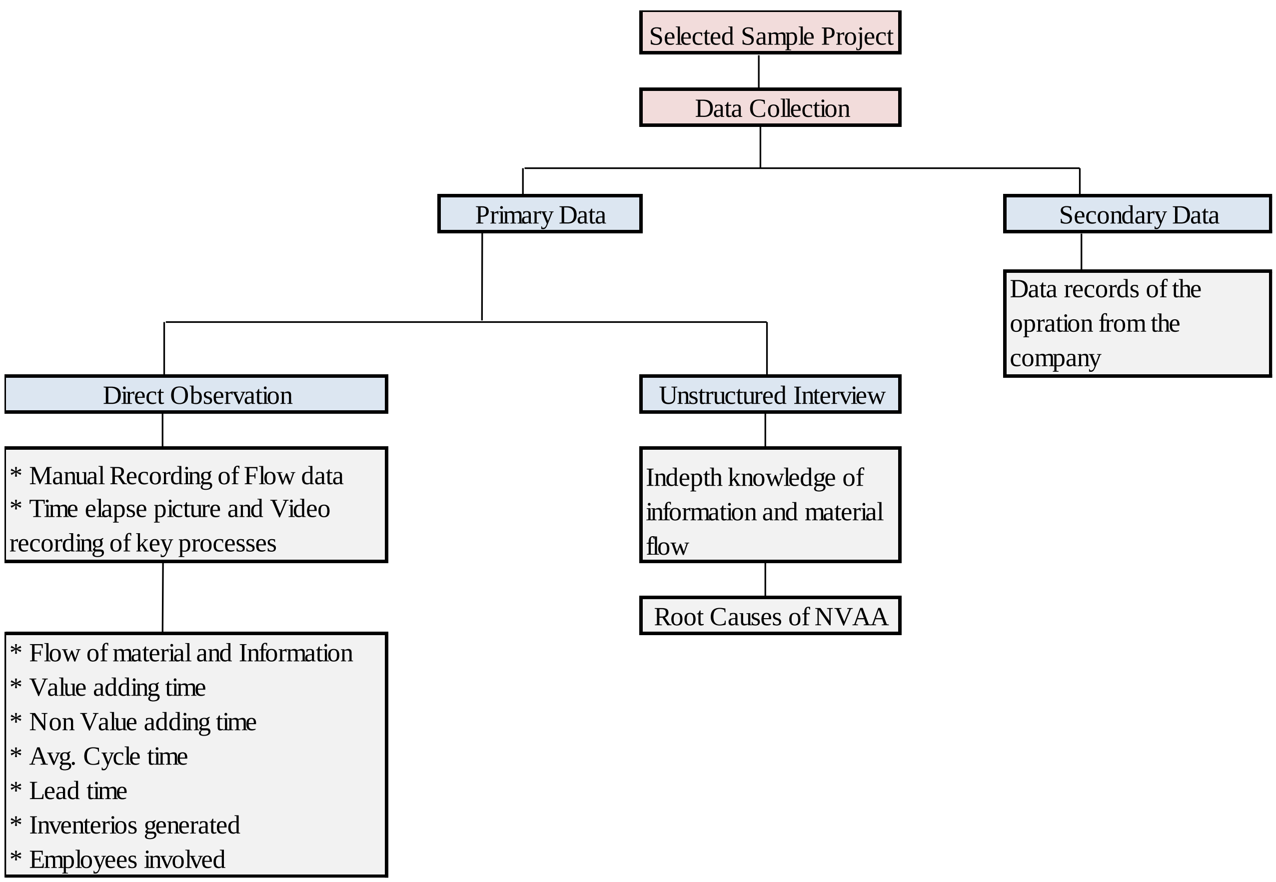
Particularly, unstructured interviews were employed to explore the production steps in depth, as the interviewee has a possibility to steer the interview. It is preferable to use unstructured interviews for the purpose of gathering detailed qualitative data (DiCicco & Crabtree, 2006, as cited in Goodwin & Pantzar, 2017). Also, Saunders et al. (2009) in an exploratory study, in-depth interviews can be very helpful to identify what is happening. Additionally, the researcher was present in site meetings, which helped to know more about the information flows.

2. Secondary Data.

Documents that were available such as daily labor productivity of production steps were collected from the company and were used for triangulation purpose only.

Figure 7

Data Collection Method



3.2. VSM And DES Implementation Stages and Framework

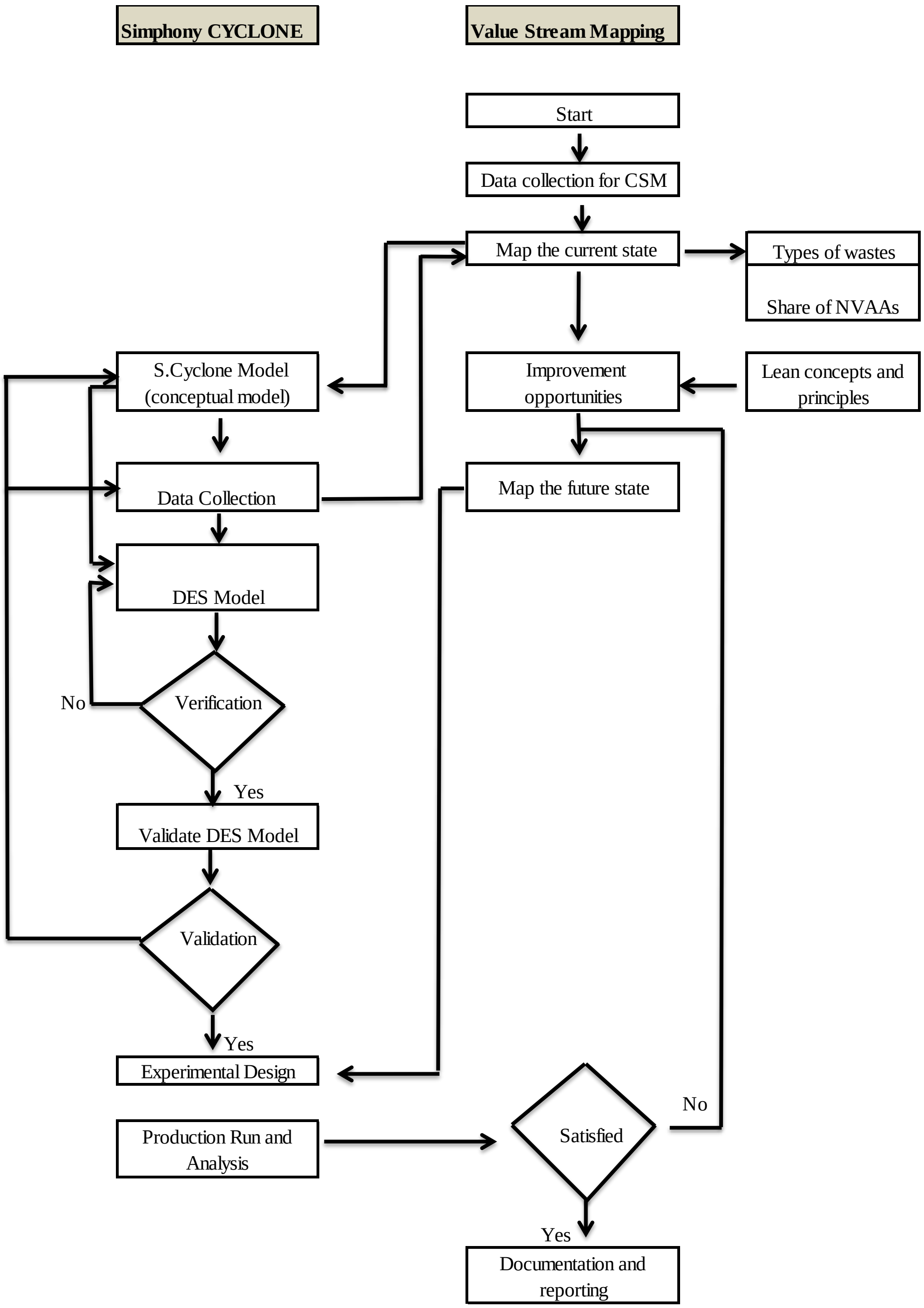
Yu et al. (2009) “Two management decisions must be made prior to the commencement of VSM: 1) select a value stream; and 2) decide on the level of mapping” (p. 783).

1. In manufacturing selection of a value stream according to Rother and Shook (1999) is a product that passes through similar processing step over a common equipment. However, in the case of construction, each large stage occurs progressively during a long period of time and has different processes producing different products. According to Pasqualini and Zawislak (2005), different stages of the construction can be interpreted as different orders of the customers (direct customers) since a general schedule of the construction, programming the period of production of each great stage in order to fulfill the contracted deadline. Thus, instead of selecting a family of products to initiate VSM in construction as in manufacturing, a stage of the productive process of construction is selected, which in this case is a slab reinforcement and HCB work. Yu et al. (2009) argues that products of a home building can be considered as “a single product family because they are generally constructed following similar processing steps and utilizing the same subtrade pool” (p.791). Also, they recommended dividing the entire production flow into stages since including all activities in a house construction in a single map is “too large and cumbersome for small researchers’ team” and set as a rule of thumb for value stream, to not include more than 12 process stations. However, for a single researcher with a novel subject analyzing the production stage from the supply of raw material to the beginning of the next construction stage would be an apposite strategy to pursue.

2. Yu et al. (2009) indicated that the operation of trade crew can be regarded as a continuous flow and would be shown with one activity box on the map. However, Rother and Shook (1999) continuous flow is for materials and information flow. Thus, trade crew movement shouldn’t be a determinate for continuous flow as it would violate the stream and could conceal WIP and other wastes. Consequently, sub tasks which have WIP in between is shown in two boxes. After making decisions, simulation study steps recommended by Banks et al. (2010) was amended to integrate VSM steps. The framework used is shown in the figure below and the elaborated discussion of the steps taken follows.

Figure 8

Framework for Integrating VSM and DES[7]



[7] Banks et al. (2010) project methodology for conducting a simulation study modified by integrating VSM.

1. **Process study preparation:** in this stage, CPM schedule of the operations were reviewed and a quick walkthrough along the entire process was done in order to comprehend material and information flow. AbouRizk et al. (2016) when a model is created, one should be able to describe the general workflow of the real construction process by simply following the journey of the entity within the model. Thus, for both VSM and DES, this step is necessary.

2. **Gemba walk:** in order to identify and categorize VAA and NVAA and their impacts gemba-walk was used. It consists of observing and finding evidence of the aforementioned wastes in the literature. Gemba walk is used to represent the walks managers engage in order to see production tasks' whereabouts and observe as they happen. Personnel who are familiar with lean concepts often call their team members to go to the Gemba and see work practices themselves (Samudio et al., 2011, as cited in Etges, 2018). A series of questions raised to gather background information of the process flow; detailed information about the process with regard to its suppliers, customers, and operational steps so that a greater understanding can be obtained; and the general information for a section such as working days, working hours, work-force. Also, as stated by Mehta (2009, as cited in Björnfot et al., 2011) VSM does not support the identification of bottlenecks. Thus, Björnfot et al. (2011) suggested interviews and walking around the factory to identify or measure bottlenecks, which could be validated through the DES.

3. **Data collection:** data collection sheets were prepared depending on the type of operations (sub constructions). Observation alone seldom yields sufficient understanding of the system behavior, thus people familiar with the system were questioned, as suggested by (Banks et al., 2010). The aforementioned data necessary to draw the current map was collected and after the data collection for DES, input modelling proceeded. A fishbone analysis was used to identify the root cause that could have been overlooked by VSM and to present it in a comprehendible manner. Fishbone analysis is a process of visual brainstorming to identify the most probable causes for the problem which is also known as the Ishikawa diagram. Aziz et al. (2017) it helps to study and analyze the possible reasons that can negatively affect the process output target.

4. **Map the current state:** current state mapping was done to know how things are done and where the improvement solutions lie. Thus, after collecting the required information such as (value-adding time, non-value-adding time, cycle time, lead time, personnel involved including customers and suppliers and inventories generated in each process, and so on), the VSM' was sketched on paper. Icons were used to represent material and information flows. Then, a digital copy of the map was created. When a map of the current situation is documented a parallel map was developed which instead describes the ideal future state (Solding & Gullander, 2009). Also, Rother & Shook (1999) developing the current and future state are overlapping efforts.

5. **Analyzing the current state map/existing practice:** Jarkko et al. (2013) the current state gap presents a visual representation of the value-adding and NVAA in a process. After the review of the current state map by the key person in the operation, the improvements proposed were brought to discussion to the involved stakeholders. Rother & Shook (1999) pointed out some propositions to serve as guidelines for analysis of the map of the current state and Pasqualini and Zawislak (2005) summarized them:

   - which are producing according to takt time;
   - producing for expedition or for a supermarket of finished products;
   - developing a continuous flow where possible;
   - Using "supermarket" to control production where continuous flow is not possible;
   - Sending a customer's programming to a production process only, which is called pulling process, since it controls production rhythms for all preceding processes and
   - Finally, uniform distribution of the production of different items in the pulling process period and leveling the product mix along manufacturing

6. **Map the future state:** after drawing the draft and possible future state in parallel with the current state, the next future state is designed after identifying the potential improvements. Then, a future state design is drawn showing a value stream where the identified problems of the current state have been remedied.

7. **Conceptual model:** the current state map will be used as a conceptual model, as the VSM current state map consists of assumptions about the components and the structure of the system. Donatelli and Harris (2009) the VSM process provides the model and the data and makes simulation easier.

8. **Data collection and analysis for DES model:** Banks (1998, as cited in Goodwin and Pantzar, 2017) the accuracy of the model is directly related to data that is used as input. Thus, data collection and analysis are as important as the model itself. The selected level of significance is 5% for the paper, as it is a research paper. Elapsed time for each process in the operations was taken and recorded whilst workers were engaged in their work, without affecting their normal working pattern. Also, video recordings of the main sub processes and time-lapse pictures were taken for detailed analysis. Afterward, various continuous distribution functions were checked against the collected data, and the best fit according to the goodness-of-fit tests was selected. The continuous similarity of best fit outcomes indicated whether enough samples had been gathered or if more samples were going to be needed. And until consistency is met, data collection proceeded.

9. **DES model (operational model):** the conceptual model after the data collection translated into a working draft Simphony CYCLONE simulation model. A comprehensive simulation model is built to thoroughly understand the operation after the data were collected by observing the operations precisely. The simulation model incorporates each sub-process in the operation with the corresponding cycle times. It is used to model a system to create a visual view of the process and analysis of current performance to present the need for change, which provides a better understanding of the process dynamics to engage participants. Afterward, various continuous distribution functions were tested against the collected data, and the best-fit according to the goodness-of-fit tests were selected.

10. **Simulation model verification and validation:** face validation for the conceptual model validation; VSM, trace logs, entity counter and integrity checks for verification; and parameter variability - sensitivity analysis and comparisons of output behaviors for operational validation are used to validate the model. For the decision-making approaches, whether a simulation model is valid or not, the researcher has proposed the use of “independent verification and

validation”. The Simphony simulation system reports logical errors and data errors that can be identified prior to the model execution. Messages displayed to guide the simulationist on what they need to do to fix these errors. The detailed discussions are presented in the following chapter.

11. **Application of improvements into DES:** after construction and validation of the base model, relevant lean thinking concepts and principles proposed on future state maps were modeled. It was done to assess the effectiveness of the proposed lean systems to understand the intended benefits and evaluate the alternative lean scenarios to predict and evaluate change outcomes. Finally, the studied impact of lean improvement on the system by comparing pre- and post-improvement in productivity were measured.

12. **Discuss simulation model output results:** the final objective of the modelling strategy is to discuss the general finding of the research depending on the result of the simulation experiment.

3.3. Case Study

3.3.1. Building Construction Operations Selection

Improvement in labor productivity of every operation involved in building construction will have effect on the overall project performance as a whole. However, the main interest of the researcher is to measure the improvement of labor productivity through the application of lean concepts and principles using VSM integrated with DES. Thus, the operations were selected based on the following characteristics.

1. level of the labor force that are involved in the production, in other words, based on their labor intensiveness;
2. knowledge of the researcher on the activity. In order to move towards a leaner process, understanding the process, its requirements and methods are necessary (Al-Sudairi, 2007, as cited in Nikakhtar et al., 2015);
3. recurring nature of the activity; and
4. findings of previous researches done in the country.

a. Slab reinforcement bar operation

VSM is an iterative method used to map and analyze value streams (Lasa et al., 2008, as cited in Jarkko et al., 2013; Aziz. et al., 2017; Rother & Shook, 1999). Reinforcement operation is a repetitive process, which contains several sub processes, labors, and resources that interrelate to each other from its preparation to positioning in place. The higher the number of workers in an activity, the higher is the level of waste to be expected since the lack of production control is found. Sahlu (2017) showed that approximately 60 % is spent on NVAA in reinforcement operation. Hence, it seems to be an appropriate process for testing and evaluating lean principles application. Reinforcement of concrete is not an easy task, so it needs a detailed analysis of proper execution on site. The operation is examined from the hauling the material from storage to the start of the next activity.

b. HCB work

HCB work operation is a repetitive process, which contains several activities, labors, and resources that that are connected to one another from its preparation to placement. According to Ayalew et al. (2018), approximately 55% of the time is exhausted on NVAA in executing HCB work. Also, the operation involves different material and information flows. Consequently, VSM being a powerful tool to manage material and information flow, it is a good operation to analyze and seems an appropriate process for testing and evaluating lean principles application. The operation will be examined from the arrival of HCB on the site to the start of the next activity in the building construction.

4. CURRENT STATE MAPPING

VSM is a powerful tool than other lean tools for visualizing the flow of information and material in the production and its ability of creating collaborative working environment. Visualizing the flow creates the ability to see where, when, and how both the information and product flows through, and consequently recognize and eliminate the source of waste (Xia & Sun, 2013). In spite of the application of other lean tools showing good results, Vrijhoef et al (2002, as cited in Pasqualini and Zawislak, 2005) emphasize that, the isolated and punctual manner with which they are implemented, in addition to limiting the possibilities of improvements along the value flow, are not exhaustively mitigating the main problems and wastes of construction. Picchi (2000) one way to make possible a systemic implementation of lean construction would be through VSM application, precisely because this permits to view the production process as a whole, and so identify existing wastes, showing where improvements should really be searched. In accord Pasqualini and Zawislak (2005), VSM represents the main principles of lean production, makes it possible to identify throughout the value flow the main problems and process wastes, and to consider action for improvement.

According to Rother and Shook (1999), VSM shows the linkage between the information flow and material flow, which no other tool does. It is much more useful than quantitative tools and layout diagrams that produce a tally of non-value-added steps, lead-time, distance travelled, the amount of inventory and so on (Rother & Shook). VSM is good for describing what should be done to affect those numbers. Also, visualizing the flow creates the ability to see where, when, and how both the information and product flows through, and consequently recognize and eliminate the source of waste (Pasqualini & Zawislak, 2005; Xia & Sun, 2013). Hence, VSM is an ideal lean tool to employ for the application of lean principle and attainment of its benefit for enhancing productivity in construction process.

This study extends the issue of lean principles applicability to construction through VSM by focusing on the slab reinforcement and HCB work in building construction. Thus, a project of 1B+G+10 building, which is being constructed for a multi-purpose use were selected as a case strategy to study the slab reinforcement operation and 2B+G+12 building, which is being constructed for students’ dormitory were selected to study HCB work.

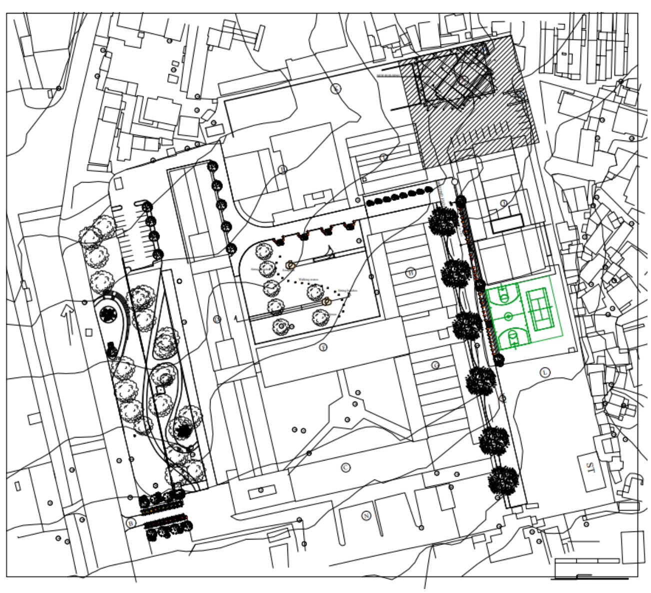
4.1. Value Stream Mapping Data Set

4.1.1. Case Study One

The company is tier one building contractor, with over twenty years of experience in the building construction. The project under study was a 1B +G+10 building, which is being constructed for a multi-purpose use. The company received the project and commenced construction on Nov 2018 and during the data collection it was at the stage of second-floor slab construction. According to the schedule, the progress should have been at the stage of finishing work by the time of the data collection. According to the contractor, some of the main causes for this delay were unanticipated underground condition and redesign, which suspended the construction for over six months. However, it's being outside the scope of the study, further research wasn't done. The updated CPM schedule shows that the rebar operation to be completed within three days of work given that rebar production will start somedays ahead.

Figure 9

Site Plan of Case Study One Project Site



Note. The shaded part is the actual site

The plotted area of the building is 633 m^2. The researcher observed the whole rebar work for the second-floor solid slab operation and collected data for every sub process involved. Reinforcement bars are stored, cut and bend on the construction site and delivered to actual working area. The sub processes observed are shown below in the table.

Table 4

Sub Processes of Slab Reinforcement Operation

Subprocess	
Hauling for Production	Hauling from storage area to the production area
Straightening	Straightening U-bars into 12m straight bar
Measuring and Marking	Arranging rebars to be measured and marked
Cutting	Cutting rebars into the required length
Hauling for Bending	Hauling rebars from cutting to bending area
Bending	Bending the rebars according to the design
Staging	Staging rebars to be taken to the positioning area
Hauling for positioning	Hauling rebars to the place of positioning
Bar Positioning and Tying	Positioning and tying rebars as specified in the design

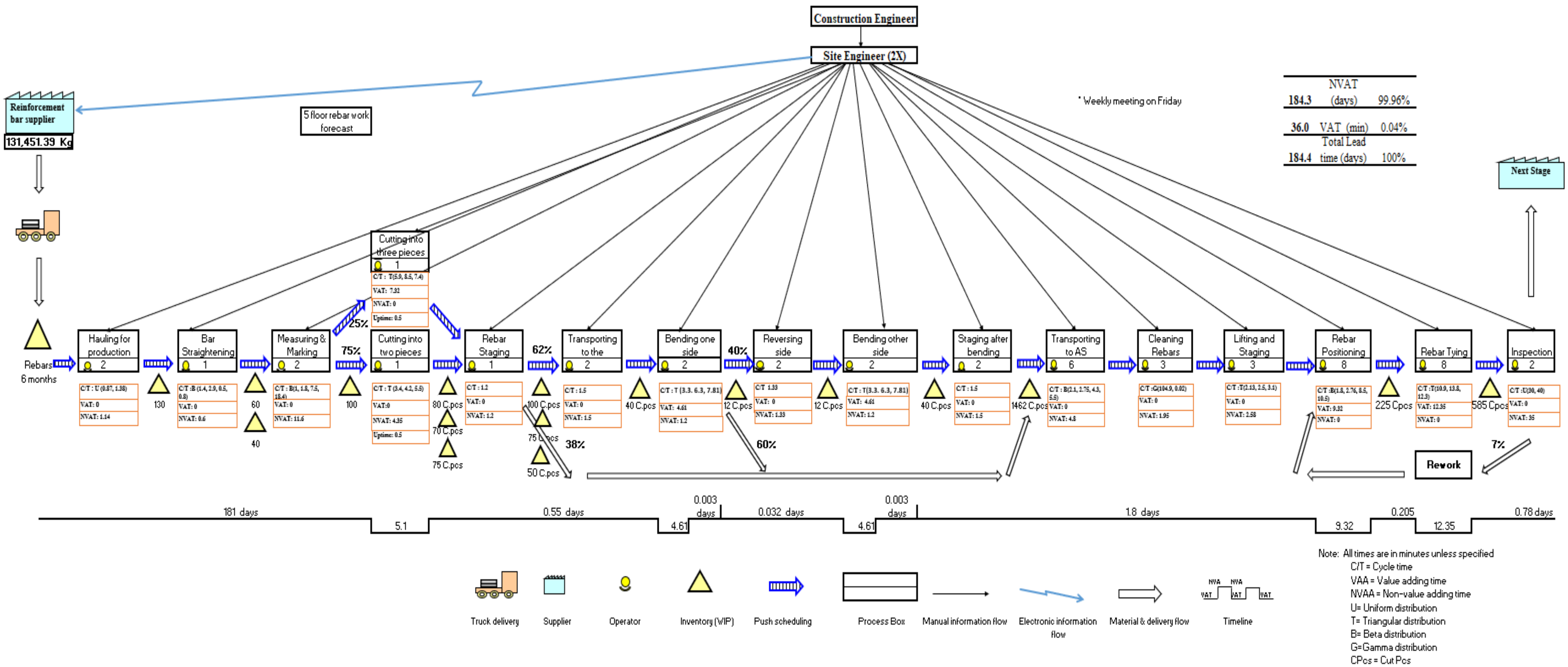
4.1.1.1. Slab Rebar Operation Current State Mapping.

Current state mapping helps to visualize VA and NVA activities in a process and to know how things are done and where the improvement solutions lie. The current status is mapped to capture a snapshot of how things are done and where the improvement solutions lie (Xia & Sun, 2013). It was done after collecting the required information such as lead time, personnel involved (including customers and suppliers), inventories generated in each process and problems affecting labor productivity (NVAA) for the second-floor solid slab rebar operation.

All rebars required to complete every rebar operations from 1st to 5th floor, were already delivered on site by the time the data collection was taking place. It was made at the completion of sub-structure structural work by anticipating demand. Every operation on site including slab rebar is executed by the supervision of the contractor and subcontractor's site engineers. The site engineer of the subcontractor, who directly controls the operation, pass orders to the foreman by reading the structural drawing of the slab. At the time the site work was at the end of the column formwork work, slab rebar production commenced by two bar bender 'BB' and two assistant bar bender 'ABB'. Before slab rebar positioning commenced, an average of 650 pieces of rebar production was completed. Rebars are hauled from the storage area for straightening then after straightening some rebars, rebar workers move to arranging rebars to be measured and marked. After measuring and marking rebars, rebars were cut and transferred to the bending site. After bending rebars, rebars were staged to be taken to the positioning area. Finally, positioning and tying was done, and a completed slab rebar product formed. Inspection was done by the contractor's site engineer with the resident engineer at the end of each working day. Each working day consists of eight hours as regular working time, with one hour as a lunch time. In the slab rebar operation, each process possesses different numbers of rebars to be executed, and cycle time is calculated by process, as suggested by (Pasqualini and Zawislak, 2005). It was not necessary to collect data about replacement time because there are no changes in product manufacturing. In order to depict the current state of the selected value stream, the researcher walked through all the steps involved and collect statistically valid data for all the activities in the process.

Figure 10

Current State Map of Slab Rebar Operation



4.1.1.2. Slab Rebar Current State Map Analysis.

Analysis is what actually allows to identify wastes and propose improvement actions for the construction of a new flow, which generates the shortest lead time, higher productivity, and highest quality. The analysis of the current state map is discussed hereinbelow in accordance with the process of the operation. So, it is important to pay attention to each action necessary to make the product, from the moment of order until its delivery to the client, challenging each step as long as it is necessary or not, that is, to identify the product's value chain.

1. Delivery and Storage of Rebars

- Inventory is the first NVAA that was prompted by delivering the rebars by push system. Tommelein and Li (1999) push systems tend to increase the amount of waste, such as long excessively large inventories because they are estimate driven. All rebar order to be used for rebar operation from the 1st to the 5th floor (131,451.39 kg) was made by anticipating demand, in other meaning by push system. Push scheduling was causing defects in the rebars because rebars were on site for a long time and it has started to corrode. Due to the defect in rebars, some were breaking during bending. In turn, the defect was causing over-processing because the rebars were being cleaned by two laborers before positioning and tying was executed, and was consuming a significant amount of time. Moreover, it was causing monetary losses due to capital tied up and cash flow was an issue in the project. Cash flow issue by itself is a cause for low labor productivity (Amanuel, 2016) and beget a vicious circle of waste.

- The rebars stored at both sites were unloaded and stored in a haphazard manner and there is no standardization of where the stock should be. Consequently, rebars were being stomped on where it was stored and was being deformed. Singh and Delhi (2018) a material storage wastage is a result of bad inventories. It is caused by inefficient methods of unloading and the lack of material flow planning (Dajadian & Koch, 2014, as cited in Koladiya, 2017), which also resulted in an unnecessary movement to find the required rebars. Singh and Delhi (2018) an unorganized way of stacking the pre-engineered components lead to huge monetary loss, due to deformation of the components.

Figure 11

Haphazardly Stored Rebars

- In construction, delivery of one piece at a time isn't realistic. Thus, continuous flow isn't applicable for delivering the rebars (Rother & shook, 1999). Consequently, a supermarket pull system should be adopted to set the stream (Rother & shook); to avoid the need to check available resources; to eliminate unnecessary movement and mitigate the inventory problem (Melo et al., 2017); to synchronize production with execution and to replace the stop and start workflow with a continuous flow (Pasqualini and Zawislak, 2005; Shou, 2017). The purpose of the supermarket pull system is to have a means of giving supply instruction. It is to reduce the supply of rebar and also improve its control, indicating when it is time to buy more rebar, which can avoid the arbitrary ordering of rebars. This supplying process is controlled by an information transmitted through a Kanban, which can be described as a control system for replenishing material based on actual demand (Burgos & Costa, 2012). The supermarket gets replenished by issuing a supplier kanban when an inventory is low. The aim of Kanban is to achieve a JIT system/concept, and this signaling system can be an empty shelf. Arbulu (2006) synchronizing demand and supply at the operations level, would minimize waste and enhance value. Thus, to synchronize the supply of rebar with demand, we have to compromise two factors. These are, the capacity of a trailer vehicle, which is 40,000kg and an average Kg of rebars required to execute a floor work (all vertical and horizontal structures), which is 38,557.54 kg. Thus, requesting a floor of work of rebar by checking the supermarket, which indicates the progress and triggers a supplier kanban, one day prior to the commencement of the operation was found to be an apposite delivery strategy.

