ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

STUDY ON THE APPLICATION OF JUST-IN-TIME PHILOSOPHY TO CONSTRUCTION: A CASE STUDY OF REINFORCEMENT BAR PRODUCTION AND DELIVERY SYSTEM

A thesis submitted to the School of Graduate Studies of the Addis Ababa University in partial fulfillment of the requirements for the degree of
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By

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Title: Study on the Application of Just-In-Time Philosophy to Construction: A Case Study of Reinforcement Bar Production and Delivery System

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DECLARATION

I declare that this thesis, entitled "Study on the Application of Just-In-Time Philosophy to Construction: A Case Study of Reinforcement Bar Production and Delivery System" is my original work. This thesis has not been presented at any other university and is not concurrently submitted in candidature for any other degree, and all sources of material used for the thesis have been duly acknowledged.

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ABSTRACT

In cities like Addis Ababa, storage and working space are usually inadequate for construction projects. Construction materials like rebar require a lot of space for storage and production. For the temporary storage and production of rebar, some firms had to pay extra to rent space. Also, some use the roadside for storage and production areas. Furthermore, most activities performed during the construction process do not add value to the project but incur unnecessary costs and time that affect the project's performance. Therefore, this study intends to analyze the rebar production practice and explore whether applying the just-in-time concept to the rebar production and delivery system would be advantageous from the perspective of value. To achieve the study objective, case studies were carried out on two contractors. The contractors were selected based on their approaches to rebar production. The first one uses the on-site rebar production method, while the other contractor uses off-site rebar production with JIT delivery. The data collected from case studies was analyzed using descriptive analysis and by developing a discrete event simulation model. Finally, the study's findings revealed that there is a considerable amount of non-value-added and necessary but non-value-adding activities on site during the production of rebars. According to the simulation analysis result, off-site rebar production with JIT delivery is shown to decrease rebar production time, increase productivity, and decrease idleness of labor and machines. Additionally, the study revealed the motivating and challenging factors for JIT implementation. In general, on the basis of value, applying JIT to rebar production and delivery is efficient. Thus, it is important for construction companies to start considering the benefits of this production and delivery system.

Key words: Just in time (JIT), Reinforcement bar (rebar), On-site rebar production, Off-site rebar production, value adding (VA), non-value adding (NVA).

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ABBREVIATIONS

BBS: Bar Bending Schedules

DES: Discrete Event Simulation

GDP: Gross Domestic Product

JIT: Just in time

MRE: Macro Research Ethiopia

MoUDC: Ministry of Urban Development and Construction

NNVAAs: Necessary non-Value-Adding Activities

NVAAs: Non-Value-Adding Activities

TFV: Transformation, Flow, Value

TPS: Toyota Production System

TQC: Total Quality Control

VAAs: Value Adding Activities

CDF: Cumulative Distribution Function

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1. INTRODUCTION

1.1. Background of Study

The construction industry is a fundamental economic sector which has great contribution for the economic growth and social development of the country. In Ethiopia, it is the second largest contributor to Gross Domestic Product (GDP) with 19.5%, just behind Agriculture (MRE, 2020). Despite the fact that this vast industry is essential for socioeconomic growth, it frequently encounters a variety of challenges, ranging from internal flaws to external risks, all of which affect and influence its efficiency. In developing countries, such challenges exist with an overall state of socio-economic stress, continuing resource shortages, organizational weaknesses, and a general inability to address the current problems (Ofori, 2000).

The construction sector has been criticized for its fragmentation, low productivity, poor quality, schedule delays, cost overruns, bad working conditions, and poor safety all of which contribute to project failure and the industry's negative reputation (El-Sokhn and Othman, 2014; Alwi et al. 2002; Koskela, 2000). Similarly, Akintoye (1995), stated issues in construction industry are related to production, quality of work, design changes, material quality and availability and capacity utilization. According to Patil and Dhawale (2018), the conventional material delivery system in construction projects has created several problems for the industry in terms of cost, quality, and time. Another major problem in the construction industry is the high level of waste. In addition to the waste of materials, there are activities that do not add value to the final product but incur unnecessary cost and time (Ismail and Yusof, 2016).

One of the challenges encountered in the construction industry is due to reinforcement bar work. Contractors undertaking this work frequently have to deal with issues related to the quality of the end product of the reinforcement bar, site area constraints, environmental factors, labor shortages, and material waste. Since reinforcement bar work is one of the important elements in construction, issues related to it led to delays in the project's completion and cost overrun on the project (Hussin and Ismail, 2014).

As a result of the increased global competition, construction firms have been forced to seek out innovative solutions to the problems they face. One of these initiatives is the Just-in-time production system, which focuses on cost reduction by eliminating non-value-adding activities (Patil and Patil, 2015; Patel and Solanki, 2020). Ofori (2000) also mentioned just-in-time as one of the techniques and tools which is relevant to the developments of the construction industries in developing countries.

The idea of just-in-time was developed by the Japanese and later translated into English as the lean production system. JIT production aims to deliver the appropriate materials at each stage of the process at the right time and in the right quantity without creating any delays resulting from storage in