2. Hauling for Production, Straightening and MMC

- The laborers were transporting more rebars than needed from storage to be straightened. Rebars were being straightened more than needed to be MMC and are also being cut more than needed. Moreover, rebars were hauled, straightened, cut and bent continuously for days (overproduction) and were creating a huge amount of WIP. Overproduction is producing more or doing more and sooner than it is needed. “It is a ‘primary’ waste driving of other wastes in a vicious circle of waste generating waste” (Ohno 1988 as cited in Koskela et al., 2013, p.6). Later, Koskela et al. (2013) argued that it can’t be justified in construction because construction is a produce-to-order process. However, when we analyze construction stages as customer orders as suggested by (Pasqualini and Zawislak, 2005), we consider not only the final requirement, which is the building, but the items in the bill of quantities the customer has ordered. In each workstation of the process, rebars were being delivered to the next workstation in mass and were creating WIP. Thus, overproduction evidently does exist. Consequently, the aforementioned activities are busy whilst positioning and tying are not active and vice versa. Thus, maintaining WIP is imperative and could be managed by making the flow of rebar constant, so that entities flow concurrently (Nikakhtar, 2015). And by incorporating the concept of CONWIP, Arbulu (2006) which is a pull production system to cap WIP, the number of entities will be maintained (small-batch sizes) in the number of average entities processed during cutting, which is 20 Pcs of rebar. The CONWIP concept is adapted because associating cards isn’t feasible since operations are far apart for their effective handover. Howell (1999) lower WIP tied up less working capital and decrease the cost of design changes during manufacture as only a few pieces are needed to be scrapped or altered. Therefore, managing buffer size (WIP) is a critical component in implementing lean principles in construction processes (Al-Sudairi et al., 1999). Additionally, applying pull technique is necessary, as its aim is producing only what is needed, when it is needed, and in the right quantities and it ensures just-in-time coordination between upstream and downstream tasks. Picchi and Granja (2004) pull and flow lean principles are the core characteristics of lean thinking and are cornerstones for the elimination of waste. When both are properly implemented, the benefits are smaller buffers, earlier project completion, and increased productivity (Howell 1999; Nikakhtar et al., 2015; Picchi & Granja, 2004).

Figure 12

Arbitrarily Placed WIP In Between Sub-Processes

- The straightening and MMC area were on the paseo and rebars were being stomped on by other trade workers passing by. Which was causing a defect and leading to over-processing. In addition, it was taking space, blocking the way, and creating congestion. Singh and Delhi (2018) the blockage of a construction site happens due to an improper envisaging of the future scenarios by the planning team and the poor housekeeping of the site. In a hurry to start the execution, the planning of site layout planning (SLP) is not given proper concern, and as a result, as the construction progresses, the site becomes a fouled-up place.

Figure 13

Defect Due to Push Delivery & Straightening

Note. Corroded and zigzagged rebars

- The most time taking activity was straightening (making U bars of 12-meter length into straight 12-meter) and defects in straightening were also creating variability in the execution of the bending work. The nature of straightening by itself is over-processing because rebars are first fabricated straight and bent for transportation purpose. However, it is necessary for some conditions, but it does not add value to the product. This can be avoided by ordering 12-meter straight rebars using a trailer vehicle. In this way the operation is simplified by minimizing the number of steps.

- The site layout problem was creating unnecessary transportation because there was no place for specific work. Thus, workers were moving around looking for cutter and rebars that were cut and placed arbitrarily. Moreover, the working area is too spread out and has led to reduced labor productivity. Rebars are laid on the ground and not stacked properly. Bending and cutting benches are wrongly placed. These are due to the improper planning of the site layout. Singh and Delhi (2018) improper site planning can lead to tremendous wastes in terms of unnecessary transport of materials and other resources around the site. Lota and Trivedi (2019) site layout planning is a critical factor for the successful execution of any construction project. Abou Dargham et al. (2019) construction site layout is a crucial step before allocating resources to it; space is a critical factor that impacts both labor productivity and ease of material reach when needed. Most construction site layout plans are developed based on the experience gained by site engineers and foremen. However, the planning of site layout is considered to be a combinatorial task where project stakeholders require collaboration and coordination among and across teams for decision making (Singh and Delhi, 2018). Thus, collaboration in planning site layout is an indispensable and necessary condition to improve labor productivity. Consequently, the redesigned site layout is shown in chapter six. Also, applying 5S workplace organization is necessary alongside site layout planning. 5S: Sort, Straighten, Shine, Standardize, and Sustain is a basis of lean thinking and continuous improvement. Thus, sorting and setting the rebars by their diameter and arranging them in a compartmented location is necessary to save time spent in searching and keep it safe at a single and easily reachable location. Keeping the work area clean and organized by cleaning after each working day and in between when necessary to maintain the standard of the workplace and good working order has paramount importance to reveal abnormalities easily. Thus, setting and maintaining the standard to achieve productivity at the desired level in a safe working environment. Finally, sustaining it through training and inspection for continuous improvement. Waste elimination and value generation can be obtained through appropriate site layout planning, leading to time and cost savings (Lota & Trivedi, 2019).

3. Bending

- Production of rebars before the commencement of positioning were taking place at the production site, which is twenty-five meters away from the positioning area, because most of the rebars required for the slab operation, diameter eight and ten, were unloaded and stored in the production area. In this area, there are two bending tables placed consecutively. An average of twelve rebars were cut, hauled from the cutting area, and placed in front of the bending table. One side of the rebars bent one by one and placed on the floor then after the BB reverse and load it back and bent the other side. This custom of doing the work is cumbersome and full of unnecessary movement, which has resulted from over-processing. This is related to the nature of the processing (conversion) activity, which could only be avoided by changing the construction technology. It was prompting a discontinued flow, yet we strive to develop a continuous flow where possible (Rother and Shook, 1999). Li and Solís (n,d) VSM was not limited only to identifying waste in a system, but could also be used to analyze and aid in designing processes.

Figure 14

Bending Site

In accord, Tommelein and Beeche (2001) innovated a cladding installation system using the principle of “decoupling linkages” and introduced “Beeche” installation system. The researcher found that it is indispensable to redesign the bending table in a way the waste could be mitigated. Which is a table that allows two BB to work in a continuous manner without creating WIP. Failing to allow a continuous flow of materials will have a negative effect on labor productivity and project costs as well as increasing waste (Khalfan et al., 2008 as cited in Burgos & Costa, 2012). It is evident that lean principles not only improve project performances but prompt innovations.

- Waiting for instruction was one of the major wastes, which was disrupting the continuous flow of work and adversely affecting labor productivity (Amanuel, 2016). The cause was the absence of the site engineer, by being tied up by other trade works, to give instruction on time. The researcher found that fundamental change in information management is indispensable since visual control can’t be applied where subprocesses are far apart (Yu et al., 2009). Consequently, proposing a signalizing kanban was found to be an appropriate measure to eliminate the waste. The signalizing kanbans will be made of plastic paper, which contains information such as the number of rebars to be processed under each aforementioned subprocesses; diameter of rebar; cutting and bending length; and delivery slab panel. It will be hung in each sub-process working area as a signalizing kanban of what, when, and by whom should be done. This reduce the necessity of the site engineer to give daily instructions to each employee since it already shows what should be done. In this way, the site engineer has more time to follow the processes by getting the required quality for the first time and analyze where the problems are, and think about possible solutions (Pasqualini and Zawislak, 2005), so that rework could be precluded. The prompted rework affects labor productivity significantly (Alemu, 2006; Amanuel, 2016). Pasqualini and Zawislak (2005) this kind of kanban is used to get all persons involved in the process to compromise to what was planned, in order to make production flow continuous, eliminating stop times between the processes. Moreover, it will avoid verbal communication and enhance transparency (Melo, 2017), and having daily hurdle meetings would amplify the benefits. The laborers also move from a workstation to another and no fixed assignment is given for individual labor. Thus, allocating labors to all the sub-operations depending on their abilities is necessary.

- Singh and Delhi (2018) have indicated that waste results out due to the improper planning of the location of the storage facility and the location of material consumption and lack of on-site waste management plans. Material wastages that were being generated in the process were one cause of low productivity. The waste was not being transported to any disposal area instead it was lying on the site and adding congestion to the site and blocking the way. Congestion of site has a significant adverse impact on labor productivity (Alemu, 2006; Amanuel, 2016; Zhao and Chua, 2003).

Figure 15

Material Wastages on Site

- Lack of process transparency increases the propensity to errors, reduces the visibility of errors, and diminishes motivation for improvement. Thus, it is an objective to make the production process transparent and observable for facilitation of control and improvement. In accord with Melo et al. (2017) application of the principle of perfection (continuous improvement) through an improvement in the construction site's layout, with the purpose of organizing the supermarket inventory by rebar diameter, a sequence of delivery and proximity to the actual site would improve project performance dramatically.

4.1.2. Case Study Two

The company is a tier one and the leading general contractor in the country with over twenty years of experience in the building construction. The project under study is a two 2B +G+12 buildings, which are being constructed for students' dormitory use. However, the researcher conducted her study on one of the two buildings, on which the operation under study was being executed. The company received the project and commenced construction on April 20, 2018, and during the data collection, it was at the stage of 5th-floor slab construction and 1st-floor blockwork. According to the schedule, the progress should have been at the stage of 7th-floor slab work by the time of the data collection. According to the contractor, one of the main causes was cash flow problem.

The plotted area of the building is 850 m^2. The researcher observed 300 m^2 HCB (20cm) work for the first floor and collected data for every sub process involved. Data collection of HCB wall construction is divided into three row groups, because of the high variability in cycle time. The sub processes observed are shown below in the table.

Table 5

Sub Processes of HCB (20cm) Work

Subprocess	
Hauling HCB to the site	Hauling from storage area to the actual site
Hauling in between	Hauling HCB and mortar in between
1st HCB row	This includes setting, marking, mortar placing, placement of the first row, one square meter of HCB and adding mortar in between to finish.
2^{nd} row to 9^{th} row	This includes mortar placing, levelling, placement of a square meter of HCB,

Subprocess	
	which are between 2nd row to 9th row, and adding mortar in between to finish.
9th row to 14th row	This includes mortar placing, levelling, placement of a square meter of HCB, which are between 9th row to 14th row, and adding mortar in between to finish.

4.1.2.1. HCB (20cm) Work Current State Mapping.

The total block work contract amount of the project is ETB 24,074,425.87. Thus, analysis and improvement of the operation is indispensable. The researcher observed 300 m^2 HCB (20cm) work for the first floor for over a period of two weeks and collected data for every sub process involved. In order to depict the current state of the selected value stream, the researcher walked through all the steps involved and collected statistically valid data for all the activities in the process. Labor productivity data collected by the contractor was available and is used as a secondary data source. The researcher studied the trend of the data collected and compared it with the primary source.

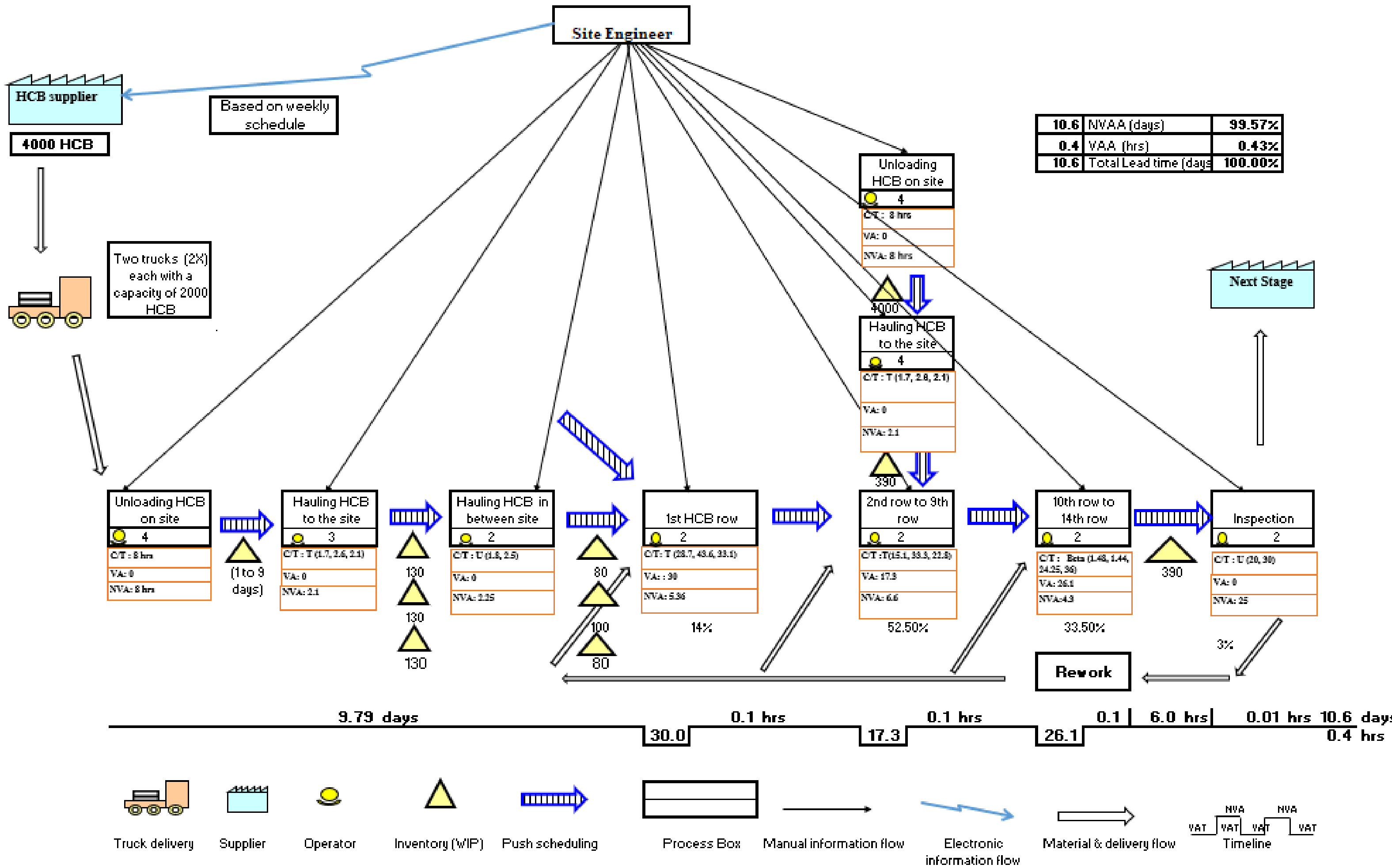
Figure 16

Site Plan of Case Study Two Project Site

HCB are delivered to the construction site once in week, by two trucks, each with a capacity of 2000 Pcs. It is unloaded by four laborers right away after delivery. The HCB is hauled to the actual site manually, three laborers were allocated for this task. After hauling all the ingredients, cement mortar was being prepared in the actual site in a common area for masons working in different locations. However, it is found sufficient to map the flow of main material HCB in this level of mapping (Rother and Shock, 1999). The HCB are hauled in between site by assigned helpers to the mason crew. The operation was being supervised by a site engineer and construction engineer. The site engineer who directly controls the operation possesses orders to the foreman by reading the drawings. Inspection was done by the site engineer of the contractor with the resident engineer near the end of the working day. Each working day consists of eight hours as a regular working time, with one hour as lunchtime. It was not necessary to collect data about replacement time because there are no changes in product manufacturing.

Figure 17

Current State Map of HCB Work



Note: All times are in minutes unless specified

VAA = Value adding time C/T = Cycle time T= Triangular distribution
NVAA = Non-value adding time U= Uniform distribution B= Beta distribution

4.1.2.2. HCB Work Current State Map Analysis.

1. Hauling HCB to the site

- HCB was being delivered on site and from the storage to the actual site continuously by push system, and were creating WIP. Moreover, on the commencement date of the data collection leftover HCB from the previous day were on site. Tommelein and Li (1999) push systems tend to increase the amount of waste, such as long excessively large inventories because they are estimate driven. The delivery of the rebars should match the demand and incorporating supermarket pull was necessary. The two-truck delivery per a single day should be made on different days of the week by checking the supermarket. As a result, defect of HCB due to inappropriate stacking could be prevented. A reduction of work in progress (WIP) and inventory levels gives shorter lead times according to Little's law and a more flexible process (Simonsson et al., 2012, as cited in Jarkko et al., 2013). A push system leads to overproduction, which is producing more or doing more and sooner than it is needed. HCB were being accumulated in one position than it was necessary, and it was prompting unnecessary transportation, when the masons move to another work location. The continuous unnecessary transportation was also causing defect in the HCB (cracks and breakages). The leftover and broken HCB were on the paseo and were creating congestion and blocking movement for other trade workers. To flow the entities in accordance with the process, first, the batch size delivered in the step will be decreased. This can be done by incorporating a FIFO system and by limiting the FIFO lane based on the capacity of a portable pallet (capacity of 60pcs, 1.4m x1.8m). FIFO and kanbans are used to set the stream, whenever it is not possible to keep a continuous stream (Rother and Shook, 1999). Yu et al. (2009) FIFO-lane-based system is used to provide a predictable flow to trade contractors. Howell (1999) lower WIP tied up less working capital and decrease the cost of design changes during manufacture as only a few pieces needed to be scrapped or altered. Thus, after laborers hauled 60 pcs, they would assume that there is no spot to place HCB and cease hauling until a flag is shown to trigger the next hauling. The Flag is a signalizing Kanban to indicate the need for HCB.

Figure 18

Unloading and Storage Area Of HCB

2. **Block Placing**

Rework was one of the issues in the project and was taking a significant amount of time. Some of the issues prompting rework were, the lack of integration between sanitary, electrical, and site engineer. Consequently, proposing a kanban and hurdle meeting was found to be an appropriate measure to eliminate the waste. The kanban will be made of plastic paper, which contains information such as the number of HCB necessary at each location; the size of HCB; and installations that exist. It will be hung on each wall section b/n columns as a signalizing kanban. This reduces the necessity of the site engineer to give daily instructions to each employee since it already shows what should be done and reduce the rework that is caused by miscommunication. In this way, the site engineer has more time to follow the processes by getting the required quality for the first time. Moreover, it will avoid verbal communication and enhance transparency (Melo, 2017).

Figure 19

WIP On Site

- Waiting for instruction and material were the major NVAA in the HCB work and have a significant impact on labor productivity (Zhao and Chua, 2003). Waiting was disrupting the continuous flow of work. The cause was the passiveness of the communication between laborers who prepare mortar and masons. Mortar is prepared for HCB and plastering work occurring near each other. Unless laborers who transport the ingredient and prepare the mortar, go and check, locating them and ordering is time taking. Thus, the researcher found that fundamental change in information management is indispensable since visual control can't be applied where subprocesses are far apart (Yu et al., 2009). Thus, a signal Kanban of flag (different one used to indicate the need of HCB) would mitigate the waiting waste.

- The most time taking activity during executing 9th to 14th row HCB work was cutting 20cm HCB to fill small openings left at the top. This over-processing waste could be removed by the principle of simplification, ordering 5cm HCB, which is available in the market. Koskela (1992) simplification can be understood as reducing the number of steps in a material or information flow. Nikakhtar et al. (2015) It leads to an increase in the value transferred in a cycle time of the process and productivity improvement.

Figure 20

Broken & Cracked HCB on the Paseo of Site

- Unnecessary or inefficient movements of masons for tools was prompting variability in cycle time, since there was no specific location to place tools. Consequently, a tool kit was found to be necessary to preclude the unnecessary movement. Additionally, material wastage that was being generated in the process was one cause of low productivity. The waste was not being transported to any disposal area instead it was lying on the site and adding congestion to the site and blocking way. Singh and Delhi (2018) indicated that waste results out due to the improper planning of the location of the storage facility and the location of material consumption and lack of on-site waste management plans (Dajadian & Koch, 2014, as cited in Koladiya, 2017). Consequently, a tool kit is proposed based on the concept of 5S, which is a basis of lean thinking and continuous improvement. By sorting the important items to perform the activity to save time in searching, setting items in a tool kit to use; keeping the work area clean and organized to maintain the standard of workplace and good working order; setting and maintaining the standard to achieve productivity at desired level; and sustaining it through training and inspection, would mitigate the unnecessary movement and wastage.

4.2. Fishbone Diagram

VSM is not only limited to identifying wastes in a system: it shows why wastes exist (Li and Solís, n.d; Pasqualini and Zawislak, 2005). Aziz et al. (2017) Fishbone diagram is a root cause analysis technique that helps to study and analyze the possible reasons that can negatively affect the process output target. In this research, a fishbone diagram is employed to aid VSM in identifying root causes and to readily present them.

Figure 21

Fishbone Diagram for Root Cause Analysis of Slab Rebar Operation

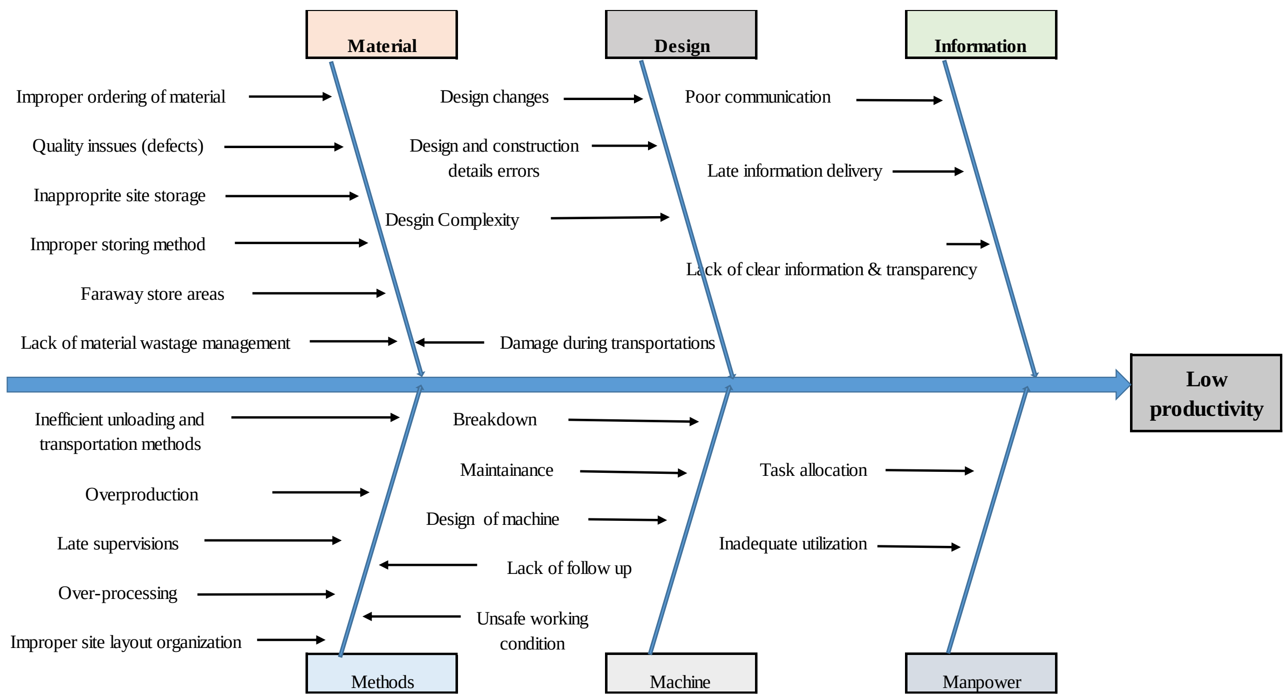
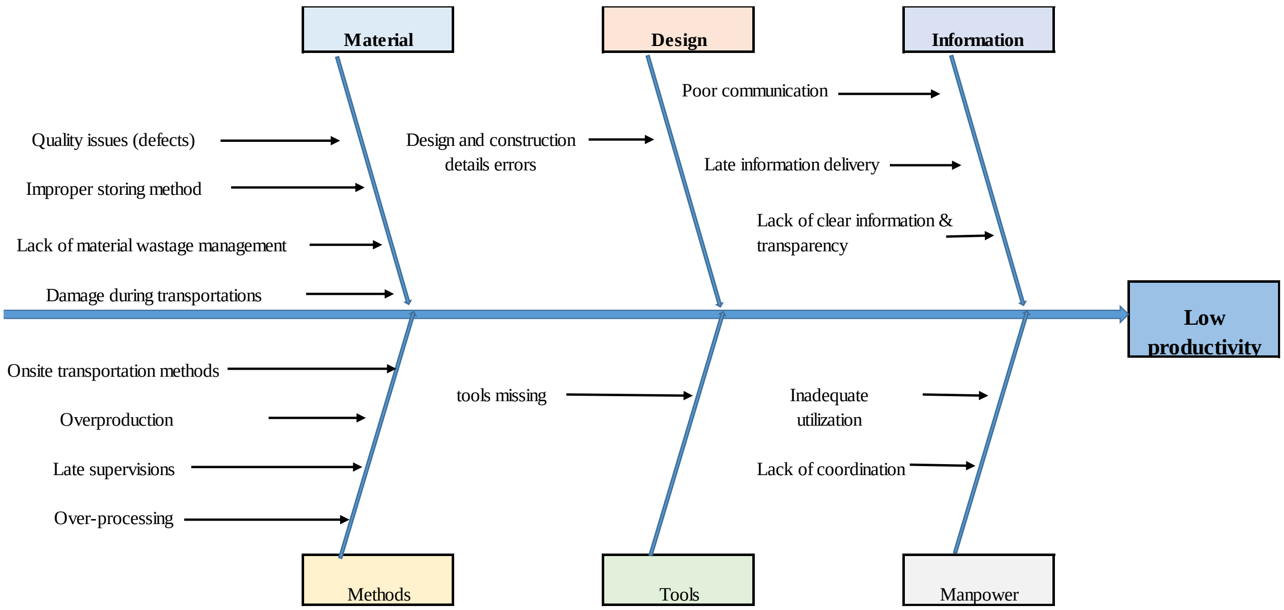


Figure 22

Fishbone Diagram for Root Cause Analysis of HCB Work



5. MODELLING AND SIMULATION

VSM presents statics view in sketchy format whereas real process is dynamic and more complex with changes happening in precise time. Simulation is the appropriate tool as it can advance the ability of VSM by adapting the dynamic view of the flow. The simulation can be used in analyzing and evaluating the current and future states. Donatelli and Harris (2009) stated that, both VSM and simulation take a holistic look at the system, but VSM is an efficient design tool, while simulation is an efficient analysis tool. Discrete event simulation has high flexibility and shows precise state change within the process, which makes it an ideal simulation technique for construction. DES is a very advanced simulation and powerful method to imitate, predict and evaluate the behavior of a real-world system by modelling repetitive processes in which durations of operations are stochastic and many resources interact (Banks et al., 2000; Law and Kelton, 2000, as cited in, Lu et al., 2007)

CYCLONE models processes based on discrete event simulation. CYCLONE is known for its simplicity and ease of use, as it only uses few modelling elements to enable a complete model of a construction operation (Newstead, 2015). Simphony CYCLONE was used to carry out the intended simulations considering it is one of the simulation software applications for its ease of use, rich functionality, such as integrity checks and capabilities of tracking different data points such as cycle time. Additionally, Symphony facilitates the development of a special purpose template for a focus area of application such that models with different configurations can be easily built Hajjar and AbouRizk, 1999. Also, AbouRizk and Mohamed (2000); Hajjar and AbouRizk (1999) it is a proven simulation software in the construction industry and implemented in higher education institutes in the past ten years. They confirmed that it is user-friendly with a graphical user interface and incorporates:

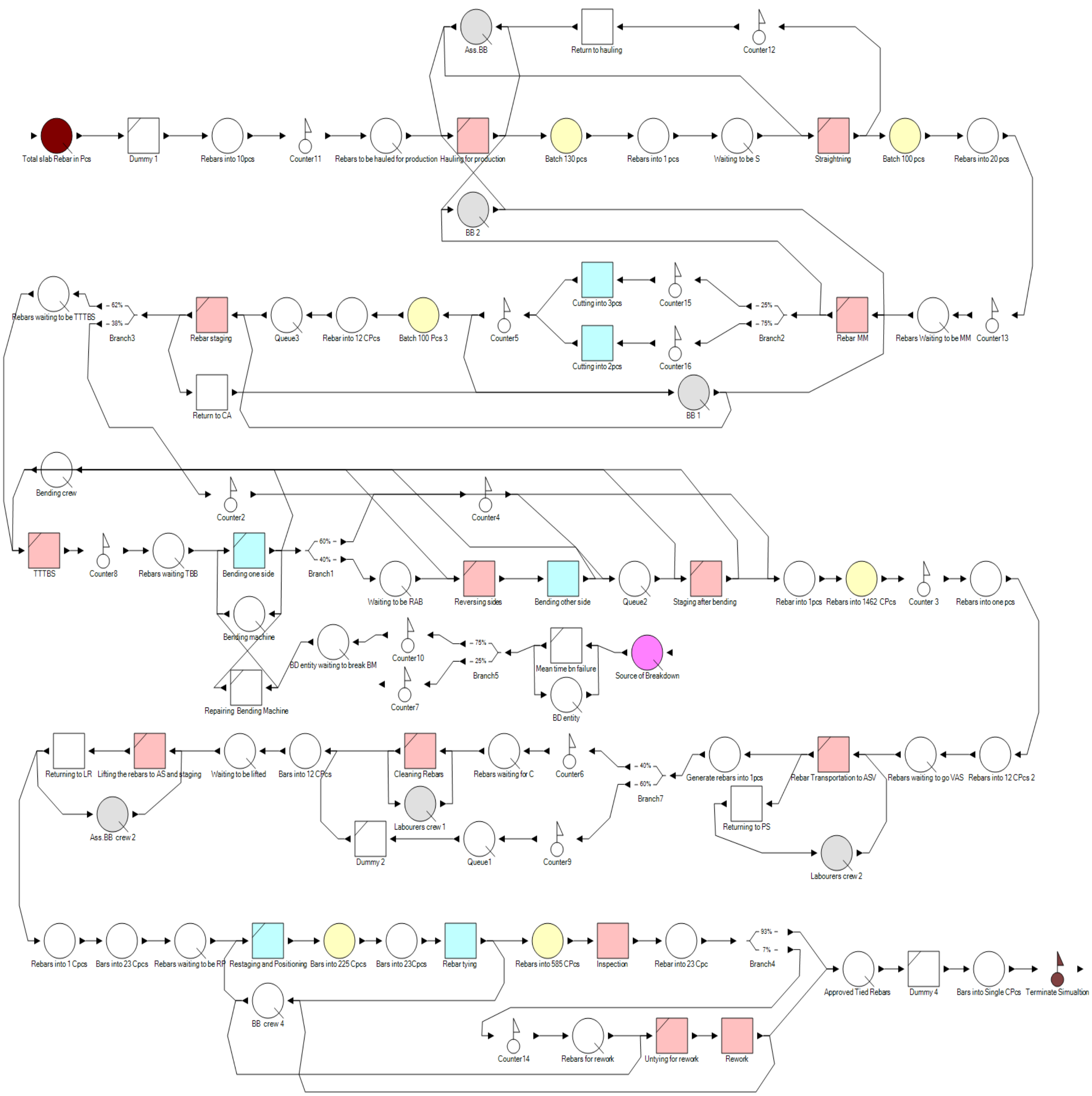
- CYCLONE template;
- tracing log, which inform a modeler the existence of a logical error; and
- built in statistical analyzing feature. Thus, “concerns of selecting statistical distributions that are supported by the simulation environment in which the model is to be built and subsequently run are no longer an issue” (AbouRizk et al., 2016, p.284).

5.1. Slab Rebar Operation Cyclone Model

Slab reinforcement operation is a labor-intensive repetitive process, which contains several sub-processes that interrelate to each other from its preparation to positioning in place. The base model is constructed based on the current state map of the operation. Every sub-process is modeled with its respective appropriate modelling element incorporated in the CYCLONE template (see Table 3). The labor resources assigned for each sub-process are identified and incorporated in the model. During the observation period, the floor rebar operation had taken nine working days, eight hours being the working hour per day.

Figure 23

Symphony CYCLONE Model of Current State Slab Rebar Operation



Note.

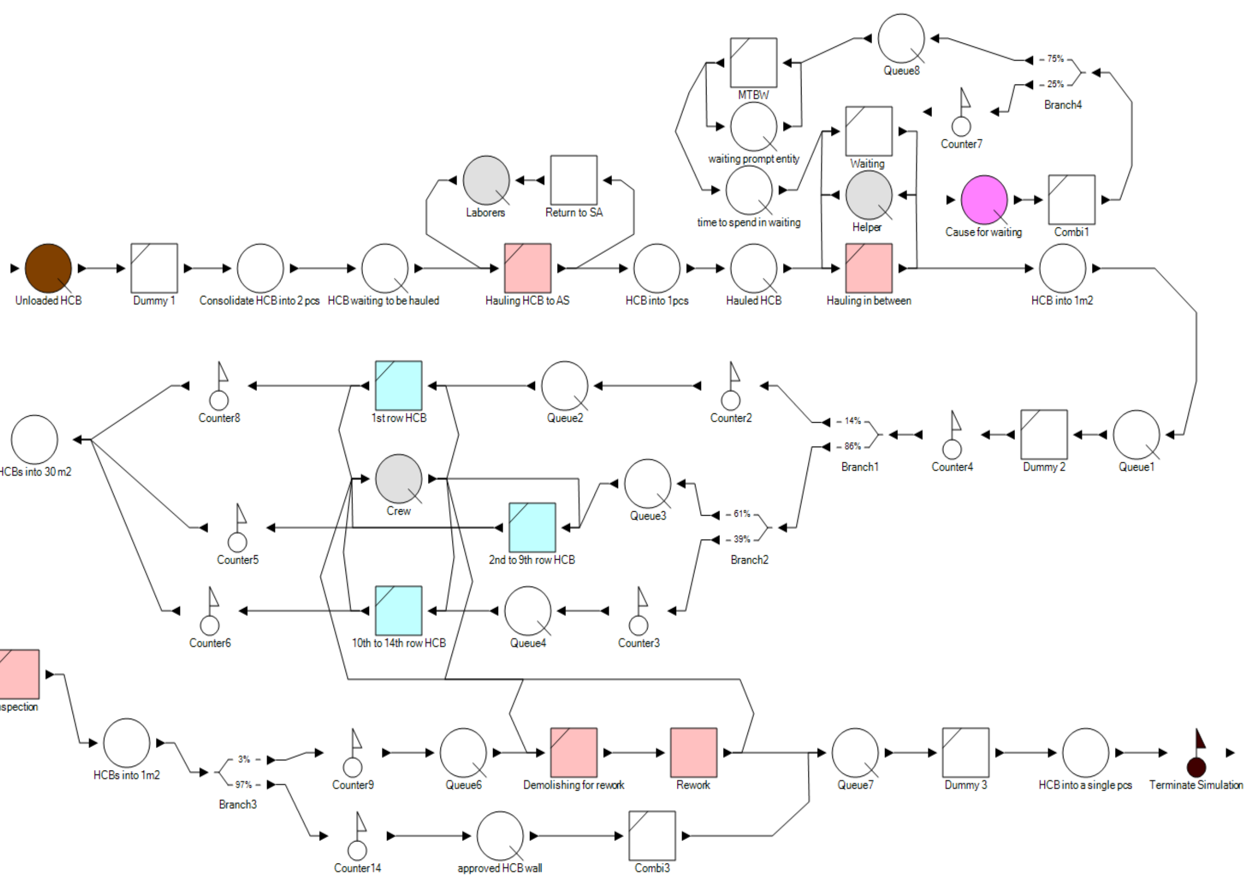
	VAA		labor resources
	NVAA		source of events
	WIP		entity path

5.2. HCB Work Cyclone Model

HCB work is a labor-intensive repetitive process, which contains several sub-processes. The base model is constructed based on the current state map of the operation. Every sub-process is modeled with its respective modelling elements incorporated in the CYCLONE template. The labor resources assigned for each sub-process are identified and incorporated in the model. During the observation period, the floor rebar operation had taken nine and half working days, eight hours being the working hour per day.

Figure 24

Symphony CYCLONE Model of Current State HCB Work



Note. VAA — labor resources; NVAA — source of events; WIP — entity path

The proper analysis of such models requires:

1. application of input modelling techniques,
2. simulating the model multiple times and sampling the required output variable so that we can statistically analyze them, and
3. verification and validation of the results.

5.3. Input Modelling

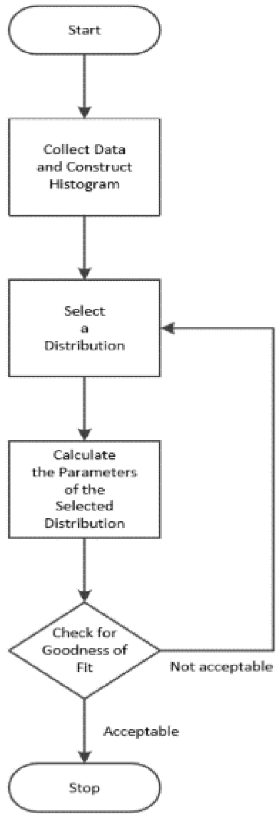
Input models provide the driving force for a simulation. Banks et al. (2016) even if the model structure is valid, if the input data are incorrectly collected, inappropriately analyzed or not representative of the environment, the simulation output data will be misleading and possibly damaging. Banks et al. (2010) regardless of the sophistication of the analyst, faulty models of the inputs will lead to outputs whose interpretation could give rise to a misleading recommendation. Duration of input is classically approached by fitting a statistical distribution (theoretical distribution) to a collected sample of observations (AbouRizk, 2016). In input modelling, the focus is on the statistical aspects of fitting probability distributions to data distributions that will later provide the driving inputs to the simulation (Banks et al., 2010). The data fitting process in Simphony passes through three important steps, these are identifying appropriate data distribution, estimating distribution parameters, and testing for the goodness of fit. The four steps in the development of a useful model of input data are discussed below.

5.3.1. Collect Data from the Real System of Interest

During the steps of understanding the practice, which are pre-observation phases, forms were designed and updated before the actual data collection. Elapsed time for each sub-process was recorded whilst workers were engaged in their work, without affecting their normal working pattern. Also, video recording of the main sub-process and time-lapse pictures were taken for detailed analysis. Observation alone seldom yields a sufficient understanding of the system behavior. Thus, people familiar with the system were questioned (Banks et al., 2010).

Figure 25

Input Modelling Steps for a Simulation Experiment[8]



5.3.2. Identify a Probability Distribution to Represent Input Process

AbouRizk et al. (2016) described numbers of techniques can be used to select a distribution to model a sample of data. Plotting the frequency histogram often gives an idea of the shape of the underlying distribution. The most basic way of selecting a statistical distribution as a model for a set of data is to relate the sample obtained to the shape (or shapes for families of distributions) of the theoretical distribution (AbouRizk et al., 2016; Banks et al., 2000). A histogram formed from the sample is analogous to the PDF (probability density function) of the theoretical distribution since both reflect the weight of the sample intervals (or sample points) that should receive in terms of their probability of occurrence. The idea would be to relate the shape of the histogram of the

[8] (AbouRizk, 2016)

sample to the shape of a known distribution. The problem with this technique, however, is the construction of the histogram itself. In the absence of a standard technique to do this, one can easily distort the real shape of the histogram by inappropriately specifying the width of the cells and their locations.

AbouRizk et al. (2016) summarized guidelines for selecting such a family as discussed by Wilson (1989) as follows:

- the family should be flexible, i.e., capable of assuming a wide variety of shapes.
- it should have tractable parameters that are intuitively and physically meaningful and easy to estimate from the sample data.
- it should allow for feasible variate generation (fast, exact, and accurate).
- it should be those that are bound to the left and are non-negative, because randomly deviated samples used to model duration in simulation cannot be negative, i.e. normal distribution (AbouRizk et al., 2016; Banks et al., 2010).

The selection was restricted to statistical distributions that are bound to the left and that are non-negative because randomly deviated samples used to model duration in simulation cannot be negative. However, no best-fit was found that was unbounded and negative.

5.3.3. Estimating Distribution Parameters

Once we have decided on the type of distribution to use as an input model, we need to determine the distribution parameters that most closely match the data. The election of an appropriate method for estimating the parameters of statistical distributions to be fit to the data is an important issue. Moment matching, percentile matching, maximum likelihood, and least square techniques can be used to arrive at estimates for the parameters of the underlying distribution. Different techniques often give different parameter estimates. Thus, the simulator is encouraged to use all fitting methods available within the software and select the parameters that produce the best fit (AbouRizk et al., 2016). Numerical estimates of the distribution parameters are needed to reduce the family of distributions to a specific distribution and to test the resulting hypothesis (Banks et al., 2010).

5.3.4. Evaluating the Chosen Distribution and Associated Parameters for Goodness of Fit

Goodness-of-fit tests provide helpful guidance for evaluating the suitability of a potential input model (Banks et al., 2010). Maio and Schexnayder (1999) the goodness-of-fit is an important statistic, which tells how probable it is that a given distribution function reproduces the data set. One should check for the goodness of fit by comparing the fitted distribution to the empirical distribution and assessing the quality of the fit obtained (AbouRizk et al., 2016; Banks et al., 2010). Both of the tests measure the harmony between the distribution of a sample of generated random numbers and the theoretical uniform distribution and are based on the null hypothesis of no significant difference between the sample distribution and the theoretical distribution (Banks et al., 2010). Maio and Schexnayder (1999) goodness-of-fit tests represent a statistical hypothesis test used to assess if the input data is an independent sample from a particular distribution function.

The selection of a goodness of fit test that will guide the choice of the best statistical distribution from the fitted options is an indispensable issue. The chi-square and the Kolmogorov-Smirnov tests are standard goodness-of-fit tests that are common in construction modelling (Maio and Schexnayder, 1999). Visual assessment of the quality of the fit, however, proves in many cases to be as powerful as any other test and is usually applied in conjunction with the statistical tests (AbouRizk et al., 2016).

1. **Chi-Square Test.**

AbouRizk et al. (2016); Banks et al. (2010) chi-squared test is based on the measurement of the discrepancy between the histogram of the sample and the fitted probability density function. When the discrepancy is large enough the test rejects the fitted model. The test is valid for large sample sizes (N > 50) and for both discrete and continuous distributional assumptions, when parameters are estimated by maximum likelihood (Maio & Schexnayder, 1999; AbouRizk et al., 2016). However, in the chi-square test, the distribution of test statistics is known approximately and the power of the test is rather low and there are no clear guidelines for selecting intervals and in some situations, you can reach different conclusions from the same data depending on how you specified the number of classes (AbouRizk et al., 2016; Banks et al., 2010; Maio & Schexnayder, 1999).

2. The Kolmogorov-Smirnov Test.

AbouRizk et al. (2016); Banks et al. (2010) the Kolmogorov-Smirnov (K-S) test is particularly useful when sample size is small and when no parameters have been estimated from the data (non-parametric test). The K-S test checks if the empirical data could have originated from a theoretical distribution with the estimated parameters (AbouRizk et al.; Maio & Schexnayder, 1999). It is based on measuring the largest discrepancy between the empirical distribution function defined by the samples and the fitted cumulative distribution function. AbouRizk et al.; Maio and Schexnayder the Kolmogorov-Smirnov test does not depend on the number of intervals and it is more powerful against alternative distributions, which makes it more powerful than the Chi-square.

3. Visual Assessment of the Quality of the Fit.

The visual assessment of the quality of fit is usually conducted in conjunction with the statistical tests as an assurance of the test results. Basically, the method is simply to plot both the empirical and fitted CDFs on one plot and compare. AbouRizk et al. (2016) "this inspection can be done by assessing the degree of dispersion of the theoretical distribution from the empirical distribution on a Probability Density Function (PDF) or a Cumulative Density Function (CDF)". Although the method does not bear much statistical or mathematical weight, it proves to be as effective as any other test (AbouRizk et al., 2016).

The two crucial issues in input modelling are the selection of the method for estimating distribution parameter and the goodness of fit test that will guide the choice of the best statistical distribution from the fitted options (AbouRizk et al., 2016). Consecutively, the method of least-square was selected for estimating distribution parameters. The method of least squares compares the empirical distribution function to the cumulative distribution function of the theoretical distribution which is using to model the samples. It sums up the squares of the residuals, the distance between the value of the empirical distribution function and the theoretical cumulative distribution function at each input of the sample data, and attempts to find parameters that make this sum as small as possible (AbouRizk et al.). The least squares method then refines the values of the parameters provided by either the method of moments or the method of maximum.

In order to test for goodness of fit, K-S and visual assessment inspection tests are performed. Maio and Schexnayder (1999) K-S test is the most appropriate for selecting a probability distribution function for construction models: 1) previously documented applications; 2) the consistency of results, and 3) the weight given to the differences of the distribution tails. In analyzing construction process model, 25% of the time resulting theoretical distribution may change if the chi-square test is used to select the best matching probability distribution function (Maio and Schexnayder, 1999). They also stated that even if Anderson Darling test detect tail discrepancies very well, less previously documented applications exist in construction process modelling. The visual inspections performed on CDF is shown below. The degree of dispersion of an overlay of the theoretical and empirical distributions were assessed. The distributions chosen are defined as an input to elements so that Simphony is able to use these to depict the cycle time and schedule events of system cycle time of sub-processes. Once obtained, the test statistic D is compared to a value from a table of critical K-S values. When the computed D, max {D +, D−} (sample statistics D), is larger than the theoretical one, $D\alpha = \frac{1.36}{\sqrt{N}}$ (critical K-S value), where N is the number of sample data collected (degrees of freedom), it is rejected. Otherwise, the best fit from the fitted is chosen.

Figure 26

Theoretical vs. Empirical PDF & CDF for Bending (Triangular Distribution)

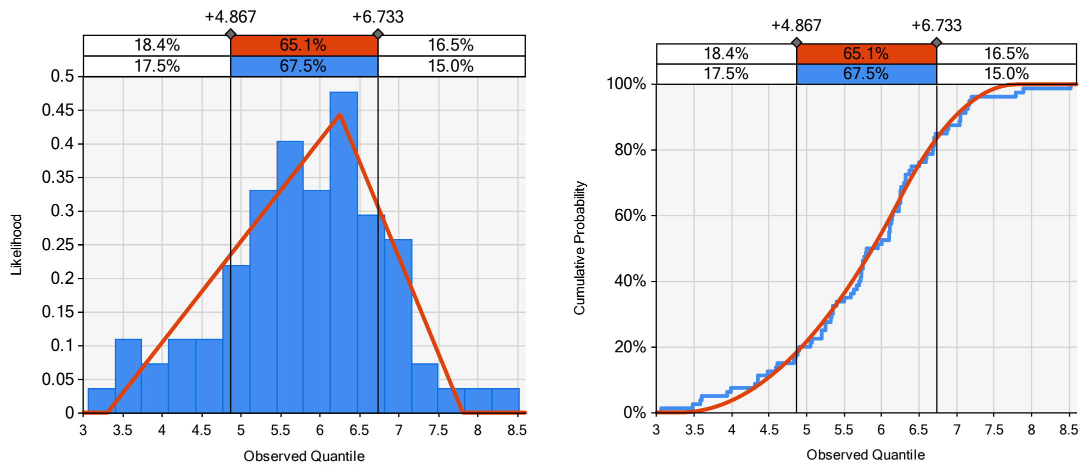


Figure 27

Theoretical vs. Empirical PDF & CDF for 10th to 14th row HCB work (Beta Distribution)

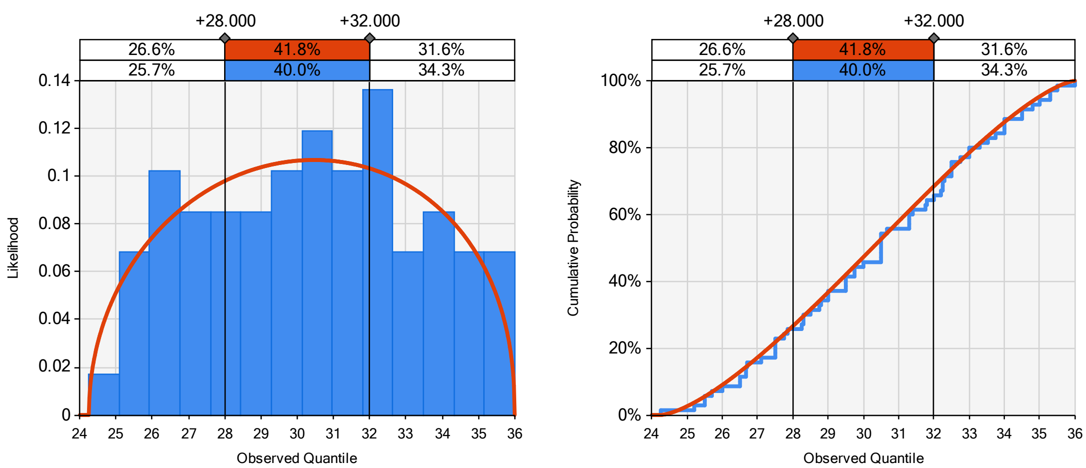


Table 6

Fitted Distribution Parameters of Slab Rebar Operation Cycle Time

Slab rebar sub-operation	Fit distribution	Distribution type	Distribution parameter	Input fit result					Goodness-of-fit test	Fitting criteria
				Min	Max	Mean	SD	Count	K-S	
	Moment matching	Beta (Alpha, beta, low, high)	Beta(0.971, 1.431, 0.9, 1.5)						0.074	
	Maximum likelihood	Beta (Alpha, beta, low, high)	Beta(0.971, 1.431, 0.9, 1.5)						0.074	
Hauling for Production from Storage Area	Least squares	Uniform (low,high)	**Uniform (0.869, 1.370)**	0.90	1.50	1.14	0.16	120	0.092	Best fit
	Moment matching	Beta (Alpha, beta, low, high)	Beta(1.277, 2.369, 0.48, 0.82)						0.075	
	Maximum likelihood	Beta (Alpha, beta, low, high)	Beta(1.277, 2.369, 0.48, 0.82)						0.075	
Straightning	Least squares	Beta (Alpha, beta, low, high)	**Beta(1.440, 2.943, 0.48, 0.82)**	0.48	0.82	0.60	0.08	120	0.084	Best fit
	Moment matching	Beta (Alpha, beta, low, high)	Beta (0.96, 1.61,7.5, 18.36)						0.053	
	Maximum likelihood	Beta (Alpha, beta, low, high)	Beta (0.96, 1.61,7.5, 18.36)						0.053	
Rebar MM (Measuring and marking)	Least squares	Beta (Alpha, beta, low, high)	**Beta (1.02, 1.78, 7.5, 18.36)**	7.50	18.36	11.56	2.78	100	0.058	Best fit
	Moment matching	Gamma (shape,scale)	Gamma (202.153, 0.036)						0.070	
	Maximum likelihood	Gamma (shape,scale)	Gamma (201.98, 0.036)						0.066	
Cutting into 3pcs	Least squares	Triangular (low, high, mode)	**Triangular (5.944, 8.473, 7.39)**	6.30	8.35	7.32	0.51	30	0.068	Best fit
	Moment matching	Gamma (shape,scale)	Gamma (98.415, 0.044)						0.057	
	Maximum likelihood	Triangular (low, mode, high)	Triangular (3.375, 4.20, 5.487)						0.041	
Cutting into 2pcs	Least squares	Triangular (low, mode, high)	**Triangular (3.362, 4.166, 5.474)**	3.46	5.40	4.35	0.44	90	0.059	Best fit
	Moment matching	Beta (Alpha, beta, low, high)	Beta (2.947,2.910,3.06,8.52)						0.078	
	Maximum likelihood	Weibull (shape, scale, location)	Weibull (4.803,4.788,1.418)						0.067	
Bending	Least squares	Triangular (low, mode, high)	**Triangular (3.303. 6.251, 7.808)**	3.06	8.52	5.81	1.04	80	0.064	Best fit
	Moment matching	Beta (Alpha, beta, low, high)	Beta (2.0, 2.448, 4.25, 5.45)						0.055	
	Maximum likelihood	Triangular (low, mode, high)	Triangular (4.213, 4.65, 5.497)						0.054	
Rebar Transportation to VAS (vicinity of actual site)	Least squares	Beta (Alpha, beta, low, high)	**Beta (2.054, 2.748, 4.25, 5.45)**	4.25	5.45	4.79	0.25	80	0.077	Best fit
	Moment matching	Gamma (shape,scale)	Gamma (118.23,0.016)						0.071	
	Maximum likelihood	Triangular (low, mode, high)	Triangular (1.57,1.85, 2.433)						0.057	
Cleaning Rebars	Least squares	Gamma (shape,scale)	**Gamma (104.97, 0.018)**	1.60	2.40	1.95	0.18	120	0.070	Best fit
	Moment matching	Beta (alpha, beta, low, high)	Beta (1.56, 2.11, 2.2, 3.1)						0.076	
	Maximum likelihood	Beta (alpha, beta, low, high)	Beta (1.56, 2.11, 2.2, 3.1)						0.076	
Lifting the rebars to AS and staging	Least squares	Triangular (low, mode, high)	**Triangular (2.128, 2.45, 3.10)**	2.20	3.10	2.58	0.21	80	0.093	Best fit
	Moment matching	Beta (alpha, beta, low, high)	Beta (1.769, 2.563, 8.5, 10.5)						0.062	
	Maximum likelihood	Beta (alpha, beta, low, high)	Beta (1.769, 2.563, 8.5, 10.5)						0.048	
Restaging and positioning	Least squares	Beta (alpha, beta, low, high)	**Beta (1.774, 2.762, 8.5, 10.5)**	8.50	10.50	9.32	0.43	90	0.062	Best fit
	Moment matching	Gamma (shape,scale)	Gamma (401,307, 0.0308)						0.043	
	Maximum likelihood	Gamma (shape,scale)	Gamma (402,307, 0.0307)						0.043	
Rebar tying	Least squares	Triangular (low, high, mode)	**Triangular (10.875, 13.791, 12.276)**	10.95	13.80	12.35	0.62	90	0.052	Best fit

Table 7

Fitted Distribution Parameters of HCB Work Cycle Time

HCB walling sub-operation	Fit distribution	Distribution type	Distribution parameter	Input fit result					Goodness-of-fit test	Fitting criteria
				Min	Max	Mean	StDv	Count	K-S	
	Moment matching	Beta (Alpha, beta, low, high)	Beta (2.712, 3.272, 1.75, 2.55)						0.058	
Hauling HCB from Storage Area to AS (actual site)	Maximum likelihood	Beta (Alpha, beta, low, high)	Beta (2.712, 3.272, 1.75, 2.55)						0.058	
	Least squares	Triangular (low, mode, high)	Triangular (1.737, 2.455, 2.104)	1.75	2.55	2.11	0.15	130	0.077	Best fit
	Moment matching	Beta (Alpha, beta, low, high)	Beta (1.27, 1.96, 0.8, 1.55)						0.070	
	Maximum likelihood	Beta (Alpha, beta, low, high)	Beta (1.27, 1.96, 0.8, 1.55)						0.070	
Returning to storage area	Least squares	Uniform (low,high)	Uniform (0.78, 1.37)	0.80	1.55	1.10	0.18	110	0.075	Best fit
	Moment matching	Gamma (shape,scale)	Gamma (2.29, 4.39)						0.088	
	Maximum likelihood	Weibull (shape, scale, location)	Weibull (0.93, 8.45, 2.5)						0.676	
Waiting	Least squares	LogNormal (location, shape)	LogNormal (2.06, 0.774)	2.50	29.00	10.07	6.65	50	0.072	Best fit
	Moment matching	Gumbel (location,scale)	Gumbel (33.86, 2.60)						0.074	
	Maximum likelihood	Gumbel (location,scale)	Gumbel (33.76, 2.97)						0.060	
1 st row HCB	Least squares	Triangular (low, high, mode)	Triangular (28.7, 43.59, 33.08)	28.50	43.80	35.36	3.33	35	0.071	Best fit
	Moment matching	Gamma (shape,scale)	Gamma (41.21, 0.58)						0.041	
	Maximum likelihood	Triangular (low, mode, high)	Triangular (15,82, 33.21, 22.5)						0.038	
2nd to 9th row HCB	Least squares	Triangular (low, mode, high)	Triangular (15.06, 33.33, 22.78)	16.50	32.00	23.88	3.72	100	0.042	Best fit
	Moment matching	Beta (Alpha, beta, low, high)	Beta (1.52, 1.38, 24.25, 36)						0.046	
	Maximum likelihood	Beta (Alpha, beta, low, high)	Beta (1.52, 1.38, 24.25, 36)						0.046	
10th to 14th row HCB	Least squares	Beta (Alpha, beta, low, high)	Beta (1.48, 1.44, 24.25, 36)	24.25	36.00	30.40	2.97	70	0.069	Best fit

5.4. Model Verification and Validation

When creating simulation models errors could occur. According to Whitner and Balci (1989, as discussed by, AbouRizk et al., 2016) errors arise from input data; the conceptual model; the simulation model (its implementation); and the simulation model development environment. Verifying the model developed and validating the results is critical in getting acceptance of the simulation. Verification deals with constructing the model correctly and validation deals with building the correct model (Banks et al., 2010). If the model is not verified and validated, it can be impossible to convince model users that the model is correct and the model can't be used for drawing conclusions and decision making (Sargent, 2011).

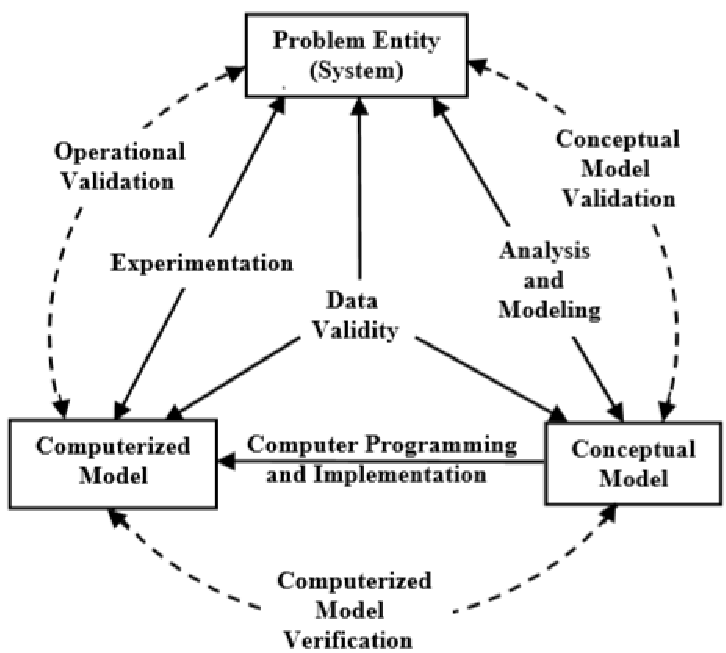
Verification of a model can be described as to make sure that each element in the model is behaving correctly and that it is correctly coded (Sargent, 2013, as cited in Goodwin & Pantzar, 2017). It is to make sure that the behavior of the model is an accurate representation of the real world. Sargent (2011) verification is ensuring that the computer program of the computerized model and its implementation are correct. It is a continuous process and needs to be performed concurrently with the development of the computer model rather than at the end (Banks, 2000; Sargent, 2011). Xia and Sun (2013) verification is a highly necessary step that ensures the simulation model sufficiently represents and adequately replicates the real system. "Model validation is substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model" (Schlesinger et al., 1979, as cited in Sargent, 2011, p.183). Model's validity should be determined for the purpose it is developed for (Sargent, 2011).

Model verification and validation is a part of the total model development process (Banks et al. 2010; Sargent, 2011). To decide whether a simulation model is valid or not, there are four basic decision-making approaches (Sargent, 2011). Which are the model development team, model users/sponsors, a third party who is independent ("independent verification and validation", IV&V), and scoring model. In Accord, Banks et al. (2010) advises checking the operational model by an independent expert. In agreement, the researcher adopted IV&V approach to decide whether the model is valid or not. Sargent (2011) there are two ways to conduct IV&V, during the development of the model and after model development, and the researcher adopted the latter for convenience due to the existence of few professionals in the area. Since it is costly and time consuming, Wood (1986, as cited in Sargent, 2011) recommended the independent decision maker to only evaluate the verification and validation that the model developer has already performed.

The main response of interest in this research is productivity and it is directly correlated with the total cycle time (Pasqualini and Zawislak, 2005), which is the researcher used to model the systems. "Modeler should use the main responses of interest as the primary criteria for validating a model" (Banks et al., 2010). The appropriate factor to show how the actual process and simulated process are alike is cycle time, which is used for validation (Al-Sudairi, 2007; Hassan & Gruber, 2008, as cited in Nikakhtar et al., 2015).

Figure 28

Simplified Version of The Modelling Process[9]



[9] Sargent (2011)

5.4.1. Conceptual Model Validation

"The conceptual model is the mathematical/logical/verbal mimic of the problem entity developed for a specific study" (Sargent, 2011, p.185). "It is identifying and documenting the specifications and requirements of the domain, its environment and boundaries" (AbouRizk et al., 2016, p.55). Conceptual model validation involves determining that the theories and assumptions (structural and data) underlying the conceptual model have been abstracted and appropriately represented and confirming the correctness of the abstracted domain boundaries, for the intended purpose of the model (AbouRizk et al.; Sargent).

5.4.1.1. Modelling Assumptions of Slab Rebar Operation.

Assumptions that are made in order to facilitate the simulation modelling process:

1. The cycle time which takes to process diameter 8 and 10 rebars (rebars used for slab rebar) and number of rebars processed for every subprocess is assumed to be equal.

2. The probability threshold value of 75% specified in the probabilistic branch element for deciding the probability of breakdown entity prompting bending machine failure. The probability value of 93% and 7% specified in the probabilistic branch element for deciding the tied rebar entities which get approved and go through rework respectively. The values for the respective forking are assumed based on proportioning the observed quantity with the total quantity.

3. Probability values assigned for entities leaving activities such as bending, and MM are based on the number of quantities. At those elements, Simphony will route each rebar entity out the top output port with a probability assigned for it and the same for the bottom.

4. Distribution types for activities are assumed based on the nature of the activities and are presented in the following table.

Table 8

Assumed Distribution Types for Slab Rebar Sub-Processes

Slab rebar sub-operation	Distribution type	Distribution parameter
Return to hauling	Constant	0.5
Rebar staging	Constant	1.2
Return to CA (cutting area)	Constant	0.5
TTTBS (transporting to the bending site)	Constant	1.5
Repairing bending machine	Uniform (low, high)	Uniform (8, 12)
Mean time between failure	Uniform (low, high)	Uniform (160, 240)
Reversing sides	Constant	1.33
Staging after bending	Constant	1.5
Returning to PS (positioning site)	Constant	2
Returning to LTR (lift the rebars)	Constant	0.6
Inspection	Uniform (low, high)	Uniform (30, 40)
Untying for rework	Triangular (low, mode, high)	Triangular (12, 18, 15)
Rework	Triangular (low, mode, high)	Triangular (22, 36, 28)

5.4.1.2. Modelling Assumptions of HCB Work.

Assumptions that are made in order to facilitate the simulation modelling process:

1. The probability threshold value of 75% specified in the probabilistic branch element for deciding the probability of waiting. The probability value of 97% and 3% specified in the probabilistic branch element for deciding the placed HCB entities which get approved and go through rework respectively. The values for the respective forking are assumed based proportioning on the observed quantity with the total quantity.

2. Probability values assigned for entities leaving for 1st row HCB, 2nd-9th row HCB, and 10th-14th row HCB are based on the number of quantities.

3. Distribution types for activities are assumed based on the nature of the activities and are presented in the following table.

Table 9

Assumed Distribution Types for HCB Work Sub-Processes

HCB work sub-operation	Distribution parameter	Distribution parameter
Hauling in between sites	Uniform (low, high)	Uniform (1.8, 2.5)
MTBW (Mean time between waiting)	Uniform (low, high)	Uniform (90, 160)
Inspection	Uniform (low, high)	Uniform (15, 20)
Demolishing for rework	Triangular (low, mode, high)	Triangular (15, 28, 22)
Rework	Triangular (low, mode, high)	Triangular (24, 36, 28)

At this stage in model development process the researcher used:

5.4.1.3. Face Validation.

Face validation includes examining the flowchart or graphical model (Sargent, 1986, as cited in, Sargent, 2011). Face validation entails domain (real system) experts and users of the model evaluating the model output for correctness (AbouRizk et al., 2016). Experts, site and construction engineers, on the problem entity (slab rebar and HCB work), validated the model by examining the logic of VSM, which is the current state map, and the reasonableness of input-output. The way priorities are assigned for resources and probability threshold values used to model stochastic processes were discussed with experts and validated through iteration. The structural assumption of how the system operates, cycle time, and the average number of processed bars in each subprocess were validated. Statistical methods on problem entity data are used for fitting distributions and estimating parameter values (Sargent, 2011). As recommended by Sargent, whether or not appropriate detail and relationships have been used for the model's intended purpose are checked.

5.4.2. Simulation Model Verification

AbouRizk et al. (2016); Sargent (2011) simulation model verification is a process performed to confirm the correctness of computer programming and implementation of the conceptual model. Banks et al. (2010) it is to ensure that the conceptual model is reflected accurately in the operational model and asks, "is the conceptual model, its assumptions about the system components and system structure, parameter values, abstractions, and simplifications, accurately represented by the operational model?" AbouRizk et al. (2016) simulation model implementation verification is to trap errors, namely: logical errors (infinite loops and deadlock situations), data errors (using normal distribution as the best fit) and experimental errors (failure to seed and perform multiple runs) that could occur during modelling in Symphony cyclone. There are many ways to verify simulation models (AbouRizk et al., 2016; Banks et al., 2010; Sargent, 2011). The researcher found the following verifying techniques to be more appropriate considering the simulation environment adopted.

1. Mapping flow diagram (current state VSM) that includes all logically possible actions and making the operational model self-documenting as possible to aid in verification, and closely documenting the reasonableness of the output, suggested by (Banks et al., 2010).

2. Traces log: entities are traced to determine if the model's logic is correct and accurate enough. Symphony provides trace logs that facilitate tracing information as the model executes. The existence of logical errors can be checked by examining the order in which events are traced (AbouRizk et al., 2016).

3. Entity counters: to check for the presence of logical errors by tracking the flow of entities as simulation events evolve and verifying that the models are working as intended (AbouRizk et

al., 2016). The counter elements are used at strategic locations to verify that the right number of entities got to that part of the simulation model. Entities routed into them keep owing in a cyclic fashion triggering the schedule and processing of simulation events until the simulation is terminated.

4. Integrity checks provided by the Simphony (AbouRizk et al., 2016). The Simphony simulation system reported logical errors and data errors prior to model execution and after iterative procedures the researcher fixed the errors and proceeded.

5.4.3. Operational Validation

"Operational validation is defined as determining that the model's output behavior has sufficient accuracy for the model's intended purpose over the domain of the model's intended applicability" (Sargent, 2011, p.189). AbouRizk et al. (2016) it mainly entails making use of the simulation model's outputs to determine whether the model is valid for the purpose it was intended. There are two ways that operational validation can be performed based on the decision approach and system observability (AbouRizk et al.; Sargent). Those are an exploration of the model behavior (examining the output behavior of the simulation model), and a comparison of the outputs of the model being validated to outputs of a similar system/operation using graphical displays and/or statistical tests and procedures. Operational validation techniques the researcher adopted and found to be useful in construction engineering and management simulation modelling are the following:

5.4.3.1. Parameter Variability - Sensitivity Analysis.

Parameter variability sensitivity analysis is used for quantitative model exploring analysis, by examining both the directions and the precise magnitudes of the output behaviors in consultation with experts in the systems and modelling (Sargent, 2011). Since input data of the real system is available (observable), an objective scientific sensitivity test was adopted (Banks et al., 2010; Sargent). It consists of changing the values of the input and internal parameters of a model to determine the effect upon the model's behavior or output, and witnessing whether the same relationship occurs in the real system (Sargent).

Table 10

Parameter Variability - Sensitivity Analysis of CS Slab Rebar Operation Model

Sub Process	Best-fit distribution parameter	Changed distribution parameter	Production rate output
Cutting into two pieces	T (3.362, 4.166, 5.474)	U (16, 18)	Production rate decreased reasonably as the value of input increased
Hauling for production	U (0.869, 1.370)	U (5, 10)	Production rate decreased reasonably as the value of input increased

Table 11

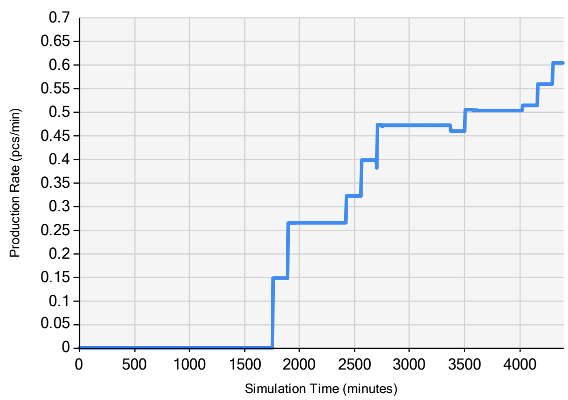
Parameter Variability - Sensitivity Analysis of CS HCB Work Model

Sub Process	Given distribution parameter	Changed distribution parameter	Production rate output
Hauling HCB from storage	T (1.7, 2.5, 2.1)	T (2, 18, 8)	Production rate decreased reasonably as the value of input increased

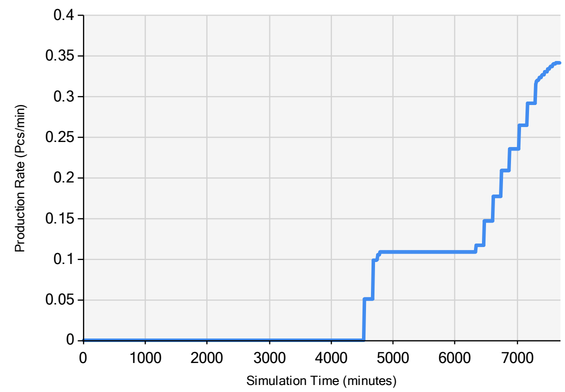
Figure 29

Quantitative Exploring of CS Slab Rebar Operation Model Using Parameter Variability - Sensitivity Analysis: (a) Production rate by the best fit; (b) Production Rate of Changed Input Distribution Type and Parameter of Cutting; (c) Production Rate of Changed Distribution Parameter of Hauling

(a)



(b)



(c)

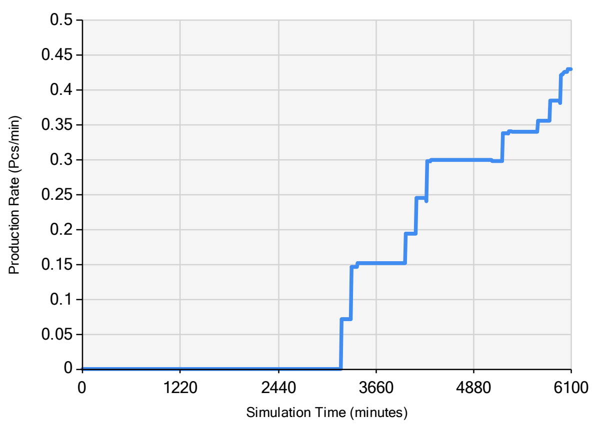
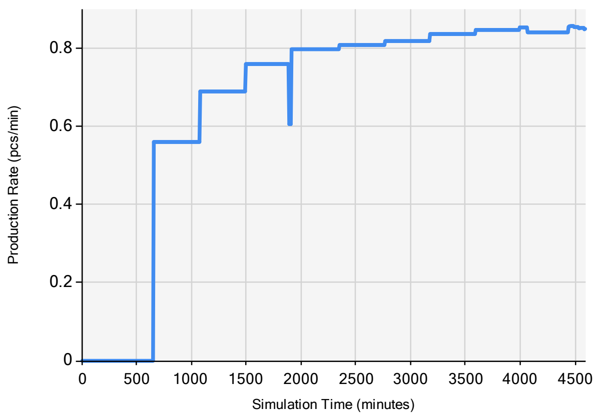


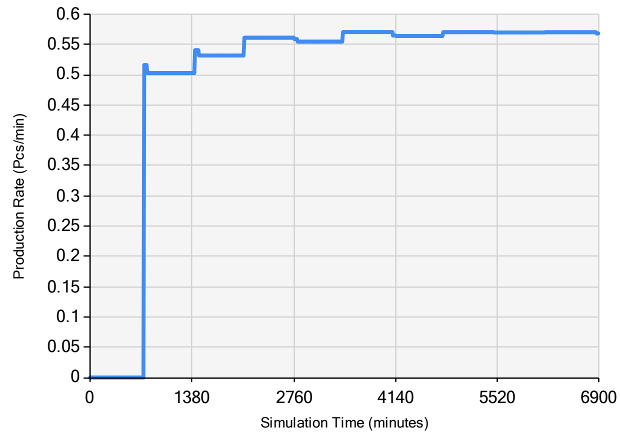
Figure 30

Quantitative Exploring of CS HCB Work Model Using Parameter Variability - Sensitivity Analysis: (a) Production rate by the best fit; (b) Production Rate of Changed Input Distribution Parameter of Hauling

(a)



(b)



5.4.3.2. Comparisons of Output Behaviors.

Comparisons of output behaviors means comparing the simulation model output behavior to either the system output behavior or another model output behavior" (Sargent, 2011, p.189). Production time result of the simulation model are compared to the real system output behavior. Then, the confidence interval is used to make an objective decision for comparing result of simulation data with system output. The detail of this step is discussed in detail in the next section.

5.5. Output Analysis

Output analysis is the examination of data generated by a simulation, either for estimating relative or absolute performance system designs. A distinction should be made in analyzing simulation output data, as terminating/transient and steady-state simulations. "Transient simulation is one that runs for some duration of time $T_{E,}$ where E is a specified event that stops the simulation" (Banks et al., 2010, p.436). As noted by AbouRizk et al. (2016) most construction operations discussion of output analysis is specific to that range of simulation models that can be classified as transient simulations. For transient simulation two types of analysis are relevant: (1) analysis of output parameters that do not significantly deviate from normality, and (2) analysis of output parameters that have non-normal responses, which hasn't been frequently encountered in the simulation of construction processes (AbouRizk et al.).

Unlike deterministic simulation, stochastic simulation will not produce the same output when run repeatedly with independent random seeds. AbouRizk et al. (2016) "this requires one to make a number of runs with independent seeds for the random-number-generating streams to ensure that a true picture of the system under investigation is provided" (p.35). Law and McComas (1986, as cited in AbouRizk et al.) one of the most common dangerous practices in simulation is making only one run of a stochastic simulation, and decisions based on a stochastic simulation of a system with one replication can be costly. As discussed by him, a larger number of runs leads to more accurate results because:

1. In a small number of runs, the properties of the system may not be completely revealed (experimental error); and

2. The confidence intervals for the mean and variance of the results shrink as the number of runs increases. It is a measure of error and we can simulate away error by making more and more replications (Banks et al., 2010).

Accordingly, the researcher derived the number of required runs and performed the analysis based on multiple runs and developed confidence intervals for every estimate under investigation (AbouRizk et al., 2016).

5.5.1. Output Analysis of Slab Rebar Operation

After the model is verified and validated an initial sample size of 15 replications were made, that is, the initially made 15 independent replications, 10 or more being the desirable of initial replication (Banks et al., 2010). A seed value was set to zero, for a pseudo-random number generator to be seeded using the system time, which resulted in a different sequence of pseudo-random numbers each time the scenario is executed (AbouRizk et al., 2016). A level of significance, α is assumed to be 5%. Thus, a confidence interval of $100(1 - \alpha)\%$= 95%, was chosen, because it was found necessary to increase the trust of the decision maker, of the interval to bound the error between the mean of the normal distribution and the average production time. Using the initial replications, an initial estimate of the sample variance of the population was obtained.

Table 12

Simphony CYCLONE Statistics Report of CS Slab Rebar Operation Model for an Initial Run of 15

Non-Intrinsic Statistics					
Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
Slab Rebar CSM (Termination Time)	4331.212	127.358	15.000	4139.593	4598.705

The number of simulations runs to produce the desired level of accuracy, R, must be chosen to meet half-length criterion, such that R > $R_{o.}$ Thus, for 95 % confidence interval, $t_{0.025,14}$ =2.14. The standard deviation reported by Simphony, as shown in the table above is the population standard deviation. Thus, converting to sample standard deviation:

$$S_0 = \sqrt{\frac{R_0}{R_0-1}\delta^2} = \sqrt{\frac{15}{15-1}127.358^2} = 131.82$$

An error criterion, ϵ, is assumed to be 1%, in desire to estimate the long run mean to be within $\pm\epsilon$, with high probability of $1-\alpha$. And solving for the smallest integer R satisfying R ≥ R;

$$R \geq \left(\frac{t_{\alpha/2,\mathrm{Ro}-1} s_0}{\epsilon}\right)^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\mathrm{R} \geq \left(\frac{2.14*131.82}{0.01*4331.212}\right)^2 \approx 42$$

Thus, replication of R= 100 ≥ 50 was selected, where R ≥ 50, is deemed as large number of replication (Banks et al., 2010).

The confidence interval, which assumes Yi are normally distributed, is

$$\bar{Y} \pm H \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$\bar{Y} \pm t_{\alpha/2,R-1} \frac{S}{\sqrt{R}}$$

Where:

S is the sample variance; R is the number of replications;

H is the half length of 100(1-α) % (confidence interval width), $t_{\alpha/2,n-1}\frac{S}{\sqrt{R}}$, which has to be small to facilitate the decision that the simulation is supposed to support (Banks et al., 2010);

$t_{\alpha/2,n-1}$ *is the quantile of t-distribution with R-1 degrees of freedom that cuts off $\alpha/2$ of the area of each tail of the normal distribution curve.*

The simulation experiment was repeated 100 times using the multiple-run feature of Simphony. Each run was independently seeded in order to attain a random independent sample of the output parameters. The experiment resulted in 100 observations for each of the output parameters, the total production time required to complete the job being the main interest parameter.

Table 13

Simphony CYCLONE Statistics Report of CS Slab Rebar Operation Model for 100 Run Count

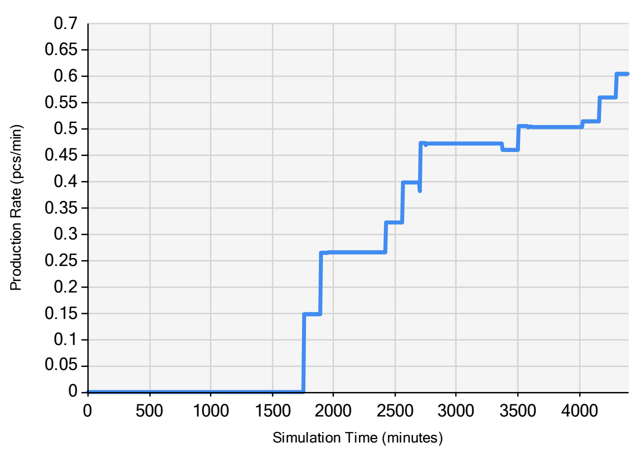
Non-Intrinsic Statistics					
Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
Slab Rebar CSM (Termination Time)	4306.089	112.778	100.000	4069.082	4615.771

$$4306.089 \pm 1.987\frac{113.35}{100} = 4306 \pm 2.25$$

H = 2.25 $\leq \epsilon Y = 0.01 * 4306.089 =$43.06, which satisfy the requirement, $P(|\bar{Y} - \theta| \leq \epsilon) \geq 1 - \alpha = 0.95$, where, θ is the population mean. This is in conformity with the actual data observed, 4305 minutes, or close to nine working days. And the production rate is 0.604 Pcs/min, or 290 Pcs/day.

Figure 31

Production Rate vs. Simulation Time of CS Slab Rebar Operation Model



5.5.2. Output Analysis of HCB Work

After the verification and validation of the current state HCB work model, a number of simulation-runs to produce the desired level of accuracy, R, was chosen to meet the half-length criterion, such that R > R_o. Thus, for 95 % confidence interval, $t_{0.025,19}$ =2.09. The standard deviation reported by Simphony, shown in the figure below is the population standard deviation.

Table 14

Simphony CYCLONE Statistics Report of CS HCB Work Model for An Initial Run of 20

Non-Intrinsic Statistics					
Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
HCB CS (Termination Time)	4563.203	75.122	20.000	4451.278	4758.353

Thus, converting to sample standard deviation:

$$S_0 = \sqrt{\frac{R_0}{R_0-1}\delta^2} = \sqrt{\frac{20}{20-1}75.122^{\ 2}} = 77.07$$

An error criterion, ϵ, is assumed to be 1 %, in desire to estimate the long run mean to be within $\pm\epsilon$, with high probability of $1-\alpha$. And solving for the smallest integer R satisfying R ≥ $R_{0,}$

$$R \geq \left(\frac{t_{\alpha/2,\mathrm{Ro}-1} S_0}{\epsilon}\right)^2$$

$$\mathrm{R} \geq \left(\frac{2.09 * 77.07}{0.01 * 4563.203}\right)^2 \approx 13$$

Thus, replication of R= 100 ≥ 13 was selected, where R ≥ 50, is deemed as a very large number of replications. Then, the simulation experiment was repeated 100 times using the multiple-run feature of Simphony.

Table 15

Simphony CYCLONE Statistics Report of CS HCB Work Model for 100 Run Count

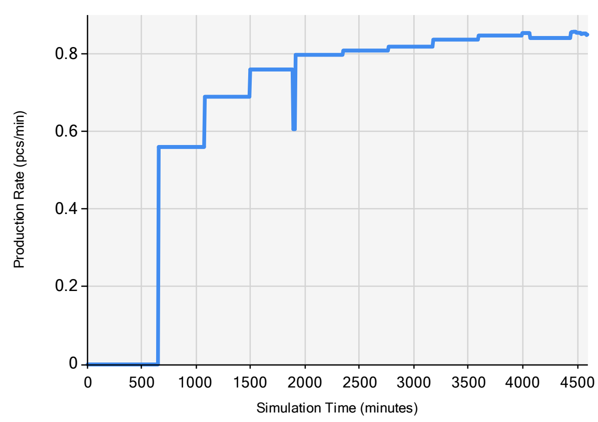
Non-Intrinsic Statistics					
Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
Slab Rebar CSM (Termination Time)	4579.640	69.689	100.000	4383.754	4825.971

$$4579.64 \pm 1.987\frac{69.689}{100} = 4579.6406 \pm 1.38$$

H = 1.38 ≤ $\epsilon Y = 0.01 * 4579.64$ =45.8, which satisfy the requirement, $P(|\bar{Y} - \theta| \leq \epsilon) \geq 1 - \alpha = 0.95$, where, θ is the population mean. This is in conformity with the actual data observed, which is 4580 minutes or close to nine and half working days. And the production rate is 0.85 Pcs/min, or 409 Pcs/day.

Figure 32

Production Rate vs. Simulation Time of Current State HCB Work Model



5.6. Lean Concepts and Principles Application

After the model development, verification, validation, and output analysis of current state models, the aforementioned proposed lean concepts and principles were applied to witness the labor productivity improvement. The application of the concepts and principles was made in different scenarios.

5.6.1. Lean Concepts and Principle Application on Slab Rebar Model

The proposed lean concepts and principles in the current state map analysis were applied on the CYCLONE current state model and a significant improvement in labor productivity was witnessed.

5.6.1.1. Pull Scheduling.

As shown in the current state CYCLONE model, tasks such as hauling, staging, straightening, and bending share a common labor resource. In this situation, higher priorities are given for activities that are in the upstream, so that they get completed first. However, the concept of pulling is delivering the right quantity, at the right time so that waiting time and WIP could be reduced. Thus, to depict the pull concept, the priorities given to downstream tasks were made higher. Priorities assigned for tasks that share the same resources are listed in the following table.

Table 16

Current State Model Vs. Pull Model Priorities

Sub-processes	Current state model	Pull model
Hauling for Production	3	0
Straightening	2	1
Rebar measuring and marking	1	2
Rebar staging	0	3
Transporting to the bending site	4	0
Repairing bending machine	3	1
Bending one side	2	2

Sub-processes	Current state model	Pull model
Bending the other side	1	3
Staging after bending	0	4

After changing the priorities, the total cycle time was improved moderately as shown in table 17. The cycle time (simulation time) reduced to 4054.9 min and the production rate improved to 0.64 Pcs/min or 307.8 Pcs/day respectively.

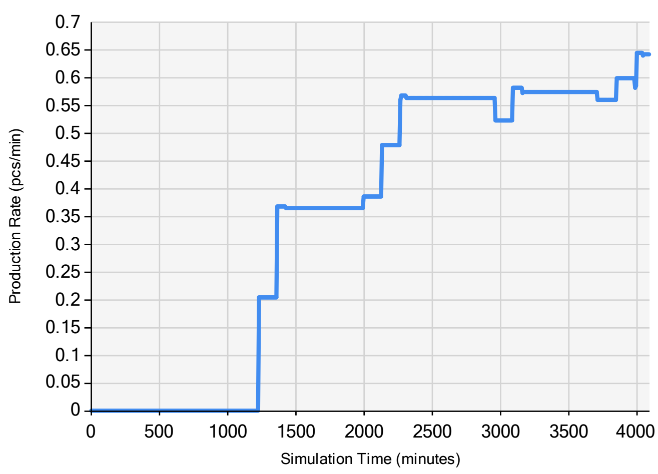
Table 17

Simphony CYCLONE Statistics Report of Slab Rebar Operation Pull Model for 50 Run Count

Non-Intrinsic Statistics					
Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
Slab Rebar Pull (Termination Time)	4054.910	41.610	50.000	3969.527	4147.693

Figure 33

Production Rate vs. Simulation Time of Slab Rebar Operation Pull Model



5.6.1.2. Workplace Organization/Standardization (WOS) and Production Scheduling (PS).

The applied workplace organization/ standardization (WOS) includes 5S, simplification and site layout redesigning sub principles and production scheduling (PS) includes signalizing kanban for detailed crew instructions; allowing small-batch sizes to flow; and supermarket-pull system. These principles applied simultaneously because the application of one prompts the other and so on. Supermarket pull applied to synchronize demand and supply, and by pulling resources from the supermarket, maintaining a small-batch flow becomes possible. A small batch of rebar, 20 pieces, was allowed to flow without any more batching of rebars. Accordingly, managing buffer size (WIP) is a critical component for implementing lean principles in construction processes (Al-Sudairi et al., 1999). When the supermarket pull system applied and standardization of rebar storage made, simplification opportunities sprouted. Thereafter, cleaning of rebars becomes no longer a requirement since rebars won't stay on-site long enough to corrode. And straightening task was avoided since it is an over-processing by its nature. Moreover, site layout redesign and 5S go hand in hand and mitigate the "in-between" transportations, which in turn prompt cycle time reduction of subprocess such as measuring and marking; and cutting. Another simplification was possible by avoiding reversing rebars to bend the other side. Finally, the proposition of hurdle meetings and kanban for detailed crew instruction aid in reducing waiting times and rework that is caused by miscommunication and late delivery of information. To recapitulate, there are unnecessary steps that are either scheduled or begotten in the circle of waste creation.

Thus, tasks such as straightening, cleaning rebars, and reversing were taken out to emulate the application of simplification. Cycle time of tasks such as rebar staging, transportation of rebars to the bending site, and returning times was reduced by the application of site layout redesign. The reduction of transportation times was applied by proportioning the distance traveled in between tasks. Although, site layout aid in the reduction of traveling time and in simplification, allowing rebars to flow in small-batches and 5S have a major contribution to the reduction of cycle time.

Table 18

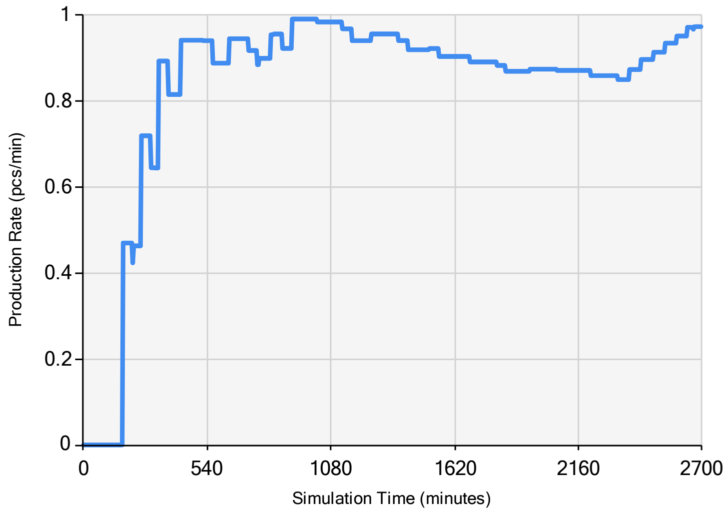
Simphony CYCLONE Statistics Report Slab Rebar Operation WOS & PS Model for 50 Run Count

Non-Intrinsic Statistics					
Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
Slab Rebar WOS & PS (Termination Time)	2680.927	44.307	50.000	2678.055	2821.948

After the application of the foregoing principles, a significant improvement in total cycle time was recorded. As shown in the table above, the cycle time reduced to 2680.93 min and production rate was enhanced to 0.97 Pcs/min or 466 Pcs/day.

Figure 34

Production Rate vs. Simulation Time of Slab Rebar Operation WOS & PS Model



5.6.1.3. WOS and PS with pull.

After independently applying pull concept and WOS and PS, simulation of the first future state scenario was experimented. As shown in the table below, the total cycle time becomes 2697 min and production rate equals to 0.965 Pcs/min or 463 Pcs/day. As can be seen, there is no additional improvement in total cycle time when the two scenarios combined. To assess the redundant concept, small-batch flow and pull were modeled with WOS and PS alternately. Then, the result indicated that small-batch flow would be sufficient to mitigate the waiting & WIP, that was being prompted by the overproduction in the upstream. Thus, it was found that the application of WOS and PS without pull would be sufficient to improve the labor productivity.

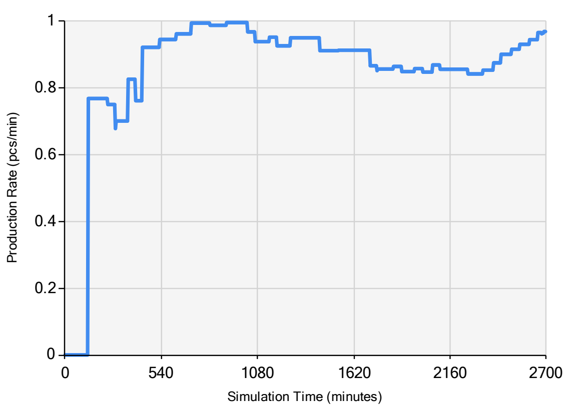
Table 19

Simphony CYCLONE Statistics Report of Slab Rebar Operation WOS & PS with Pull Model for 50 Run Count

Non-Intrinsic Statistics					
Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
Slab Rebar WOS & PS with pull (Termination Time)	2697.015	55.242	50.000	2678.055	2821.948

Figure 35

Production Rate vs. Simulation Time of Slab Rebar Operation WOS & PS with Pull Model



5.6.1.4. Optimizing Utilization of Labor Resource (Future State Model).

During the implementation of the foregoing principles, tasks that are deemed as unnecessary removed with labor resources they consume. To study the possibility of more improvements, a comparison of outputs was made for different combinations of labor resources. A pair of laborers used for transportation of rebars to the actual site and positioning and tying tasks were eliminated. Consequently, the total cycle time becomes 2797.72 min and the production rate equals 0.93 Pcs/min or 446 Pcs/day. In this scenario, the labor resource (input) reduced significantly, and this indicates a higher labor productivity improvement. The details are discussed at the end of this chapter.

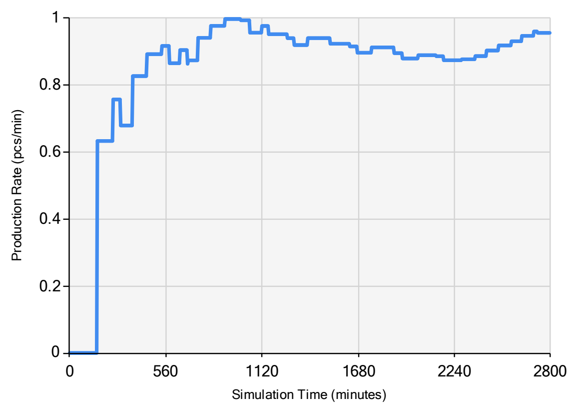
Table 20

Simphony CYCLONE Statistics Report of Slab Rebar Operation Future State Model for 50 Run Count

Non-Intrinsic Statistics					
Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
Slab Rebar FS (Termination Time)	2797.720	55.035	50.000	2622.753	2910.148

Figure 36

Production Rate vs. Simulation Time Slab Rebar Operation Future State Model



5.6.2. Lean Concepts and Principles Application on HCB Work Model

The proposed lean principles in the current state map analysis were applied on the CYCLONE current state HCB work model and total cycle time was improved significantly.

5.6.2.1. Future State Model (FS 1).

The future state scenario was proposed by applying supermarket pull system for supply delivery; FIFO (portable pallet with a capacity of 60pcs HCB) with a kanban (flag) to control the flow of material between sub-processes; signalizing kanban (plastic paper for detailed crew instruction and flags), tool kit based on the concept of 5S; simplification; and hurdle meeting. Delivery of HCB was changed to be made every four days (one day prior to the commencement of the operation), by checking the supermarket that is organized in typologies. FIFO application by the use of portable pallet significantly aids in forefending the continuous in between transportation, which was taking a significant amount of time and causing a defect in the HCB. The application of signalizing kanban by hanging a plastic paper, use of a flag to trigger material supply, and daily hurdle meetings have mitigated the issue of waiting time and the time spend doing rework. Additionally, the adoption of 5S and simplification abated cycle time by eliminating searching times and over-processing steps such as cutting HCB to fill the gaps by ordering 5cm HCB.

Table 21

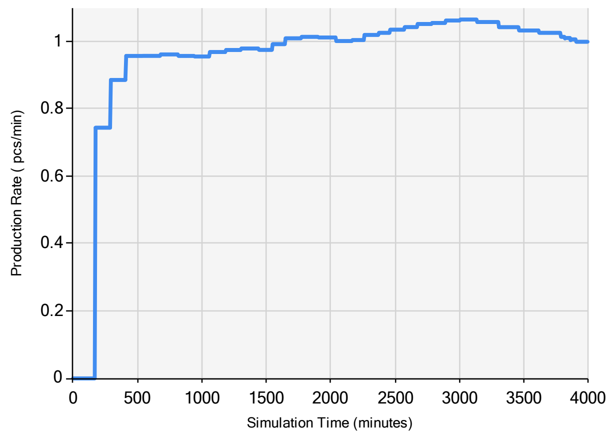
Simphony CYCLONE Statistics Report of HCB Work Future State 1 Model for 100 Run Count

Non-Intrinsic Statistics					
Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
HCB FS 1 (Termination Time)	3937.584	70.425	100.000	3791.540	4095.527

As shown in the table above, a moderate improvement in cycle time was insured. The cycle time becomes 3937.584 min and production rate improved to 0.99 Pcs/min or 38 m2/day.

Figure 37

Production Rate vs. Simulation Time of HCB Work Future State l Model



5.6.2.2. Final Future State Model (Final FS)

To study the possibility of more improvements, on the future state 1, a comparison of outputs was made for different combinations of labor resources. A laborer from the three laborers that is used for hauling HCB to the actual site was reduced. Consequently, the cycle time becomes 3968.386 min and the production rate became 0.983 Pcs/min or 37.7 m2/day.

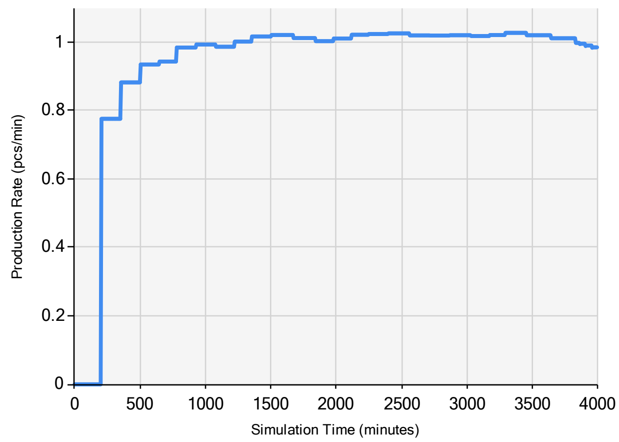
Table 22

Simphony CYCLONE Statistics Report of HCB Work Final Future State Model for 100 Run Count

Non-Intrinsic Statistics					
Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
HCB FS 1 (Termination Time)	3968.386	70.970	100.000	3769.614	4167.884

Figure 38

Production Rate vs. Simulation Time of HCB Work Final Future State Model



5.7. Summary of Findings

As shown in the previous sections, the application of lean concepts and principles has improved total cycle time and as shown below labor productivity has improved significantly in both slab rebar and HCB operations. Lean construction gives attention to an increment and continuous improvement in project performance. The principles proposed and applied are improvements that are deemed capable to be applied by the construction companies and that don't pose an additional cost of operation. Consequently, improvement in labor productivity for every scenario modeled for both operations are calculated and presented in tables 23 & 24 below.

In the effort to optimize the utilization of labor, no change is detected in the production rate. This is because the production rate and productivity are not similar. Production rate tells us the duration it took to produce a quantity of work. However, productivity determines how resources are utilized for the generation of the outputs. Numerous researchers agree that productivity is a ratio of output and input (CII 2010, as cited in Muralidharan et al., 2018). Subsequently, as shown below in table 23, the application of workplace organization/standardization, production scheduling, and optimization of utilization of labor resources have improved labor productivity of slab rebar operation by 36.3%.

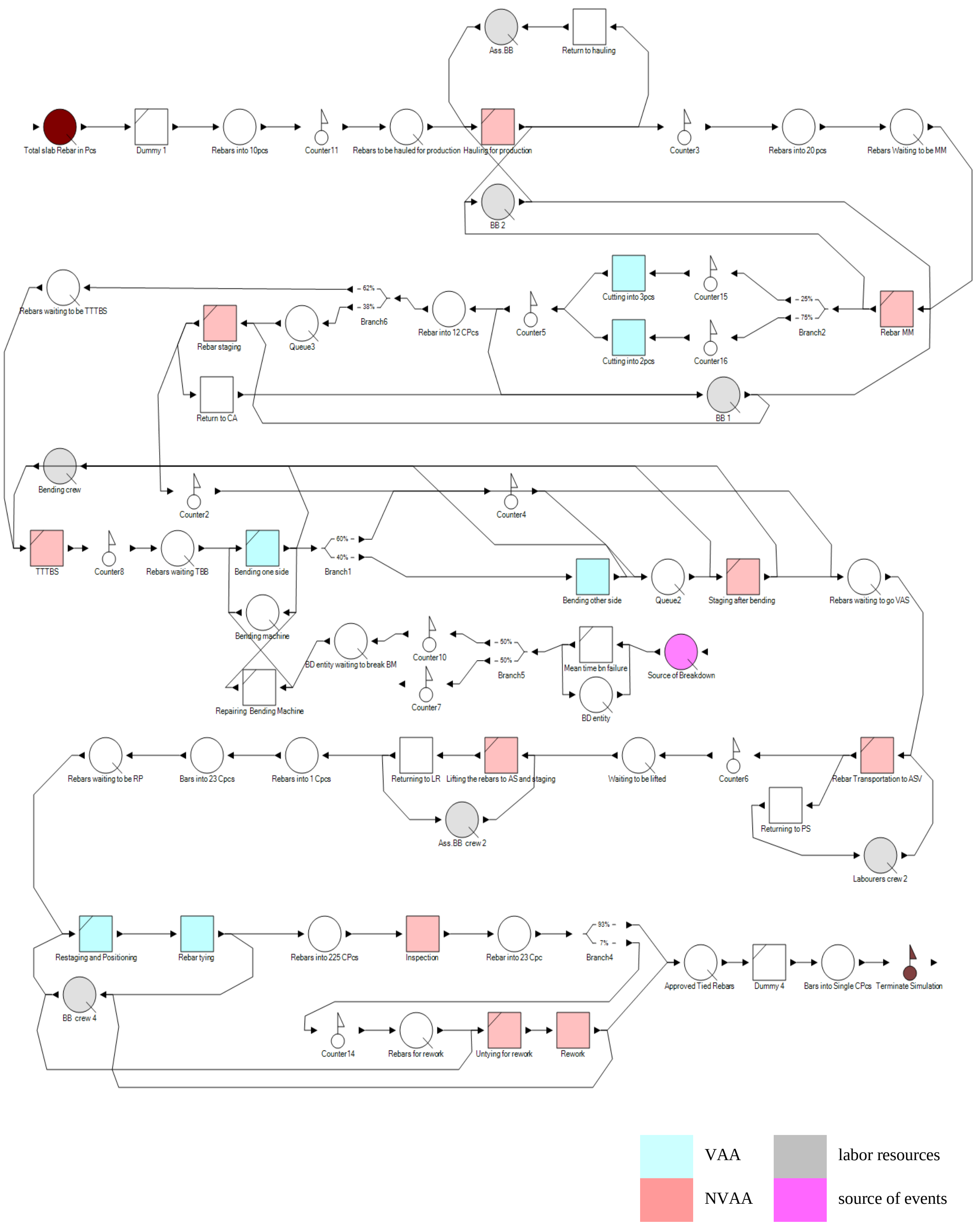
Table 23

Comparison of Labor Productivity Output for Slab Rebar Operation Current State and Lean Models

	Scenario	Cycle time (min)	Production rate (pcs/min)	Average no of Manpower	Total man hour (TMH)	Labor Productivity (Kg/mhr)	Improvement (%) in labor productivity
1	Current State Model (CSM)	4306.09	0.604	23	1080	15.25	
2	Pull model	4054.91	0.640	23	1017	16.19	6.2
3	WOS & PS model	2680.93	0.970	21	938.32	17.56	15.1
4	WOS & PS with pull	2697.02	0.965	21	943.95	17.45	14.4
5	Optimizing utilization of labor resources (final future state)	2797.72	0.930	17	792.7	20.78	36.3

Figure 39

Slab Rebar Operation Future State CYCLONE Model



The lean concepts and principles were applied simultaneously on the CSM of the HCB work model, then further possibility of improvement was checked by optimizing utilization of labor for a different combination of labor resources. FIFO (portable pallet with a capacity of 60pcs HCB) with a kanban (flag) to control the flow of material between sub processes; signalizing kanban (plastic paper for detailed crew instruction and flags), tool kit based on the concept of 5S; simplification; hurdle meeting; and then optimization of utilization of labor resources contributed to the 34.6 % improvement in labor productivity. The corresponding future state CYCLONE model is shown below in figure 40.

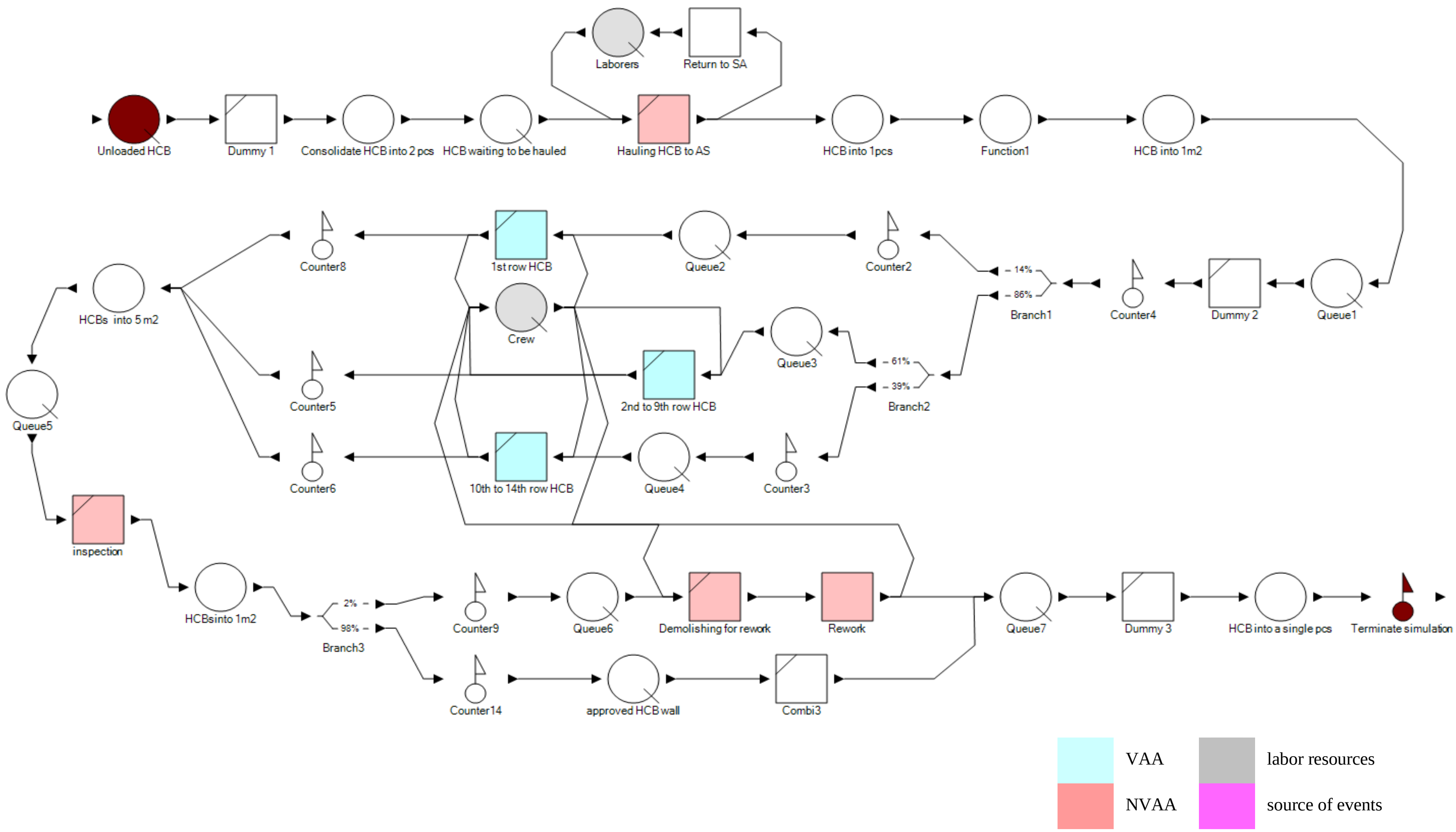
Table 24

Comparison of Labor Productivity Output for HCB Work Current State and Lean Models

	Scenario	Cycle time (min)	Production rate (pcs/min)	No of Manpower	Total man-hour (mhr)	Labor Productivity (m^2/mhr)	Improvement (%) in labor productivity
1	Current State Model	4579.64	0.85	7	534.30	0.56	
2	Future state model 1 (FS 1)	3937.58	0.99	7	459.38	0.65	16.3%
3	Final Future state model	3968.39	0.98	6	396.84	0.76	34.6%

Figure 40

HCB Work Future State CYCLONE Model



6. FUTURE STATE MAPPING

When the map of the current status quo is documented a parallel map is developed which instead describes the ideal future state (FS). Rother & Shook (1999) developing the current and future state is an overlapping effort. Subsequently, the proposed lean concepts and principles tested after modelling the scenarios by Simphony CYCLONE. Finally, based on the output, the final future state map of the operations is mapped by incorporating the appropriate and necessary lean concepts and principles.

6.1. Future State Map of Slab Rebar Operation

Based on the simulation result, the concept of pull was found redundant. Instead, the small-batch flow could be integrated with site layout redesign, and FIFO could be adopted in a way each work sub-stations are designed not to hold more than 20 Pcs. The kanban, the newly developed bending machine, and the redesigned site layout are shown below in figure 41.

The site layout was redesigned by incorporating:

- the supermarket-pull integrated with the 5S concept. All straight 12m rebars required for a floor work (the horizontal and vertical structure) are placed with respect to their diameter in a compartmented box of size 1.2m x 1.2m structure;

- the FIFO concept, in a way each work sub-stations are designed not to hold more than 20 Pcs of rebar;

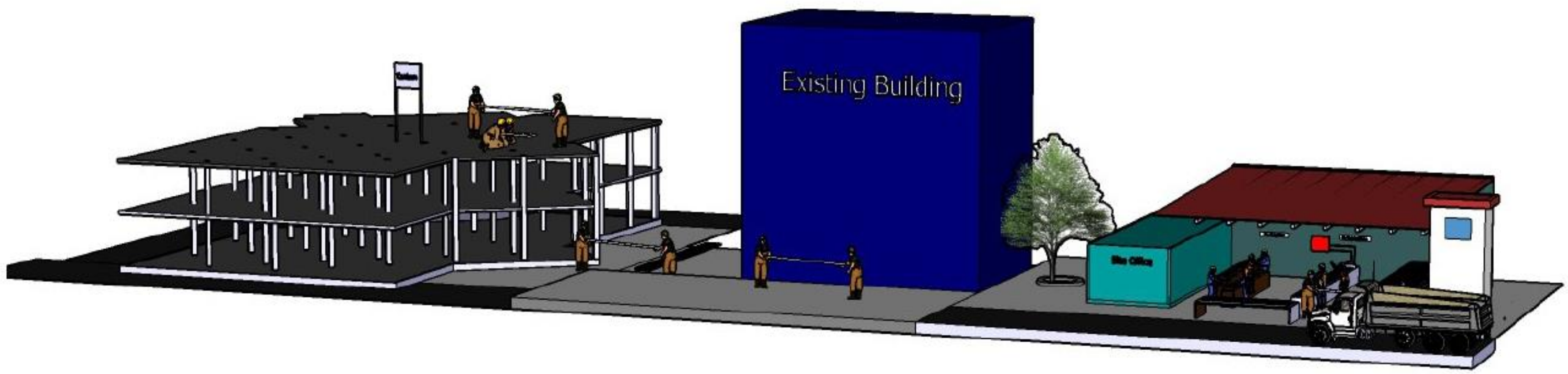
- the standardized cutting bench of size, 12m x 1m. The cutting bench is modified by raising the one side based on the concept of 5S. Which aids in reducing the measuring and marking cycle time and to act as a compartment, which helps to avoid the contact between the rebar and the machine wire, so that accidents could be forfended; and

- the newly developed bending table, which allows two bar-benders to work in a continuous flow without reversing the rebars and creating WIP.

Figure 41

Site Plan After Site Layout Redesign: (a) Redesigned Site Plan; (b) Kanban at the Production Site; (c) Kanban at the Actual Site

(a)



(b)

2

1

* Dia: 8

* Cut length: 5.5m

* Bend 1 side: 13cm

* No of member: 55 C. Pcs

(c)

Panel 2

Panel 1

* C. Pcs: 5.5m (BL1: 13) x 50

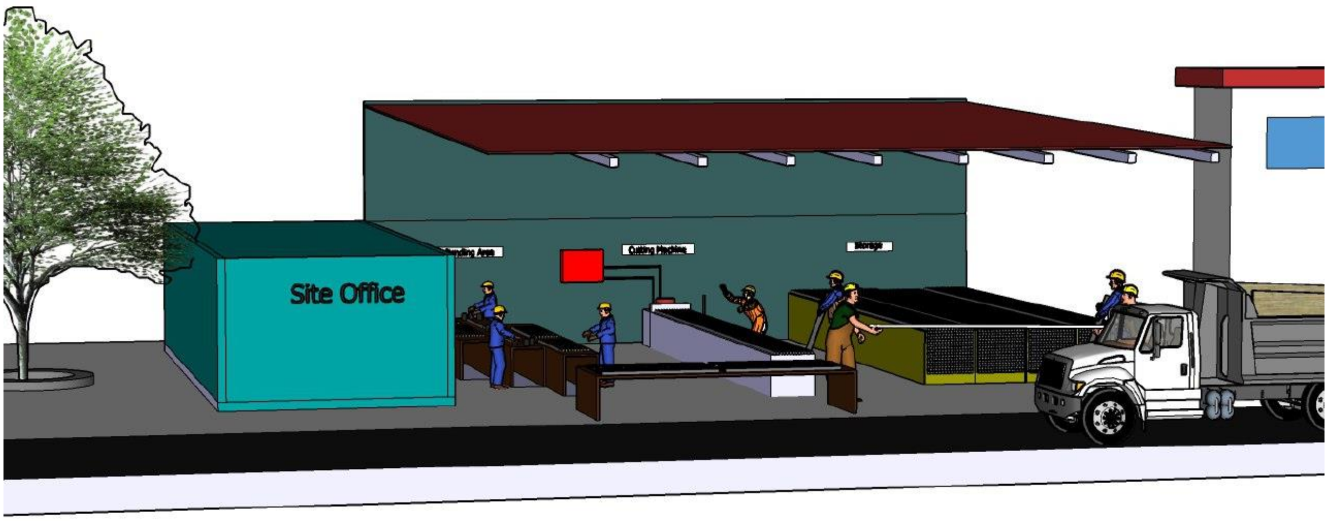
* C. Pcs: 3.5m (0) x 50

* C. Pcs: 3.5m (BL 1:13 * BL2) x 40

Figure 42

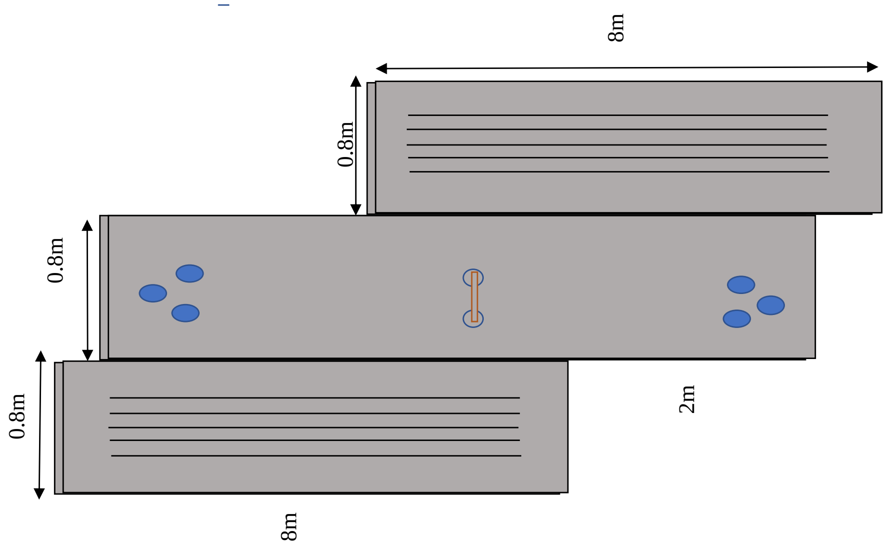
Redesigned Rebar Production Site Layout: (a) View Towards the Storage Area; (b) View Towards the Bending Table; (c) 2-D View of the Bending Table

(a)



(b)

(c)



The applied lean concept and principles to design the future state map from the delivery to the final task is discussed in detail in the analysis part. This part summarizes the concept and the principles applied, and the future state map. A lead time of one hundred eighty four and three hours (184.4 days) was reduced to seven days and five hours (7.58 days), which is approximate to one hundred and seventy seven days (177 days) of reduction in lead time, or 95.9 % improvement in lead time which has mainly resulted from the push delivery method. This indicates that the money that could be spent on other early works is spent on rebar which was not going to be changed to a final product in a short time after purchasing. Instead, the rebars delivered on-site prompted different NVAA and affected labor productivity tremendously.

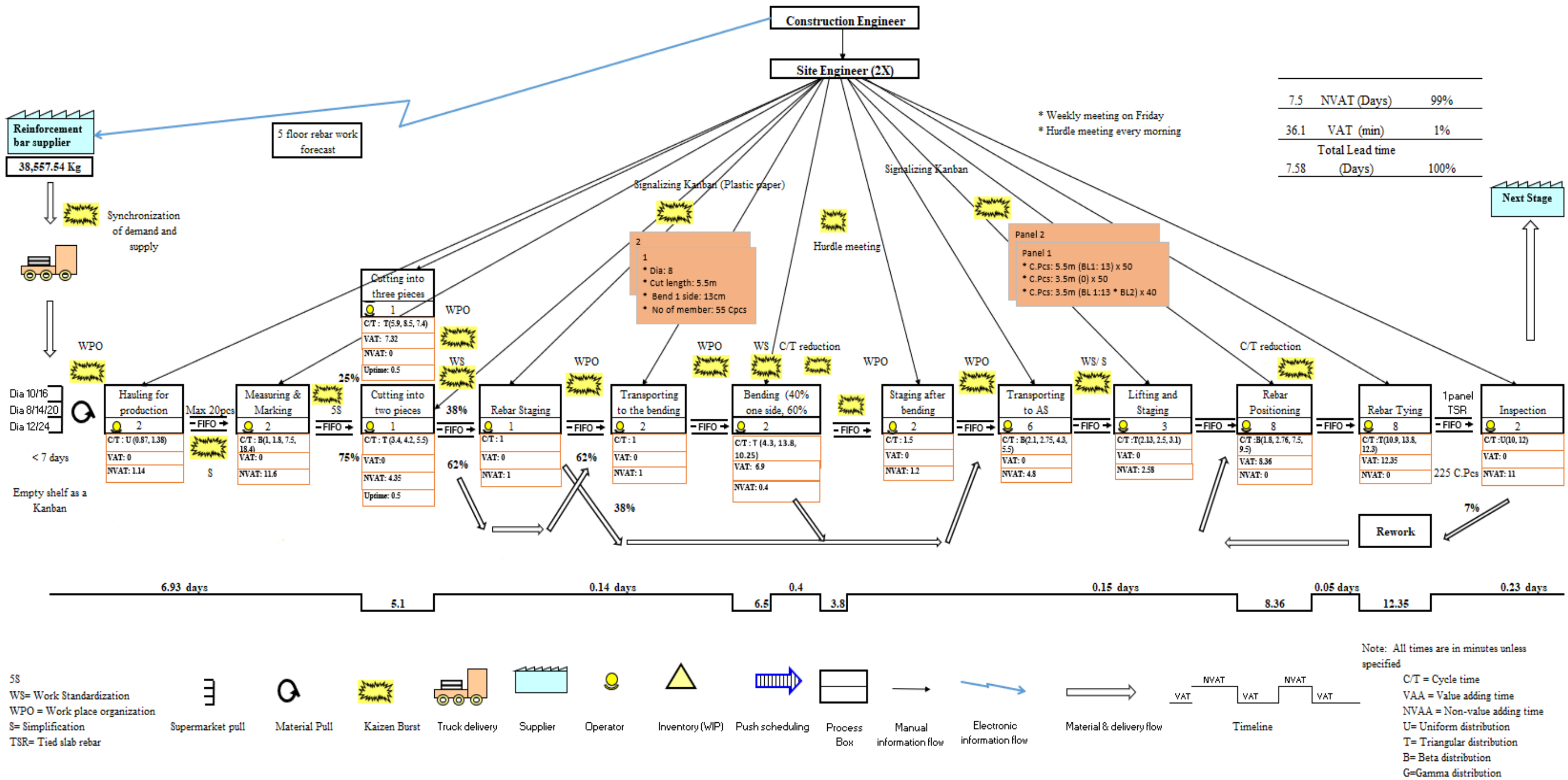
Table 25

Summary of The Lean Concepts and Principles Proposed for The Slab Rebar Operation

Lean concepts and principles	Significance
FIFO with small-batch flow	▪ Reduction of WIP, unnecessary transportations and defects ▪ Reduction of waiting times caused by overproduction
Supermarket pull system (empty shelf as a supplier kanban)	▪ To limit inventory which prompted a longer lead time, defect and over-processing steps (Cleaning rebars), ▪ To synchronize demand and supply ▪ To avoid the need to check available resources ▪ To mitigate cash flow and monetary loss issues
Workplace organization and standardization (WOS)	▪ Site layout planning to avoid unnecessary transportations, waiting times and material wastages and reduction of cycle time ▪ 5S to compress cycle time spent in searching for the required rebar, machine and avoid congestion on site. ▪ Redesigning the bending table to eliminate the over-processing step, which resulted in higher cycle time ▪ Simplification to eliminate the over processing steps (straightening)
Signalizing kanban (Hanging plastic papers)	▪ To enhance quality and transparency, ▪ To avoid waiting and rework due to late delivery of information and miscommunication
Hurdle meeting	▪ Increase transparency, reliability and reduce rework
Continuous Improvement	▪ To continuously improve and enhance labor productivity

Figure 43

Future State Map of Slab Rebar Operation



6.2. Future State Map of HCB Work

In this section, the concept and the principles applied are summarized and the future state map is presented. A lead time of ten days and five hours (10.6 days) was reduced to five and three hours (5.4 days), which is approximate to a five-day (5 days) reduction in lead time, or 49% improvement in lead time.

Figure 44

Portable Pallet to Apply FIFO And Supermarket-Pull

Figure 45

Kanban at the Actual Site

* Axis A-B between column A1-A2 (20cm)

* Insert 3m conduit 5m away from column A1

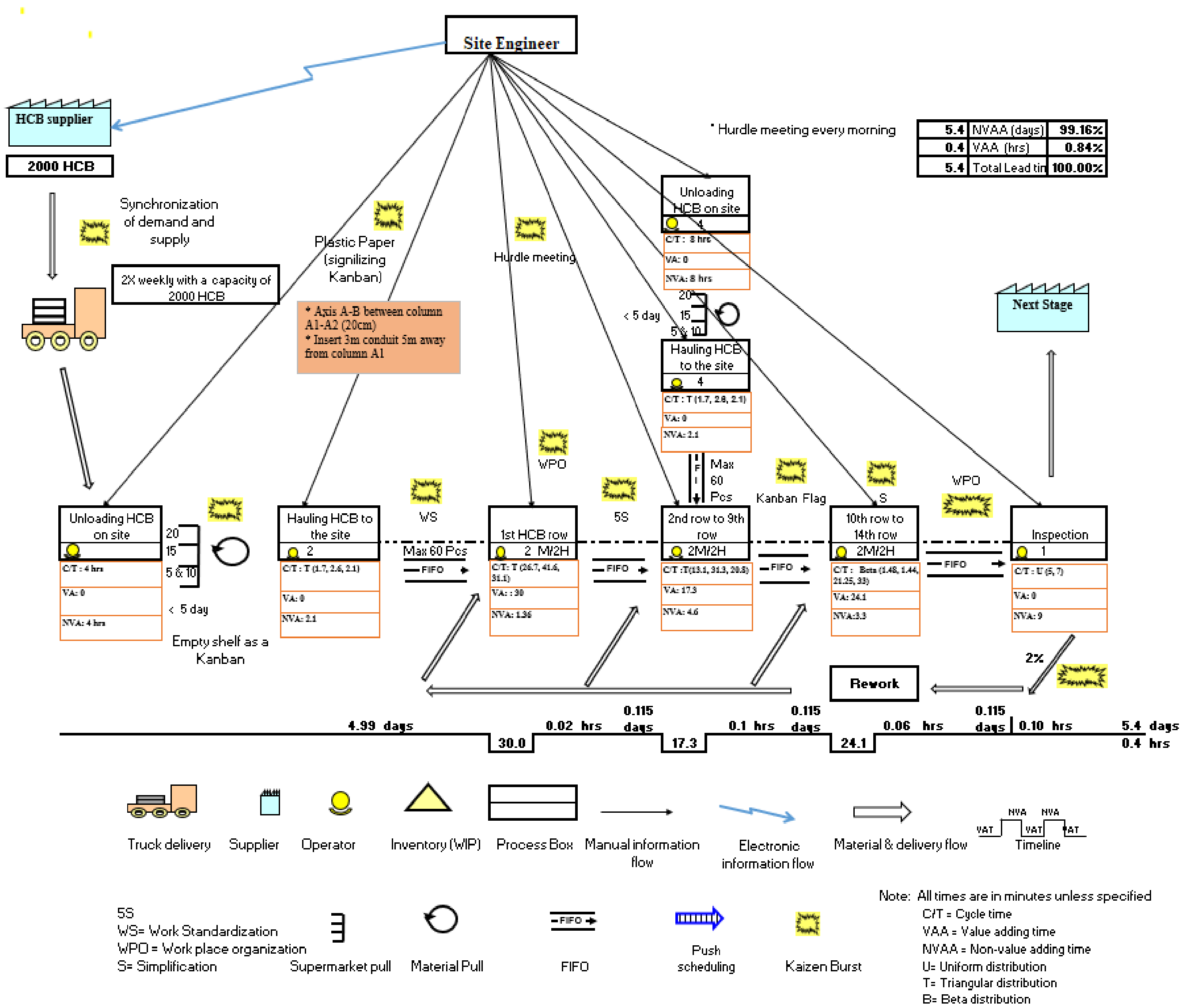
Table 26

Summary of the Lean Concepts and Principles Proposed for HCB Work Model

Lean concepts and principles	Significance
Supermarket pull system	▪ To limit inventory which prompted a longer lead time, defect and over-processing steps ▪ To synchronize demand and supply ▪ To avoid the need to check available resources
FIFO (portable pallet with a capacity of 60pcs HCB) with Kanban (yellow flag)	▪ To manage WIP, to limit the overproduction caused by the push system ▪ To mitigate unnecessary transportation waste in between the site
Hurdle meeting	▪ Hurdle meeting based on the concept of last planner system, to enhance transparency and reduce rework
Kanban	▪ Plastic paper as a signalizing kanban to avoid verbal communication and enhance transparency ▪ Red flag as a supplier kanban for a better information flow to reduce waiting time
Workplace organization and standardization	▪ Tool kit based on the concept of 5S to avoid inefficient movement of labors in searching for tools so as to reduce cycle time and material wastage ▪ Simplification to eliminate the over processing steps ▪ To eliminate unnecessary transportations

Figure 46

Future State Map of HCB Work



7. CONCLUSION AND RECOMMENDATION

7.1. Conclusion

Whenever there is a product for a customer, there is a value stream. The challenge lies in seeing it.

Rother and Shook

The construction industry's long-standing low labor productivity has been a major concern. At the outset of this research, three specific objectives were identified with a general objective of enhancing labor productivity using VSM integrated with DES. The study principally employed observation and unstructured interviews to gather the necessary data and proceeded to the construction of VSM and DES, targeting to attain what is aimed for. Accordingly, the following conclusions are forwarded with their respective objectives:

1. *To determine the share of wastes or non-value-adding activities in the selected building construction operations.*

   Since the adaptation of lean theory to construction began, NVAA has been identified. Recently, by initiatives taken by a few researchers, NVAA in the Ethiopian construction has started to be identified. However, NVAA and their vicious circle is an overlooked insight. In a broader aim of reducing these wastes, the researcher maneuvered in identifying and studying their vicious circle. In doing so, the value stream of the current state of operations was mapped and analyzed by raising questions the lean concepts and principles give insight into. So, that their application complements project performance, particularly, labor productivity.

   In analyzing the CSM of slab rebar operation of the case study, it was found that 99.96 % of the operation is constituted by NVAA and only 0.04% of the time is spent on VAA. Similarly, 99.57% of NVAA and 0.43% VAA comprise the HCB work. It seems as no work is being done. However, according to TFV theory, what is flow and what isn't generating value to our customers is a waste, which we should continuously strive to avoid. This level of waste is present by the traditional status quo management system, which only sees construction as a transformation only (Ballard & Howell 1994; Howell 1999; Koskela 1992; Koskela et al. 2013). In analyzing the current state value stream, a waste begets another waste, and a vicious circle of wastes has been witnessed. NVAA that are found in slab rebar operation are, viz: overproduction, which had prompted WIP and which in turn was causing unnecessary transportation, defect, and over-processing; inventory, which has instigated defect and over-processing; transportation, which had prompted waiting and unnecessary movement of employees; waiting; and reworks. Similarly, NVAA found in HCB work are, namely: overproduction, which had prompted WIP and unnecessary transportation, which had in turn caused defect; rework; waiting; unnecessary movement of employees; and over-processing steps.

2. *Identifying the root causes of non-value-adding activities.*

Merely measuring the level of waste wouldn’t create an opportunity for improvement. Hence, analyzing what is promoting these wastes was found to be indispensable. The industry has endeavored into identifying the root causes of NVAA. However, a mere approach of tallying NVAA and their causes would lead to sub-optimization only (Koskela, 1992 & Rother & Shook, 1999). In this research, VSM steered the path in identifying root causes by bringing attention to the satisfaction of customer values; the need for a redesign of the processes; and the essences of lean concepts and principles in guiding the flow of material and information. Furthermore, a fishbone diagram was used to identify and present the root cause of NVAA with the aid of unstructured interviews for the data gathering. Accordingly, the root causes were presented from six perspectives, namely: material; design; information; methods; manpower and machine/tools.

In analyzing the CSM of slab rebar operation and questioning the four W’s, six root causes were determined from the perspective of material: improper ordering of material; quality issues (defects); inappropriate site storage, location and storing method; lack of material wastage management; and damage during transportations. Root causes related to the perspective of methods employed are inefficient unloading and transportation methods; overproduction; late supervisions; over-processing; improper site layout organization; lack of follow up; and unsafe working conditions. In addition, root causes such as design changes and detailing errors from the perspective of design; machine design faults, breakdown and maintenance time from the perspective of machine; poor communication, late information delivery, lack of clear information & transparency from the perspective of information; and task allocation and inadequate utilization of labor resources from the perspective of manpower were identified as the root causes of NVAA.

Analyzing the CSM of HCB work similarly, root causes such as quality issues (defects), improper storing method, lack of material wastage management and damage during transportations from the perspective of material; onsite transportation methods, overproduction, late supervisions, and over-processing from the perspective of methods; poor communication, late information delivery, lack of clear information & transparency from the perspective of information; design and construction details errors, and complexity from the perspective of design; missing tools related to the usage of tools; and inadequate utilization and lack of coordination from the perspective of manpower were identified as the root causes of NVAA.

To recapitulate, root causes related to the perspective of material and methods took a huge share. And it has implied that waste minimization and value generation can be obtained mainly through appropriate site layout planning.

3. *Measuring the improvement in labor productivity by the application of lean concepts and principles using VSM integrated with DES.*

After the share of NVAA measured and root causes were identified, lean concepts and principles that would embellish the labor productivity were applied in different scenarios on the verified and validated CYCLONE models.

The concept of pull; the principle of workplace organization/standardization (WOS); and production scheduling (PS) were applied to the current state slab model independently. Subsequently, the two scenarios were combined to witness the combinational effect and then another scenario of comparison of outputs was made for different combinations of labor resources. Subsequently, the concept of pulling was found redundant and FIFO was adopted to aid the small-batch flow employment. Finally, simulating the proposed future state model, by the application of all the proposed concepts and principles, labor productivity was enhanced by 36.3 %. Accordingly, the final future state model mapped based on the simulation outcome, and the lead time of 184.4 days was reduced to 7.58 days, which is approximate to 177 days of reduction in lead time, or 95.9% improvement in lead time.

Lean concepts and principles, namely: FIFO (portable pallet with a capacity of 60pcs HCB) with a kanban (flag) to control the flow of material between sub processes; signalizing kanban (plastic paper for detailed crew instruction and flags for signaling material need), tool kit based on the concept of 5S; simplification; and hurdle meetings were applied simultaneously on the CSM of the HCB work model. Furthermore, the possibility of improvement was checked by optimizing utilization of labor for a different combination of labor resources. Consequently, labor productivity was enhanced by 34.6 %. The future state mapped accordingly, and the lead time reduced to 5.4 days from 10.6 day, which is approximate to a five-day reduction in lead time, or 49% improvement in lead time.

The foregoing discussion indicates that VSM has paramount importance to study and analyze operations in a profound manner. It unwraps wastes hidden in an operation that couldn’t be noticed just by tallying. Moreover, it guides in the application of lean concepts and principles. VSM isn’t limited only to identifying wastes and their root causes, but helps in the development of new products and redesigning processes. Integrating DES with VSM has enabled the researcher to model the operations in a detailed manner. More relevantly, it aids to assess and comprehend the proposed lean concepts and principles’ effectiveness in enhancing labor productivity by evaluating alternative scenarios. Furthermore, it gives assurance for the application of lean concepts and principles in the real world.

Moreover, to what was aimed to achieve, other performances of project enhancements have been witnessed. An unsafe working environment was one of the issues due to the ineffective site layout arrangement. The cutter was moving across the site, over the piled rebars, and whilst, it was getting stuck and was being pulled to be released. In such a manner, the cover of the cutter wire could get pealed and in contact with the rebar, it would create electric shock accidents. Thus, by redesigning the site layouts integrating the concept of 5S, based on the principle of workplace organization/ standardization, a safer working environment could be created.

In conclusion, VSM incorporates and ties the most relevant concept and principles, which directs the pathway for improvements. Therefore, VSM in every level of the task, from the single to the overall is necessary to improve labor productivity. Furthermore, integrating DES with VSM would help in appraising the significance of lean concepts and principles adoption and leads to a more pragmatic approach to lean construction management.

7.2. Recommendations

7.2.1. Recommended Actions

It is shown that the share of NVAA is high in both case studies and it has resulted in low labor productivity. As a result, actions must be taken. Therefore, based on this research outcome the following recommendations are directed, viz:

1. Only, one of the projects from the case studies collects labor productivity data, and plan based on that. It is recommended the others do the same since the initiative for improvement offset by understanding the status quo of one’s performance.

2. It is seen that both projects are far behind schedule and the solution to compensate for the delay has been crashing the project. This is because of the traditional thinking and project management that is diffused in the industry. Thus, it is recommended that the team of these projects give due attention to the flow dimension of construction.

3. In doing so, for the slab rebar operation, NVAA such as inventory, one of the causes of the vicious circle of waste, due to the push delivery system should be substituted by supermarket pull system to synchronize demand and supply. WIP prompted by overproduction should be mitigated by the application of small-batch flow and FIFO. Waiting and reworks, which are mainly caused by miscommunications and late information deliveries should be avoided using signalizing kanbans and by having hurdle meetings. The over-processing step of straightening should be eliminated, and the discontinuous flow of material during bending must be changed into continuous flow by using the redesigned bending table. Moreover, 5S should be employed: for stacking the rebars according to their sizes in a compartmented supermarket; and to keep

the site clean, so that abnormalities get revealed. Adopting the redesigned cutting bench is a recommended action since it would aid in reducing cycle time, and forfending accidents. As it is modified to only hold 20 straight rebars and separated from the cutting machine by raising the shorter side based on the concept of 5S.

It would be prudent that the stakeholders adopt the redesigned site layout. Moreover, they should collaboratively, coordinately, and continuously enhance construction site layouts before allocating resources to it. As a result, in-between unnecessary transportations could be reduced. To recapitulate, adopting workplace organization/ standardization; production scheduling; and optimizing labor resource principles through continuous improvement is an indispensable action to eliminate NVAA and improve labor productivity.

4. In the same manner, for the HCB work, the inventory caused by pursuing a push delivery system should be substituted by supermarket pull, by making the delivery every four days and using empty shelf being as a supplier kanban. Overproductions caused by the continuous hauling of HCB from the storage area should be replaced by FIFO systems, using portable pallet with a capacity of 60 pcs. As a result, unnecessary in-between transportations could be eliminated. The rework caused by miscommunications and late information delivery could be mitigated by using plastic papers as a signalizing kanban and by having a daily hurdle meeting. The waiting time prompted by the late delivery of mortar could be precluded by using a flag as a supplier kanban. The time spent searching for tools could be mitigated by adopting a tool kit based on the 5S concept. Finally, the time being wasted on cutting HCB to fill openings could be obviated by ordering 5cm HCB based on the concept of simplification. To summarize, adopting workplace organization/ standardization; production scheduling; and optimizing labor resource principles through continuous improvement is an indispensable action to eliminate NVAA and improve labor productivity.

5. Finally, decision tools such as DES should be employed. It would aid in comprehending the efficacy of lean concepts and principles and to assess labor resource optimizing opportunities. And it would lead to a more pragmatic approach to lean construction management.

7.2.2. Recommended Research Areas

Lean construction concepts, principles, and tools are vast. However, this research is mainly focused on the enhancement of labor productivity by adopting lean concepts and principles using VSM integrated with DES. Thus, there are vast areas of research that could be recommended, yet specific to what this research has emphasized on, the following research areas are recommended, viz:

1. Enhancing labor productivity using other lean constriction tools;
2. Enhancing labor productivity of other selected building construction operations using VSM integrated with DES.
3. Studying the improvement of other performance indicators by adopting VSM integrated with DES for selected building construction operations; and
4. Integration of VSM and DES to improve the overall productivity of a selected highway construction process.

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APPENDIX A: OBSERVATION DATA

Table A 1

Daily Labor Productivity Data of Slab Rebar Operation

Addis Ababa Institute of Technology
School of Civil and Environmental Engineering
Graduate Program in Construction Technology and Management
Thesis on: Enhancing Labor Productivity of Building Construction Operations Using VSM Integrated with DES
Observation Data Collection Sheet Format: 1

Data: Labor Productivity
Project: Case Study One (Slab Rebar Operation)
Location: Addis Ababa

		Crew Composition					Installed Quantity- Level of effort			Labor Productivity
Date	Crew Size	BB	Ass. BB	Laborers	Total man-hours (mhr)	Unit	Weight of Task	Level of effort (%)	Completed Unit	Installed Quantity /T. Manhours
Dec 24-2019	4	3	1	-	32	Kg	2154.24	32	689.36	21.54
Dec 25-2019	4	3	1	-	32	Kg	2280.96	32	729.91	22.81
						Kg	2407.68	68	1637.22	
						Kg	3801.60	32	1216.51	
Dec 26-2019	23	12	3	8	184	Kg	633.60	9	57.02	15.82
						Kg	2534.40	68	1723.39	
						Kg	3345.41	32	1070.53	
Dec 27-2019	23	12	3	8	184	Kg	1584.00	9	142.56	15.96
						Kg	3358.08	68	2283.49	
						Kg	2217.60	32	709.63	
Dec 28-2019	23	12	3	8	184	Kg	633.60	9	57.02	16.58
						Kg	2534.40	68	1723.39	
Dec 30-2019	23	12	3	8	184	Kg	1647.36	32	527.16	12.23
Dec 31-2019	15	6	3	6	120	Kg	2629.44	59	1551.37	12.93
Jan 1-2020	10	6	2	2	80	Kg	2090.88	59	1233.62	15.42
Jan 2-2020	10	6	2	2	80	Kg	1900.80	59	1121.47	14.02

Table A 2

Daily Labor Productivity Data of HCB Work

Addis Ababa Institute of Technology
School of Civil and Environmental Engineering
Graduate Program in Construction Technology and Management
Thesis on: Enhancing Labor Productivity of Building Construction Operations Using VSM Integrated with DES
Observation Data Collection Sheet Format: 1

Data: Daily Productivity Output
Project: Case Study Two (HCB work)
Location: Addis Ababa

Date	Crew Size	Crew Composition		Man-hours (mhr)	Unit	Installed Quantity	Productivity
		Masons	Laborers				Installed Quantity /T. Manhours
Jan 22-2020	7	2	5	56	m2	32.40	0.58
Jan 23-2020	7	2	5	56	m2	28.60	0.51
Jan 24-2020	7	2	5	56	m2	32.62	0.58
Jan 25-2020	7	2	5	56	m2	35.40	0.63
Jan 27-2021	7	2	5	56	m2	36.40	0.65
Jan 28-2022	7	2	5	56	m2	28.40	0.51
Jan 29-2023	7	2	5	56	m2	30.00	0.54
Jan 30-2024	7	2	5	56	m2	27.60	0.49
Jan 31-2025	7	2	5	56	m2	33.40	0.60
Feb 1-2026	7	2	5	28	m3	15.28	0.55

Table A 3

Cycle Time Data for Hauling & Straightening

Addis Ababa Institute of Technology
School of Civil and Enviromental Engineering
Graduate Program in Construction Technology and Management
Thesis on: Enhancing Labor Productivity of Building Construction Operations Using VSM Integrating with DES
Observation Data Collection Sheet Format: 2

Data: Cycle time of Sub-processes
Project: Case Study One (Slab Reinforcemment Operation)
Location: Addis Ababa

Hauling for Production from Storage Area

Data C.	Avg no of Rebar	CT (min)	Avg no of manpower	Data C.	Avg no of Rebar	CT (min)	Avg no of manpower	Data C.	Avg no of Rebar	CT (min)	Avg no of manpower
1	10	0.95	2	41	10	1.25	2	81	10	1.20	2
2	10	1.25	2	42	10	1.1	2	82	10	1.15	2
3	10	0.93	2	43	10	1.2	2	83	10	0.95	2
4	10	1.05	2	44	10	1.2	2	84	10	1.25	2
5	10	1.10	2	45	10	1.23	2	85	10	1.50	2
6	10	1.00	2	46	10	1.25	2	86	10	1.10	2
7	10	1.27	2	47	10	0.95	2	87	10	1.40	2
8	10	1.50	2	48	10	0.92	2	88	10	1.05	2
9	10	0.97	2	49	10	1.33	2	89	10	1.00	2
10	10	1.00	2	50	10	1.1	2	90	10	1.20	2
11	10	1.05	2	51	10	1.45	2	91	10	0.90	2
12	10	1.35	2	52	10	1.25	2	92	10	1.00	2
13	10	1.20	2	53	10	0.97	2	93	10	1.05	2
14	10	1.30	2	54	10	1.4	2	94	10	1.00	2
15	10	1.23	2	55	10	1.35	2	95	10	1.20	2
16	10	1.10	2	56	10	0.95	2	96	10	1.45	2
17	10	1.30	2	57	10	1.19	2	97	10	1.10	2
18	10	1.05	2	58	10	1.05	2	98	10	0.90	2
19	10	1.25	2	59	10	1	2	99	10	0.95	2
20	10	1.07	2	60	10	1.23	2	100	10	1.28	2
21	10	0.98	2	61	10	1.3	2	101	10	1.3	2
22	10	1.28	2	62	10	1.16	2	102	10	0.95	2
23	10	1.48	2	63	10	0.97	2	103	10	1.05	2
24	10	1.30	2	64	10	1.25	2	104	10	1.2	2
25	10	0.95	2	65	10	1.05	2	105	10	1.42	2
26	10	1.15	2	66	10	0.97	2	106	10	1.08	2
27	10	1.32	2	67	10	1.22	2	107	10	1	2
28	10	1.25	2	68	10	1.13	2	108	10	1.2	2
29	10	1.05	2	69	10	0.9	2	109	10	1.1	2
30	10	0.95	2	70	10	1.12	2	110	10	0.95	2
31	10	0.90	2	71	10	1.05	2	111	10	0.9	2
32	10	1.25	2	72	10	1.07	2	112	10	1.35	2
33	10	1.09	2	73	10	1.09	2	113	10	1.25	2
34	10	1.14	2	74	10	1.12	2	114	10	1.15	2
35	10	1.12	2	75	10	1	2	115	10	0.95	2
36	10	1.48	2	76	10	1.2	2	116	10	0.9	2
37	10	1.28	2	77	10	1.15	2	117	10	1.05	2
38	10	1.15	2	78	10	0.92	2	118	10	1.3	2
39	10	1.50	2	79	10	1.12	2	119	10	1.45	2
40	10	1.10	2	80	10	0.92	2	120	10	1.2	2

Bar Straightning

Data C.	Avg no of Rebar	CT (min)	Avg no of manpower	Data C.	Avg no of Rebar	CT (min)	Avg no of manpower	Data C.	Avg no of Rebar	CT (min)	Avg no of manpower
1	1	0.51	1	41	1	0.57	1	81	1	0.6	1
2	1	0.48	1	42	1	0.6	1	82	1	0.5	1
3	1	0.56	1	43	1	0.48	1	83	1	0.56	1
4	1	0.53	1	44	1	0.78	1	84	1	0.55	1
5	1	0.65	1	45	1	0.58	1	85	1	0.6	1
6	1	0.73	1	46	1	0.53	1	86	1	0.72	1
7	1	0.63	1	47	1	0.72	1	87	1	0.63	1
8	1	0.56	1	48	1	0.68	1	88	1	0.48	1
9	1	0.64	1	49	1	0.54	1	89	1	0.52	1
10	1	0.55	1	50	1	0.62	1	90	1	0.51	1
11	1	0.53	1	51	1	0.65	1	91	1	0.53	1
12	1	0.75	1	52	1	0.58	1	92	1	0.75	1
13	1	0.57	1	53	1	0.55	1	93	1	0.82	1
14	1	0.55	1	54	1	0.57	1	94	1	0.63	1
15	1	0.59	1	55	1	0.72	1	95	1	0.55	1
16	1	0.82	1	56	1	0.66	1	96	1	0.65	1
17	1	0.55	1	57	1	0.64	1	97	1	0.68	1
18	1	0.54	1	58	1	0.63	1	98	1	0.56	1
19	1	0.63	1	59	1	0.58	1	99	1	0.55	1
20	1	0.53	1	60	1	0.65	1	100	1	0.68	1
21	1	0.58	1	61	1	0.58	1	101	1	0.54	1
22	1	0.5	1	62	1	0.6	1	102	1	0.58	1
23	1	0.62	1	63	1	0.63	1	103	1	0.62	1
24	1	0.65	1	64	1	0.78	1	104	1	0.68	1
25	1	0.57	1	65	1	0.58	1	105	1	0.62	1
26	1	0.51	1	66	1	0.62	1	106	1	0.62	1
27	1	0.6	1	67	1	0.72	1	107	1	0.57	1
28	1	0.62	1	68	1	0.65	1	108	1	0.55	1
29	1	0.5	1	69	1	0.54	1	109	1	0.5	1
30	1	0.52	1	70	1	0.64	1	110	1	0.53	1
31	1	0.68	1	71	1	0.52	1	111	1	0.57	1
32	1	0.6	1	72	1	0.58	1	112	1	0.58	1
33	1	0.62	1	73	1	0.65	1	113	1	0.5	1
34	1	0.48	1	74	1	0.55	1	114	1	0.64	1
35	1	0.65	1	75	1	0.72	1	115	1	0.6	1
36	1	0.52	1	76	1	0.66	1	116	1	0.6	1
37	1	0.7	1	77	1	0.53	1	117	1	0.7	1
38	1	0.68	1	78	1	0.48	1	118	1	0.59	1
39	1	0.58	1	79	1	0.57	1	119	1	0.5	1
40	1	0.5	1	80	1	0.65	1	120	1	0.57	1

Table A 4

Cycle Time Data for MM & Bending

Addis Ababa Institute of Technology
School of Civil and Enviromental Engineering
Graduate Program in Construction Technology and Management
Thesis on: Enhancing Labor Productivity of Building Construction Operations Using VSM Integrating with DES
Observation Data Collection Sheet Format: 2

Data: Cycle time of Sub-processes
Project: Case Study One (Slab Reinforcemment Operation)
Location: Addis Ababa

Measuring and Marking								Bending							
Data C.	Avg no of Rebar	CT (min)	Avg no of manpow	Data C.	Avg no of Rebar	CT (min)	Avg no of manpower	Data C.	Avg no of Rebar	CT (min)	Avg no of manpower	Data C.	Avg no of Rebar	CT (min)	Avg no of manpower
1	20	14.6	2	51	20	8.8	2	1	5	4.48	2	41	5	6.37	2
2	20	11.25	2	52	20	13.5	2	2	5	3.06	2	42	5	7.2	2
3	20	13.2	2	53	20	7.78	2	3	5	3.48	2	43	5	5.67	2
4	20	11.65	2	54	20	8.3	2	4	5	3.99	2	44	5	5.79	2
5	20	10.9	2	55	20	11.9	2	5	5	5.72	2	45	5	5.73	2
6	20	11.97	2	56	20	10.9	2	6	5	5.32	2	46	5	5.59	2
7	20	12.85	2	57	20	14.5	2	7	5	8.52	2	47	5	5.63	2
8	20	18.36	2	58	20	12	2	8	5	7.79	2	48	5	6.89	2
9	20	12.25	2	59	20	14.6	2	9	5	7.89	2	49	5	6.87	2
10	20	8.2	2	60	20	12.5	2	10	5	6.25	2	50	5	3.94	2
11	20	8	2	61	20	12.25	2	11	5	7.12	2	51	5	5.25	2
12	20	8.8	2	62	20	8.2	2	12	5	5.33	2	52	5	5.4	2
13	20	16.1	2	63	20	16.3	2	13	5	6.32	2	53	5	6.1	2
14	20	13.4	2	64	20	8.52	2	14	5	6.25	2	54	5	4.61	2
15	20	17.7	2	65	20	13.4	2	15	5	6.11	2	55	5	4.35	2
16	20	15.3	2	66	20	11.25	2	16	5	6.72	2	56	5	4.85	2
17	20	8.52	2	67	20	13.7	2	17	5	6.5	2	57	5	5.73	2
18	20	12.5	2	68	20	10.5	2	18	5	7.05	2	58	5	6.23	2
19	20	14.25	2	69	20	18.3	2	19	5	6.15	2	59	5	5.95	2
20	20	12	2	70	20	8	2	20	5	3.58	2	60	5	5.05	2
21	20	10.66	2	71	20	11.8	2	21	5	5.2	2	61	5	6.7	2
22	20	9.5	2	72	20	10.6	2	22	5	4.59	2	62	5	3.6	2
23	20	15.8	2	73	20	11.65	2	23	5	5.07	2	63	5	6.13	2
24	20	11.2	2	74	20	9.5	2	24	5	4.31	2	64	5	5.75	2
25	20	13.5	2	75	20	13.2	2	25	5	4.88	2	65	5	6.3	2
26	20	8.05	2	76	20	10.66	2	26	5	5.2	2	66	5	6.7	2
27	20	9.3	2	77	20	7.5	2	27	5	6.26	2	67	5	6.23	2
28	20	9.98	2	78	20	14.5	2	28	5	4.83	2	68	5	5.7	2
29	20	10.6	2	79	20	15.5	2	29	5	5.8	2	69	5	5.35	2
30	20	7.72	2	80	20	8.7	2	30	5	6.32	2	70	5	6.25	2
31	20	7.78	2	81	20	16.1	2	31	5	6.4	2	71	5	6.6	2
32	20	10.5	2	82	20	10.5	2	32	5	7.17	2	72	5	6.1	2
33	20	11.5	2	83	20	7.7	2	33	5	5.77	2	73	5	7.05	2
34	20	10.15	2	84	20	9.7	2	34	5	7.04	2	74	5	5.5	2
35	20	13.7	2	85	20	10.1	2	35	5	5.75	2	75	5	5.25	2
36	20	12.3	2	86	20	10	2	36	5	6.68	2	76	5	5.35	2
37	20	7.5	2	87	20	8.05	2	37	5	6.69	2	77	5	6	2
38	20	11.8	2	88	20	12.3	2	38	5	6.11	2	78	5	4.35	2
39	20	8.35	2	89	20	9.1	2	39	5	6.59	2	79	5	4.9	2
40	20	10.1	2	90	20	15.3	2	40	5	6.14	2	80	5	7.15	2
41	20	10.5	2	91	20	9.55	2								
42	20	16.1	2	92	20	9	2								
43	20	10	2	93	20	15.2	2								
44	20	14.5	2	94	20	13.5	2								
45	20	7.5	2	95	20	9.5	2								
46	20	7.8	2	96	20	11.3	2								
47	20	9.8	2	97	20	11	2								
48	20	11.5	2	98	20	13.2	2								
49	20	12.8	2	99	20	16.5	2								
50	20	17.7	2	100	20	9.1	2								

Table A 5

Cycle Time Data for Cutting into two & Three pieces

Addis Ababa Institute of Technology School of Civil and Enviromental Engineering Graduate Program in Construction Technology and Management Thesis on: Enhancing Labor Productivity of Building Construction Operations Using VSM Integrating with DES Observation Data Collection Sheet Format: 2															
Data: Cycle time of Sub-processes															
Project: Case Study One (Slab Reinforcemment Operation)															
Location: Addis Ababa															
Cutting into two pieces								Cutting into three pieces							
Data C.	Avg no of Rebar	CT (min)	Avg no of manpow	Data C.	Avg no of Rebar	CT (min)	Avg no of manpower	Data C.	Avg no of Rebar	CT (min)	Avg no of manpower	Data C.	Avg no of Rebar	CT (min)	Avg no of manpower
1	20	4.3	2	31	20	3.88	2	61	20	4.85	2	1	20	8.35	2
2	20	4.56	2	32	20	4.28	2	62	20	4.1	2	2	20	8.3	2
3	20	4.2	2	33	20	4.42	2	63	20	4.5	2	3	20	7.6	2
4	20	3.56	2	34	20	4.2	2	64	20	4.3	2	4	20	6.75	2
5	20	4.05	2	35	20	4.22	2	65	20	5.2	2	5	20	6.5	2
6	20	5.25	2	36	20	4.16	2	66	20	4.85	2	6	20	6.96	2
7	20	3.62	2	37	20	4.74	2	67	20	4.68	2	7	20	7.3	2
8	20	4.44	2	38	20	4.36	2	68	20	4.2	2	8	20	7.25	2
9	20	3.52	2	39	20	4.08	2	69	20	3.62	2	9	20	7.85	2
10	20	4.68	2	40	20	4.52	2	70	20	5.1	2	10	20	7.1	2
11	20	3.46	2	41	20	4.4	2	71	20	4.95	2	11	20	6.7	2
12	20	3.74	2	42	20	4.22	2	72	20	4.1	2	12	20	6.94	2
13	20	3.68	2	43	20	4.32	2	73	20	5.4	2	13	20	7.34	2
14	20	3.9	2	44	20	4.44	2	74	20	4.55	2	14	20	6.3	2
15	20	3.92	2	45	20	4.34	2	75	20	4.9	2	15	20	7.5	2
16	20	3.7	2	46	20	4.32	2	76	20	4.2	2	16	20	7.5	2
17	20	4.2	2	47	20	4.6	2	77	20	4.7	2	17	20	8	2
18	20	3.88	2	48	20	4.08	2	78	20	4.44	2	18	20	6.5	2
19	20	4.24	2	49	20	4.64	2	79	20	3.9	2	19	20	6.8	2
20	20	4.1	2	50	20	4.38	2	80	20	4.65	2	20	20	7.8	2
21	20	3.82	2	51	20	4.78	2	81	20	4.8	2	21	20	7.9	2
22	20	3.76	2	52	20	4.1	2	82	20	4.6	2	22	20	7.7	2
23	20	3.88	2	53	20	4.6	2	83	20	5.1	2	23	20	6.9	2
24	20	3.92	2	54	20	5	2	84	20	4.1	2	24	20	7	2
25	20	3.92	2	55	20	4.5	2	85	20	5.1	2	25	20	7.25	2
26	20	5.2	2	56	20	4.1	2	86	20	4.95	2	26	20	7.55	2
27	20	4.36	2	57	20	4.8	2	87	20	4.15	2	27	20	7.82	2
28	20	3.98	2	58	20	4.7	2	88	20	4.2	2	28	20	7.42	2
29	20	4	2	59	20	4.6	2	89	20	4.05	2	29	20	7.2	2
30	20	4.24	2	60	20	4.8	2	90	20	5	2	30	20	7.4	2

Table A 6

Cycle Time Data for Cleaning & Transporting

Addis Ababa Institute of Technology
School of Civil and Enviromental Engineering
Graduate Program in Construction Technology and Management
Thesis on: Enhancing Labor Productivity of Building Construction Operations Using VSM Integrating with DES
Observation Data Collection Sheet Format: 2

Data: Cycle time of Sub-processes
Project: Case Study One (Slab Reinforcemment Operation)
Location: Addis Ababa

Cleaning Rebars

Data C.	Avg no of Rebar	CT (min)	Avg no of manpower	Data C.	Avg no of Rebar	CT (min)	Avg no of manpower	Data C.	Avg no of Rebar	CT (min)	Avg no of manpower	Data C.	Avg no of Rebar	CT (min)	Avg no of manpower
1	1	1.85	1	31	1	1.7	1	61	1	1.80	1	91	1	**1.85**	2
2	1	1.75	1	32	1	2	1	62	1	1.83	1	92	1	1.9	2
3	1	2.00	1	33	1	1.98	1	63	1	2.00	1	93	1	2.15	2
4	1	2.20	1	34	1	1.68	1	64	1	1.80	1	94	1	1.7	2
5	1	1.90	1	35	1	2	1	65	1	1.76	1	95	1	1.98	2
6	1	1.98	1	36	1	2.05	1	66	1	2.15	1	96	1	1.78	2
7	1	1.60	1	37	1	1.88	1	67	1	1.95	1	97	1	2.1	2
8	1	1.80	1	38	1	1.95	1	68	1	2.17	1	98	1	2.05	2
9	1	1.93	1	39	1	1.85	1	69	1	1.75	1	99	1	2.1	2
10	1	1.85	1	40	1	1.8	1	70	1	1.73	1	100	1	2.05	2
11	1	2.00	1	41	1	1.9	1	71	1	1.83	1	101	1	2	2
12	1	2.10	1	42	1	1.78	1	72	1	2.20	1	102	1	2.03	2
13	1	2.05	1	43	1	1.9	1	73	1	1.80	1	103	1	1.72	2
14	1	2.12	1	44	1	1.78	1	74	1	1.95	1	104	1	1.95	2
15	1	1.85	1	45	1	2	1	75	1	2.15	1	105	1	2.13	2
16	1	2.30	1	46	1	1.84	1	76	1	1.90	1	106	1	1.93	2
17	1	1.70	1	47	1	2.15	1	77	1	2.20	1	107	1	2.33	2
18	1	1.78	1	48	1	1.75	1	78	1	2.40	1	108	1	2.08	2
19	1	2.35	1	49	1	1.68	1	79	1	1.88	1	109	1	1.68	2
20	1	1.97	1	50	1	2.25	1	80	1	1.75	1	110	1	1.9	2
21	1	2.03	1	51	1	1.82	1	81	1	1.95	1	111	1	1.75	2
22	1	2.05	1	52	1	1.97	1	82	1	2	1	112	1	2.25	2
23	1	1.75	1	53	1	2.2	1	83	1	1.9	1	113	1	2	2
24	1	1.90	1	54	1	1.76	1	84	1	2.25	1	114	1	1.78	2
25	1	1.95	1	55	1	1.95	1	85	1	2.35	1	115	1	1.97	2
26	1	2.10	1	56	1	1.8	1	86	1	1.65	1	116	1	2.18	2
27	1	1.85	1	57	1	2.15	1	87	1	2.16	1	117	1	2.1	2
28	1	1.88	1	58	1	1.93	1	88	1	2.05	1	118	1	2.2	2
29	1	1.75	1	59	1	1.6	1	89	1	1.71	1	119	1	1.75	2
30	1	1.90	1	60	1	1.96	1	90	1	1.95	1	120	1	2.3	2

Transporting to the Actual Site

Data C.	Avg no of Rebar	CT (min)	Avg no of manpower	Data C.	Avg no of Rebar	CT (min)	Avg no of manpower	Data C.	Avg no of Rebar	CT (min)	Avg no of manpower
1	5	4.8	2	31	5	4.8	2	61	5	4.9	2
2	5	4.85	2	32	5	4.8	2	62	5	4.6	2
3	5	4.5	2	33	5	5	2	63	5	4.48	2
4	5	5.1	2	34	5	4.67	2	64	5	4.6	2
5	5	4.57	2	35	5	5.05	2	65	5	4.65	2
6	5	4.45	2	36	5	5.3	2	66	5	4.57	2
7	5	5.15	2	37	5	5.05	2	67	5	4.6	2
8	5	4.9	2	38	5	4.8	2	68	5	4.7	2
9	5	5	2	39	5	4.7	2	69	5	4.4	2
10	5	5.05	2	40	5	4.9	2	70	5	4.25	2
11	5	5	2	41	5	4.6	2	71	5	4.55	2
12	5	4.75	2	42	5	4.75	2	72	5	4.67	2
13	5	4.75	2	43	5	5.2	2	73	5	4.28	2
14	5	5.25	2	44	5	5.1	2	74	5	4.45	2
15	5	5.35	2	45	5	4.6	2	75	5	4.5	2
16	5	4.63	2	46	5	4.72	2	76	5	4.92	2
17	5	4.95	2	47	5	4.5	2	77	5	4.6	2
18	5	4.65	2	48	5	5.05	2	78	5	5.05	2
19	5	5.15	2	49	5	4.7	2	79	5	4.4	2
20	5	4.9	2	50	5	4.7	2	80	5	4.45	2
21	5	4.95	2	51	5	4.85	2				
22	5	4.85	2	52	5	4.65	2				
23	5	5.1	2	53	5	4.55	2				
24	5	4.95	2	54	5	4.8	2				
25	5	4.72	2	55	5	5.45	2				
26	5	4.65	2	56	5	4.5	2				
27	5	5.2	2	57	5	4.9	2				
28	5	5.1	2	58	5	4.65	2				
29	5	4.85	2	59	5	4.45	2				
30	5	4.9	2	60	5	4.65	2				

Table A 7

Cycle Time Data for Positioning & Tightening

Addis Ababa Institute of Technology
School of Civil and Enviromental Engineering
Graduate Program in Construction Technology and Management
Thesis on: Enhancing Labor Productivity of Building Construction Operations Using VSM Integrating with DES
Observation Data Collection Sheet Format: 2

Data: Cycle time of Sub-processes
Project: Case Study One (Slab Reinforcemment Operation)
Location: Addis Ababa

Staging and Positioning								Tightening							
Data C.	Avg no of Rebar	CT (min)	Avg no of manpower	Data C.	Avg no of Rebar	CT (min)	Avg no of manpower	Data C.	Avg no of Rebar	CT (min)	Avg no of manpower	Data C.	Avg no of Rebar	CT (min)	Avg no of manpower
1	10	9.95	8	46	10	9.05	8	1	10	12.5	8	46	10	12.25	8
2	10	8.8	8	47	10	8.9	8	2	10	13.4	8	47	10	12.2	8
3	10	8.5	8	48	10	9.7	8	3	10	12.3	8	48	10	12.8	8
4	10	9	8	49	10	8.96	8	4	10	11.6	8	49	10	13	8
5	10	9	8	50	10	9.15	8	5	10	12.23	8	50	10	12.75	8
6	10	9.55	8	51	10	9.2	8	6	10	11.95	8	51	10	12.8	8
7	10	9.15	8	52	10	8.65	8	7	10	12.35	8	52	10	13.1	8
8	10	9.35	8	53	10	9.05	8	8	10	12.65	8	53	10	12.9	8
9	10	8.85	8	54	10	9	8	9	10	11.35	8	54	10	12.4	8
10	10	9.05	8	55	10	9.2	8	10	10	13.35	8	55	10	13.6	8
11	10	9.25	8	56	10	9.45	8	11	10	12.4	8	56	10	12.75	8
12	10	8.85	8	57	10	8.9	8	12	10	12.35	8	57	10	13.2	8
13	10	10.5	8	58	10	9.15	8	13	10	12.1	8	58	10	13.05	8
14	10	9.15	8	59	10	8.65	8	14	10	11.8	8	59	10	12.45	8
15	10	9.2	8	60	10	9.25	8	15	10	12.05	8	60	10	11.25	8
16	10	9.02	8	61	10	9.35	8	16	10	11.75	8	61	10	13.1	8
17	10	8.8	8	62	10	9.73	8	17	10	12.5	8	62	10	11.9	8
18	10	8.95	8	63	10	10	8	18	10	12.8	8	63	10	12.48	8
19	10	9.45	8	64	10	9.55	8	19	10	10.95	8	64	10	11.4	8
20	10	9.4	8	65	10	9.6	8	20	10	12.65	8	65	10	12	8
21	10	9.8	8	66	10	9.4	8	21	10	11.55	8	66	10	12.65	8
22	10	10.2	8	67	10	8.85	8	22	10	11.85	8	67	10	11.4	8
23	10	8.85	8	68	10	9.05	8	23	10	11.67	8	68	10	11.9	8
24	10	9.8	8	69	10	10.4	8	24	10	12.2	8	69	10	13.15	8
25	10	9.7	8	70	10	9.8	8	25	10	12.25	8	70	10	11.7	8
26	10	8.9	8	71	10	8.9	8	26	10	12.75	8	71	10	13.2	8
27	10	9.75	8	72	10	9.15	8	27	10	12.1	8	72	10	12.45	8
28	10	9.2	8	73	10	10.05	8	28	10	12.3	8	73	10	13.3	8
29	10	8.85	8	74	10	9.65	8	29	10	13.5	8	74	10	12.55	8
30	10	9.5	8	75	10	9.45	8	30	10	12.67	8	75	10	12.4	8
31	10	9.45	8	76	10	9.35	8	31	10	11.8	8	76	10	11.5	8
32	10	9.5	8	77	10	9.4	8	32	10	12.45	8	77	10	11.35	8
33	10	9.5	8	78	10	8.8	8	33	10	12.4	8	78	10	12	8
34	10	9.05	8	79	10	9.25	8	34	10	12.15	8	79	10	13.75	8
35	10	9.3	8	80	10	9.8	8	35	10	11.8	8	80	10	12.6	8
36	10	9.35	8	81	10	8.85	8	36	10	11.2	8	81	10	11.5	8
37	10	9.5	8	82	10	9.75	8	37	10	12	8	82	10	13.05	8
38	10	9.25	8	83	10	10	8	38	10	11.95	8	83	10	12.6	8
39	10	8.7	8	84	10	9.65	8	39	10	12.23	8	84	10	12.3	8
40	10	9.9	8	85	10	9.7	8	40	10	12.07	8	85	10	13.8	8
41	10	8.75	8	86	10	9.45	8	41	10	12.3	8	86	10	12.2	8
42	10	9.8	8	87	10	9.9	8	42	10	12.55	8	87	10	13.3	8
43	10	10.05	8	88	10	8.7	8	43	10	12.5	8	88	10	12.15	8
44	10	9.15	8	89	10	8.75	8	44	10	11.6	8	89	10	13	8
45	10	9.3	8	90	10	9.1	8	45	10	11.7	8	90	10	11.8	8

Table A 8

Cycle Time Data for Lifting & Staging

Addis Ababa Institute of Technology
School of Civil and Enviromental Engineering
Graduate Program in Construction Technology and Management
Thesis on: Enhancing Labor Productivity of Building Construction Operations Using VSM Integrating with DES
Observation Data Collection Sheet Format: 2

Data: Cycle time of Sub-processes
Project: Case Study One (Slab Reinforcemment Operation)
Location: Addis Ababa

Lifting and Staging

Data C.	Avg no of Rebar	CT (min)	Avg no of manpower	Data C.	Avg no of Rebar	CT (min)	Avg no of manpower	Data C.	Avg no of Rebar	CT (min)	Avg no of manpower	Data C.	Avg no of Rebar	CT (min)	Avg no of manpower
1	5	2.25	2	21	5	2.45	2	41	5	2.35	2	61	5	2.7	2
2	5	2.75	2	22	5	2.36	2	42	5	2.45	2	62	5	2.9	2
3	5	2.50	2	23	5	2.4	2	43	5	2.30	2	63	5	2.55	2
4	5	3.00	2	24	5	2.56	2	44	5	2.90	2	64	5	2.75	2
5	5	2.58	2	25	5	2.4	2	45	5	2.35	2	65	5	2.35	2
6	5	3.10	2	26	5	2.75	2	46	5	2.50	2	66	5	2.3	2
7	5	2.95	2	27	5	2.6	2	47	5	2.30	2	67	5	2.3	2
8	5	2.50	2	28	5	2.48	2	48	5	2.25	2	68	5	2.45	2
9	5	2.70	2	29	5	2.6	2	49	5	2.45	2	69	5	2.25	2
10	5	2.40	2	30	5	2.7	2	50	5	2.55	2	70	5	2.6	2
11	5	2.45	2	31	5	2.75	2	51	5	2.50	2	71	5	2.82	2
12	5	2.50	2	32	5	2.82	2	52	5	2.65	2	72	5	2.65	2
13	5	2.50	2	33	5	2.4	2	53	5	2.70	2	73	5	2.8	2
14	5	2.50	2	34	5	2.48	2	54	5	3.10	2	74	5	2.4	2
15	5	2.20	2	35	5	2.7	2	55	5	2.95	2	75	5	2.55	2
16	5	2.50	2	36	5	2.55	2	56	5	2.35	2	76	5	2.6	2
17	5	2.75	2	37	5	2.7	2	57	5	2.55	2	77	5	2.65	2
18	5	2.50	2	38	5	2.8	2	58	5	2.80	2	78	5	2.58	2
19	5	2.48	2	39	5	2.86	2	59	5	2.45	2	79	5	2.65	2
20	5	2.85	2	40	5	2.8	2	60	5	2.80	2	80	5	2.4	2

Table A 9

Cycle Time Data for Hauling HCB & Returning to the Storage

Addis Ababa Institute of Technology
School of Civil and Enviromental Engineering
Graduate Program in Construction Technology and Management
Thesis on: Enhancing Labor Productivity of Building Construction Operations Using VSM Integrating with DES
Observation Data Collection Sheet Format: 2

Data: Cycle time of Sub-processes
Project: Case Study Two (HCB Work)
Location: Addis Ababa

Hauling HCB from Storage Area																Returning to Storage Area							
Data C.	Avg no of HCB	CT (min)	Avg no of manpower	Data C.	Avg no of HCB	CT (min)	Avg no of manpower	Data C.	Avg no of HCB	CT (min)	Avg no of manpower	Data C.	Avg no of HCB	CT (min)	Avg no of manpower	Data C.	Avg no of HCB	CT (min)	Avg no of manpower	Data C.	Avg no of HCB	CT (min)	Avg no of manpower
1	2	1.95	3	41	10	2.02	3	81	2	2.35	3	121	2	**2.14**	3	31		1.09	3	71		1.1	3
2	2	1.90	3	42	10	2.18	3	82	2	2.25	3	122	2	2.05	3	32		0.9	3	72		1.33	3
3	2	2.05	3	43	10	2.07	3	83	2	2.20	3	123	2	2.22	3	33		1.25	3	73		1.13	3
4	2	2.10	3	44	10	1.85	3	84	2	2.20	3	124	2	2.13	3	34		0.85	3	74		1.25	3
5	2	2.12	3	45	10	2.23	3	85	2	2.10	3	125	2	1.93	3	35		1.22	3	75		1.3	3
6	2	1.98	3	46	10	2.25	3	86	2	2.33	3	126	2	2.33	3	36		1.15	3	76		1.35	3
7	2	2.33	3	47	10	2.13	3	87	2	2.30	3	127	2	1.95	3	37		1.35	3	77		1.03	3
8	2	2.03	3	48	10	2.17	3	88	2	2.40	3	128	2	1.95	3	38		1.31	3	78		0.8	3
9	2	2.18	3	49	10	2.12	3	89	2	2.10	3	129	2	1.95	3	39		1.07	3	79		0.97	3
10	2	2.21	3	50	10	2.1	3	90	2	2.25	3	130	2	1.95	3	40		1	3	80		0.85	3
11	2	2.08	3	51	10	2.25	3	91	2	1.95	3	1		1.15	3	41		1	3	81		1.25	3
12	2	2.05	3	52	10	2.04	3	92	2	2.14	3	2		0.95	3	42		0.85	3	82		1.3	3
13	2	2.10	3	53	10	1.95	3	93	2	1.92	3	3		0.95	3	43		1.05	3	83		0.9	3
14	2	2.25	3	54	10	1.97	3	94	2	2.13	3	4		0.85	3	44		0.9	3	84		1.15	3
15	2	1.80	3	55	10	2.1	3	95	2	2.25	3	5		0.9	3	45		0.95	3	85		0.85	3
16	2	2.15	3	56	10	2.13	3	96	2	1.85	3	6		0.9	3	46		0.8	3	86		0.9	3
17	2	2.08	3	57	10	2.23	3	97	2	2.30	3	7		1.1	3	47		1.24	3	87		0.8	3
18	2	2.25	3	58	10	2.05	3	98	2	2.00	3	8		1.15	3	48		1.1	3	88		1.23	3
19	2	2.18	3	59	10	2	3	99	2	2.10	3	9		1.05	3	49		0.8	3	89		1.07	3
20	2	2.16	3	60	10	2.15	3	100	2	2.15	3	10		1.05	3	50		0.8	3	90		1.2	3
21	2	2.22	3	61	10	2.38	3	101	2	2.05	3	11		1	3	51		0.96	3	91		0.85	3
22	2	2.20	3	62	10	2.2	3	102	2	2.3	3	12		0.9	3	52		1	3	92		1.2	3
23	2	2.12	3	63	10	2.08	3	103	2	1.75	3	13		1.18	3	53		1.1	3	93		1.33	3
24	2	2.34	3	64	10	2.55	3	104	2	1.9	3	14		0.85	3	54		1.25	3	94		1.25	3
25	2	2.07	3	65	10	2.1	3	105	2	2.14	3	15		0.97	3	55		1	3	95		1.13	3
26	2	2.02	3	66	10	2.15	3	106	2	2.3	3	16		0.8	3	56		0.9	3	96		1.05	3
27	2	2.12	3	67	10	2.1	3	107	2	2.3	3	17		0.8	3	57		1.15	3	97		0.95	3
28	2	2.05	3	68	10	2.25	3	108	2	1.92	3	18		0.98	3	58		1.42	3	98		1.3	3
29	2	1.92	3	69	10	2.28	3	109	2	2.15	3	19		1.1	3	59		1.2	3	99		1.2	3
30	2	2.03	3	70	10	2.36	3	110	2	2.25	3	20		1.25	3	60		1.1	3	100		0.97	3
31	2	1.95	3	71	10	2.2	3	111	2	2	3	21		1.03	3	61		1.24	3	101		0.98	3
32	2	2.07	3	72	10	2.2	3	112	2	1.87	3	22		1.2	3	62		1.08	3	102		1.16	3
33	2	1.92	3	73	10	2.1	3	113	2	1.93	3	23		1.1	3	63		1.16	3	103		1.23	3
34	2	2.22	3	74	10	1.94	3	114	2	1.95	3	24		1.55	3	64		1.05	3	104		1.26	3
35	2	2.16	3	75	10	1.85	3	115	2	2.13	3	25		1.5	3	65		1	3	105		0.87	3
36	2	2.06	3	76	10	2.1	3	116	2	2	3	26		1.2	3	66		1.3	3	106		1.22	3
37	2	1.98	3	77	10	1.9	3	117	2	2.5	3	27		1.3	3	67		1.23	3	107		1.4	3
38	2	2.00	3	78	10	1.95	3	118	2	2.43	3	28		1.2	3	68		1.25	3	108		1.3	3
39	2	1.91	3	79	10	2.4	3	119	2	2.05	3	29		1.55	3	69		0.98	3	109		0.95	3
40	2	1.99	3	80	10	2.13	3	120	2	2.33	3	30		1.35	3	70		1.2	3	110		1.08	3

Table A 10

Cycle Time Data for 1st & 2nd to 9th Row HCB

Addis Ababa Institute of Technology
School of Civil and Enviromental Engineering
Graduate Program in Construction Technology and Management
Thesis on: Enhancing Labor Productivity of Building Construction Operations Using VSM Integrating with DES
Observation Data Collection Sheet Format: 2

Data: Cycle time of Sub-processes
Project: Case Study Two (HCB Work)
Location: Addis Ababa

1st Row HCB				2nd to 9th Row											
Data C.	HCB (m2)	CT (min)	Avg no of manpower	Data C.	HCB (m2)	CT (min)	Avg no of manpower	Data C.	HCB (m2)	CT (min)	Avg no of manpower	Data C.	HCB (m2)	CT (min)	HCB (m2)r
1	1	31.30	3	1	1	22.75	3	36	1	21.80	3	71	1	**30**	3
2	1	33.50	3	2	1	24	3	37	1	25.50	3	72	1	22.5	3
3	1	36.10	3	3	1	23.5	3	38	1	17.20	3	73	1	32	3
4	1	28.50	3	4	1	19.2	3	39	1	24.75	3	74	1	24.5	3
5	1	34.50	3	5	1	20.1	3	40	1	22.80	3	75	1	21	3
6	1	35.00	3	6	1	25	3	41	1	22.50	3	76	1	21.3	3
7	1	37.50	3	7	1	21.5	3	42	1	24.80	3	77	1	27.5	3
8	1	43.80	3	8	1	23.5	3	43	1	29.20	3	78	1	28	3
9	1	32.50	3	9	1	17.5	3	44	1	26.50	3	79	1	24	3
10	1	40.50	3	10	1	22.1	3	45	1	26.00	3	80	1	18.5	3
11	1	30.50	3	11	1	25.5	3	46	1	24.30	3	81	1	20.7	3
12	1	33.00	3	12	1	26.3	3	47	1	29.30	3	82	1	23.5	3
13	1	39.50	3	13	1	30.3	3	48	1	21.10	3	83	1	28.1	3
14	1	39.30	3	14	1	18.3	3	49	1	22.20	3	84	1	28.5	3
15	1	32.00	3	15	1	25.5	3	50	1	21.80	3	85	1	22.12	3
16	1	34.00	3	16	1	24.3	3	51	1	25.75	3	86	1	23.5	3
17	1	36.30	3	17	1	16.5	3	52	1	26.80	3	87	1	23.1	3
18	1	33.50	3	18	1	23.25	3	53	1	27.50	3	88	1	20.5	3
19	1	36.50	3	19	1	22.5	3	54	1	18.50	3	89	1	29.5	3
20	1	35.20	3	20	1	19.75	3	55	1	29.50	3	90	1	25.5	3
21	1	32.20	3	21	1	20.75	3	56	1	31.5	3	91	1	28.7	3
22	1	38.50	3	22	1	19.5	3	57	1	25	3	92	1	27.8	3
23	1	31.00	3	23	1	17.5	3	58	1	26.67	3	93	1	24.3	3
24	1	41.40	3	24	1	22	3	59	1	19.2	3	94	1	25	3
25	1	33.25	3	25	1	18.5	3	60	1	28.5	3	95	1	23	3
26	1	33.50	3	26	1	20	3	61	1	18.3	3	96	1	19.3	3
27	1	38.00	3	27	1	24.5	3	62	1	23.33	3	97	1	23.5	3
28	1	33.80	3	28	1	22.5	3	63	1	32	3	98	1	27.3	3
29	1	38.50	3	29	1	27	3	64	1	25.75	3	99	1	18.5	3
30	1	35.60	3	30	1	22	3	65	1	29	3	100	1	22.55	3
31	1	35.00	3	31	1	21.3	3	66		26.5	3				
32	1	32.50	3	32	1	22.75	3	67		30.67	3				
33	1	36.30	3	33	1	20	3	68		26.5	3				
34	1	35.70	3	34	1	20.2	3	69		19.5	3				
35	1	39.50	3	35	1	23.75	3	70		30.5	3				

Table A 11

Cycle Time Data for 9th to 14th Row HCB

Addis Ababa Institute of Technology School of Civil and Enviromental Engineering Graduate Program in Construction Technology and Management Thesis on: Enhancing Labor Productivity of Building Construction Operations Using VSM Integrating with DES Observation Data Collection Sheet Format: 2 Data: Cycle time of Sub-processes Project: Case Study Two (HCB Work) Location: Addis Ababa							
9th t0 14th Row HCB							
Data C.	HCB (m2)	CT (min)	Avg no of manpower	Data C.	HCB (m2)	CT (min)	Avg no of manpower
1	1	26.50	3	36	1	31.8	3
2	1	25.20	3	37	1	25.7	3
3	1	24.25	3	38	1	33	3
4	1	28.30	3	39	1	32.5	3
5	1	26.67	3	40	1	25.5	3
6	1	29.50	3	41	1	26.7	3
7	1	27.50	3	42	1	34.8	3
8	1	32.25	3	43	1	30.5	3
9	1	32.00	3	44	1	30.67	3
10	1	33.00	3	45	1	28.25	3
11	1	29.75	3	46	1	27.5	3
12	1	34.50	3	47	1	33.3	3
13	1	32.30	3	48	1	32.75	3
14	1	31.30	3	49	1	34	3
15	1	30.00	3	50	1	30.5	3
16	1	30.50	3	51	1	31.76	3
17	1	27.75	3	52	1	31.3	3
18	1	29.50	3	53	1	33.75	3
19	1	28.30	3	54	1	35.3	3
20	1	26.00	3	55	1	36	3
21	1	27.50	3	56	1	27.85	3
22	1	32.20	3	57	1	33.53	3
23	1	28.50	3	58	1	35.3	3
24	1	30.50	3	59	1	35	3
25	1	29.50	3	60	1	31.3	3
26	1	26.67	3	61	1	34	3
27	1	28.80	3	62	1	32.5	3
28	1	31.40	3	63	1	29.75	3
29	1	35.50	3	64	1	30.5	3
30	1	34.50	3	65	1	32.5	3
31	1	34.00	3	66	1	29	3
32	1	32.25	3	67	1	28.75	3
33	1	30.50	3	68	1	29	3
34	1	27.50	3	69	1	25.5	3
35	1	26.50	3	70	1	27.1	3

Table A 12

Elapsed Time Data for Waiting

Addis Ababa Institute of Technology
School of Civil and Enviromental Engineering
Graduate Program in Construction Technology and Management
Thesis on: Enhancing Labor Productivity of Building Construction Operations Using VSM Integrating with DES
Observation Data Collection Sheet Format: 2

Data: Cycle time of Sub-processes
Project: Case Study Two (HCB Work)
Location: Addis Ababa

Waiting									
Data C.	Elapsed Time	Data C.	Elapsed Time	Data C.	Elapsed Time	Data C.	Elapsed Time		
1	4.85	11	2.8	21	11.50	31	6.5	41	8.80
2	6.81	12	8.2	22	6.35	32	5.5	42	16.50
3	3	13	2.5	23	21.00	33	9.3	43	20.05
4	5	14	22.5	24	18.70	34	3.2	44	3.80
5	8	15	3	25	12.50	35	13.3	45	13.10
6	6	16	8.5	26	26.70	36	3	46	6.80
7	12	17	16.5	27	4.90	37	17	47	5.5
8	10	18	3	28	18.30	38	11.6	48	5
9	12	19	9.5	29	14.00	39	7.5	49	5.5
10	29	20	3.5	30	6.5	40	3.2	50	21.3

APPENDIX B: SAMPLE SIMPHONY CYCLONE INPUT MODELLING OUTPUT

Figure B 1

Theoretical vs. Empirical PDF & CDF for Rebar hauling (uniform distribution)

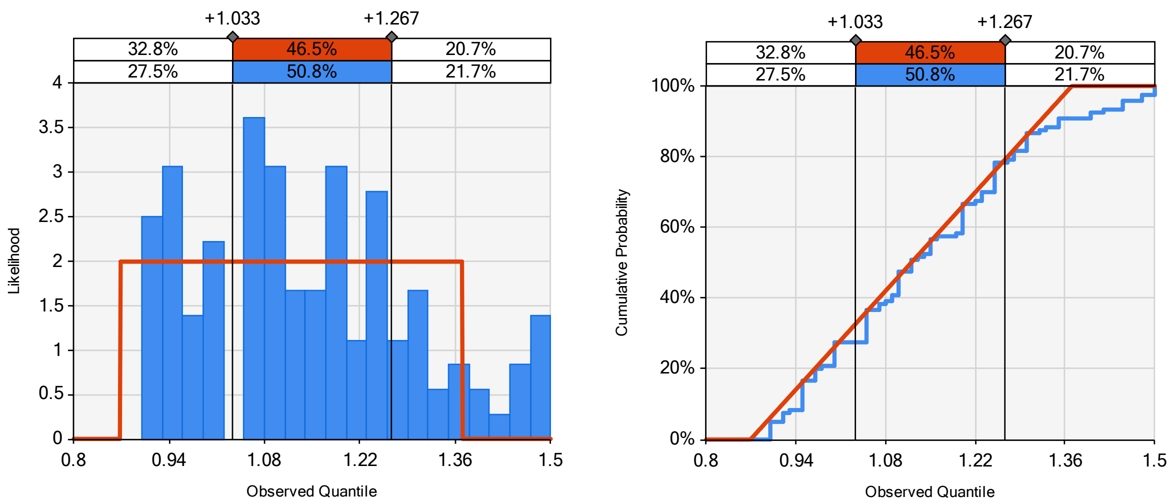


Figure B 2

Theoretical Vs. Empirical PDF & CDF for Rebar Straightening (Beta Distribution)

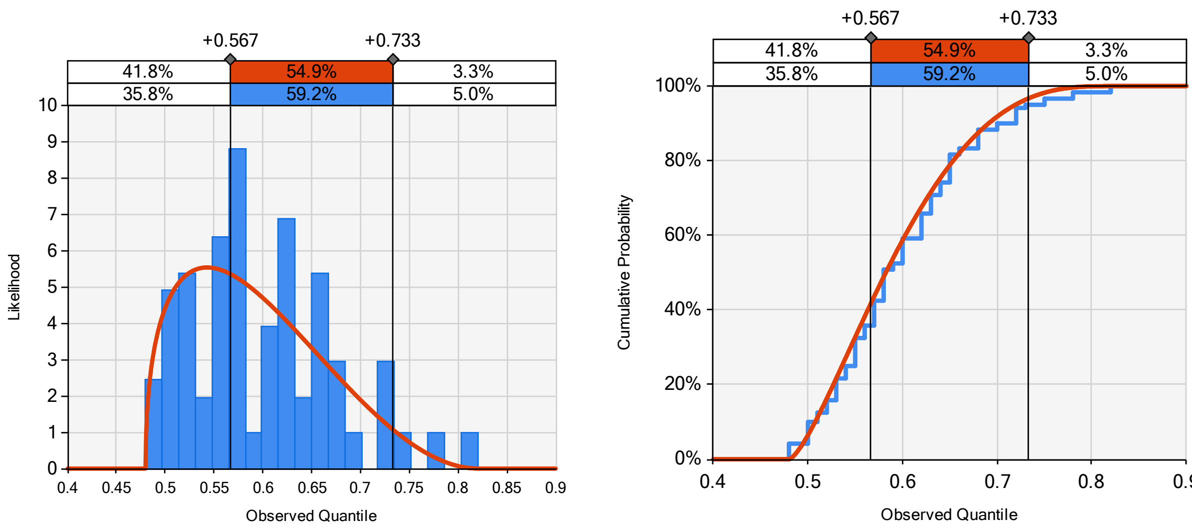


Figure B 3

Theoretical Vs. Empirical PDF & CDF for Rebar MM (Triangular Distribution)

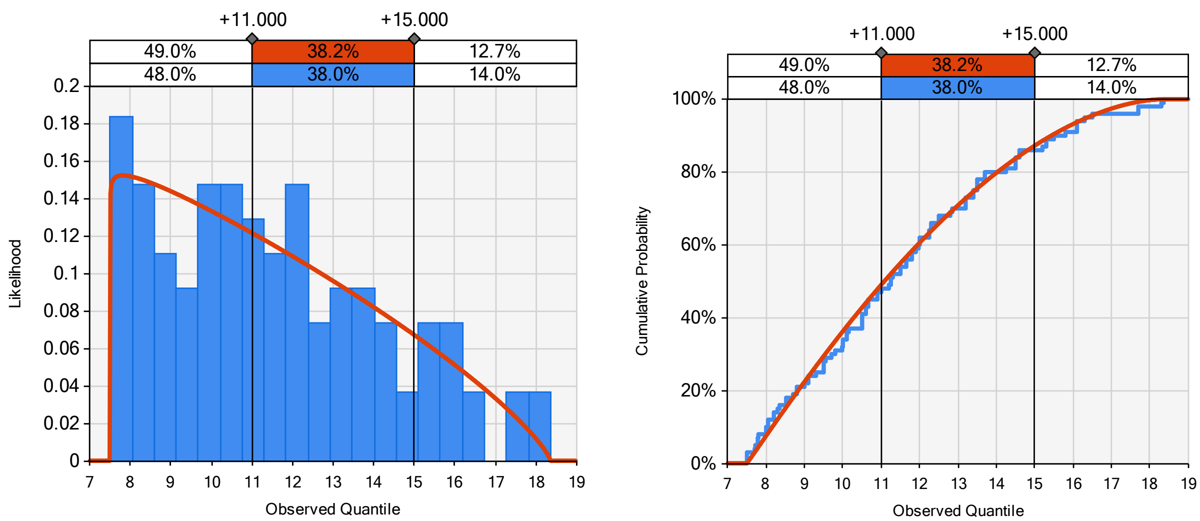


Figure B 4

Theoretical Vs. Empirical PDF & CDF for Cutting into Two Pieces (Triangular Distribution)

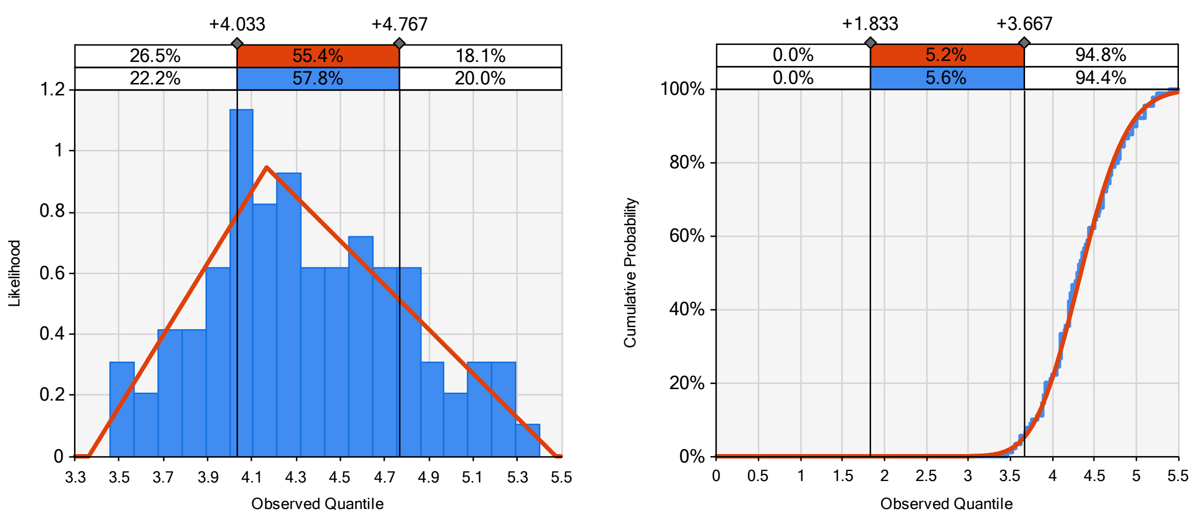


Figure B 5

Theoretical Vs. Empirical PDF & CDF for Bending (Triangular Distribution)

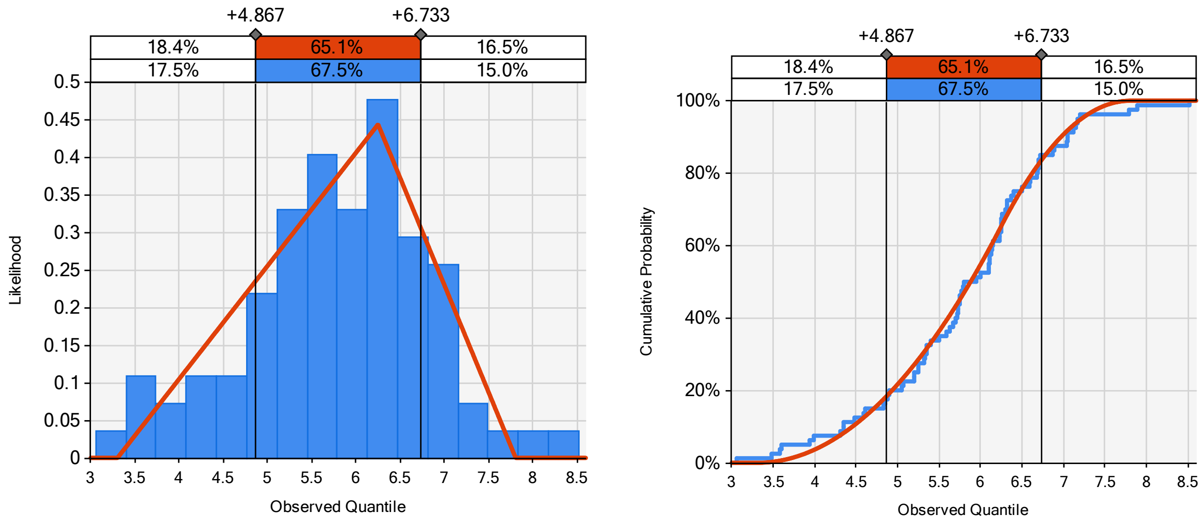


Figure B 6

Theoretical Vs. Empirical PDF & CDF for Cleaning Rebars (Gamma Distribution)

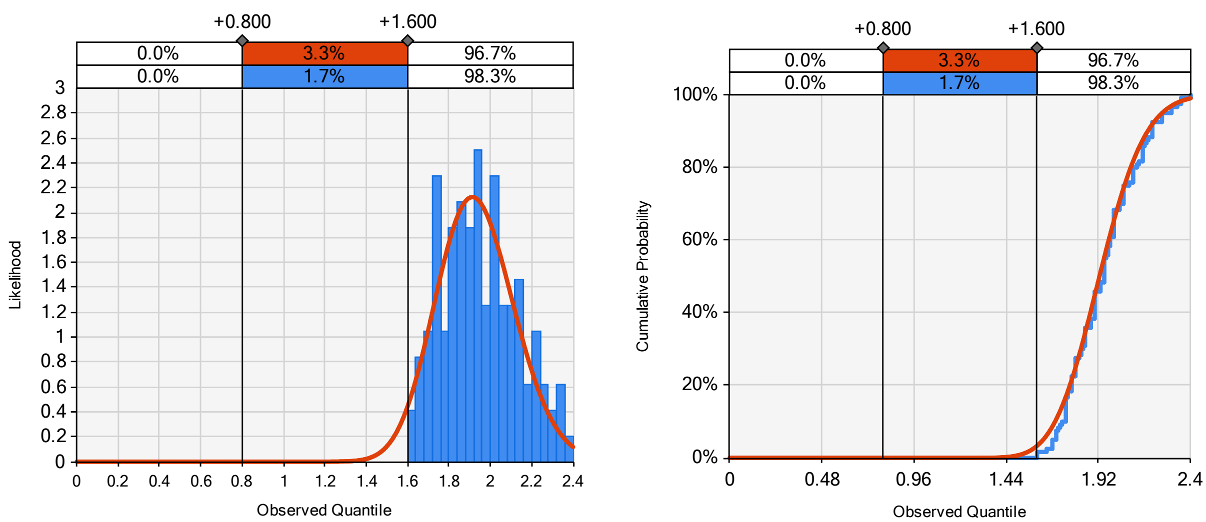


Figure B 7

Theoretical Vs. Empirical PDF & CDF for Staging & Positioning (Beta Distribution)

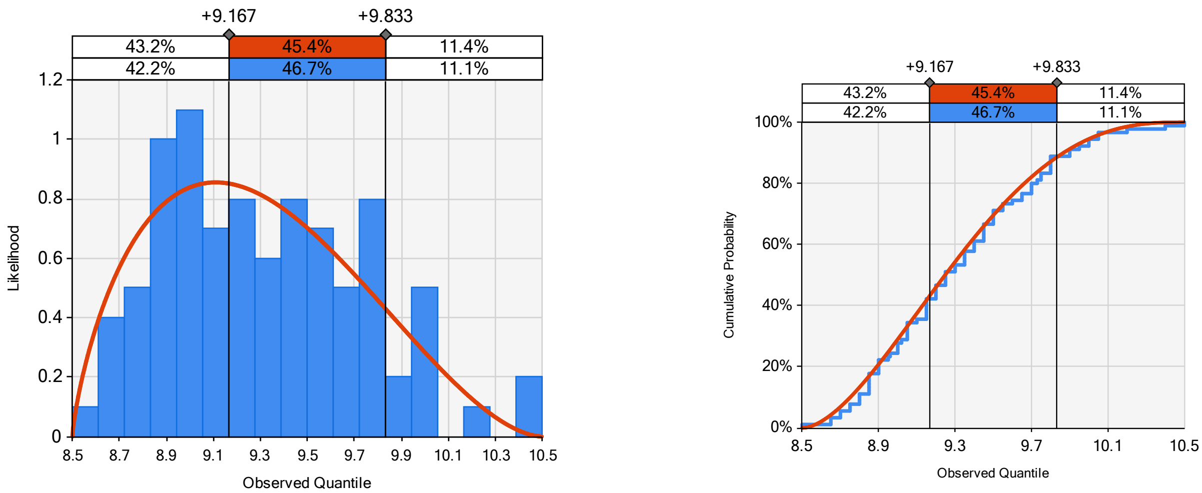


Figure B 8

Theoretical Vs. Empirical PDF & CDF for Rebar Tightening (Triangular Distribution)

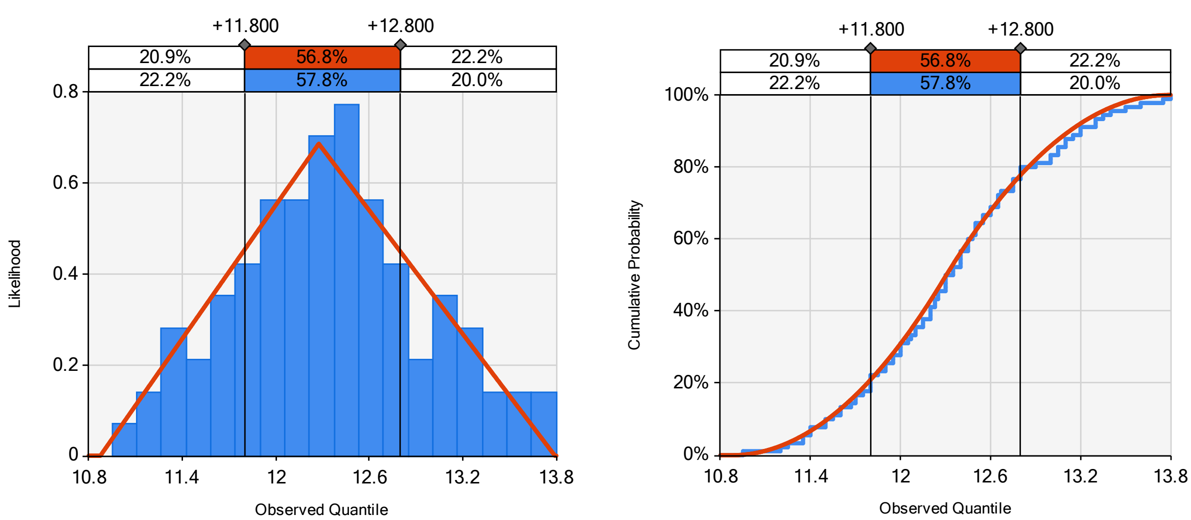


Figure B 9

Theoretical Vs. Empirical PDF & CDF for Hauling HCB (Triangular Distribution)

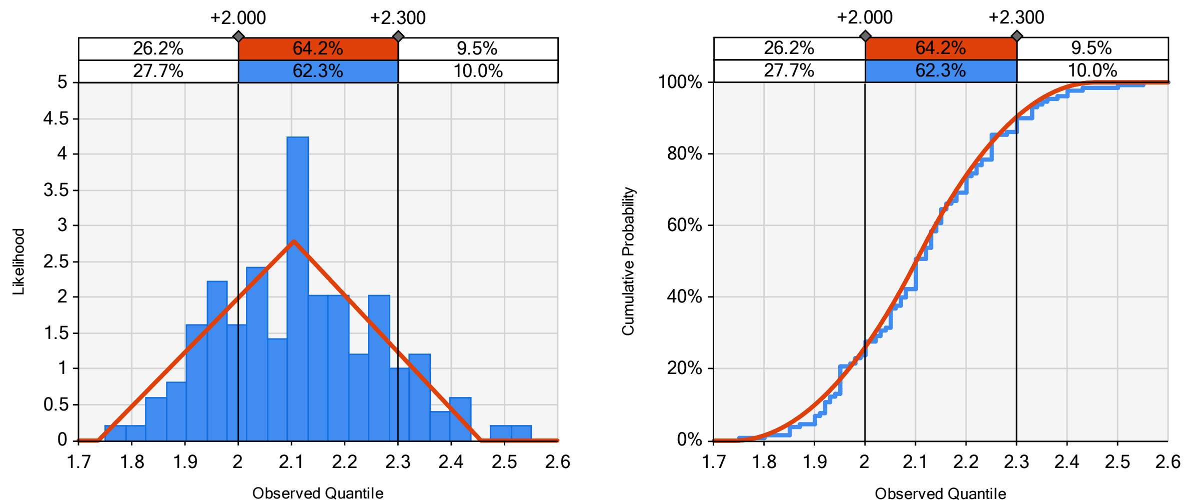


Figure B 10

Theoretical Vs. Empirical PDF & CDF for Returning to the Storage (Uniform Distribution)

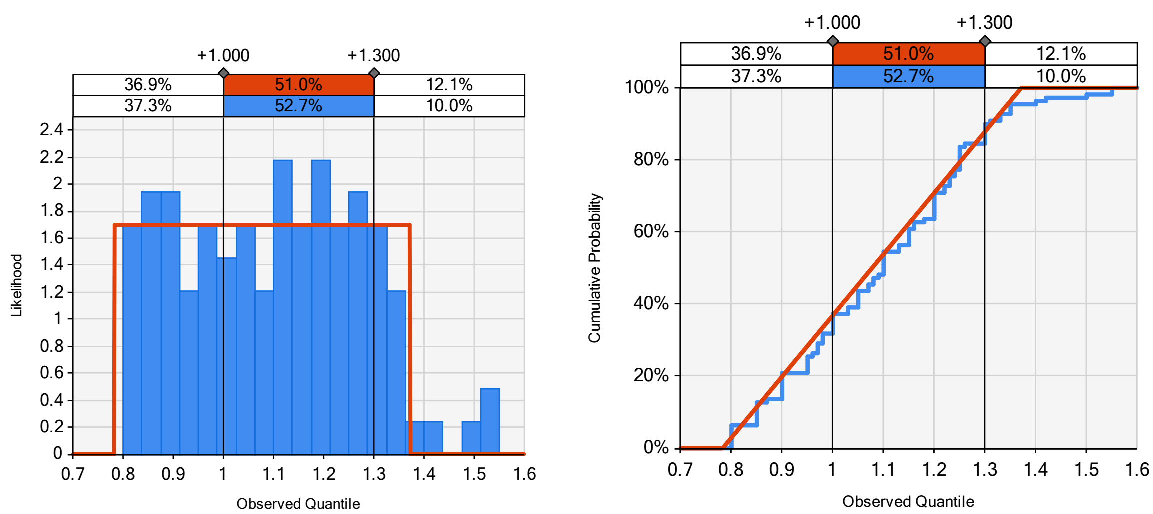


Figure B 11

Theoretical Vs. Empirical PDF & CDF for Waiting (LogNormal Distribution)

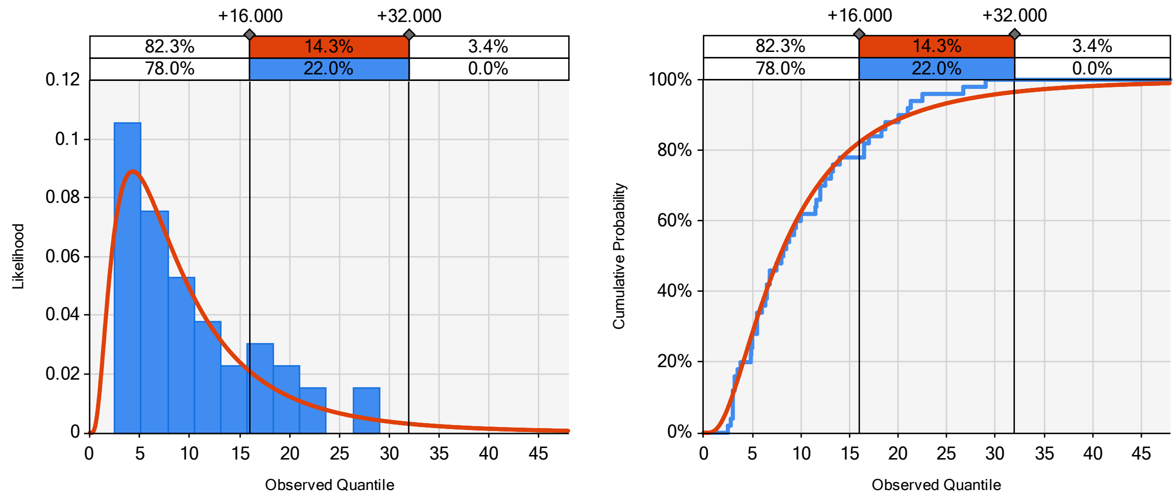
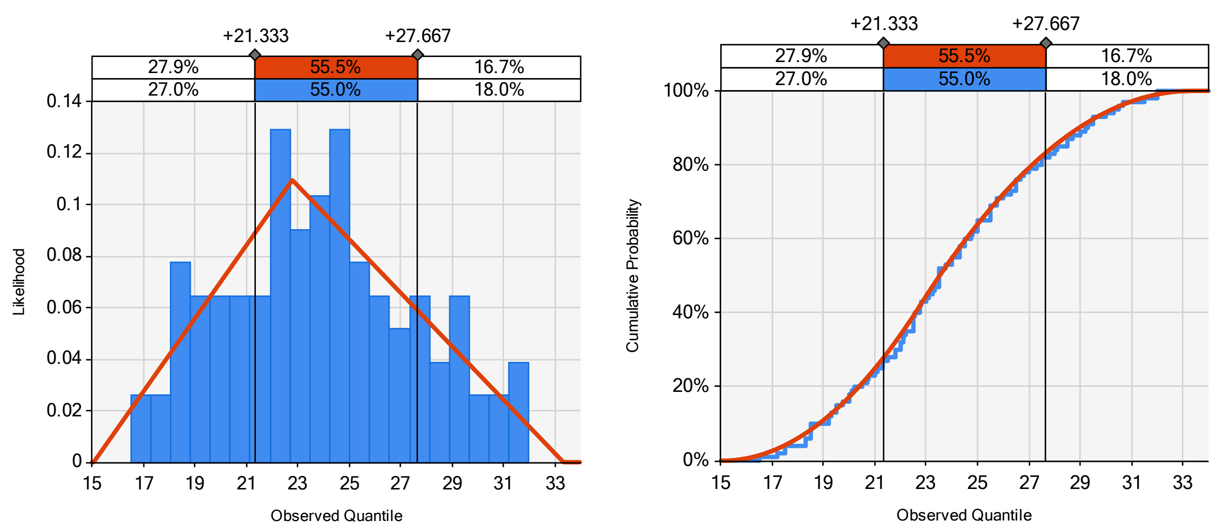


Figure B 12

Theoretical Vs. Empirical PDF & CDF for 2nd to 9th HCB Row (Triangular Distribution)



APPENDIX C: SECONDARY DATA

Table C 1

Daily Labor Productivity of HCB Work

2B +G+12 Dormitory Building Secondary Data: Daily Labor Productivity Data Data: Labor Productivity Project: Case Study Two (HCB work) Location: Addis Ababa							
Day	Crew Size	Crew Composition		Man-hours (mhr)	Unit	Installed Quantity	Productivity
		Masons	Laborers				Installed Quantity /T. Manhours
1	4	1	3	32	m2	13.80	0.43
2	4	1	3	32	m2	16.50	0.52
3	4	1	3	32	m2	17.00	0.53
4	4	1	3	32	m2	16.10	0.50
5	4	1	5	32	m2	17.50	0.55
6	7	2	5	56	m2	28.30	0.51
7	7	2	5	56	m2	27.50	0.49
8	7	2	5	56	m2	31.30	0.56
9	4	1	3	32	m2	16.30	0.51
10	7	2	5	56	m2	32.40	0.58
11	7	2	5	56	m2	28.80	0.51
12	7	2	5	56	m2	30.50	0.54
13	7	2	5	56	m2	32.50	0.58
14	7	2	5	56	m2	35.20	0.63
15	7	2	5	56	m2	33.50	0.60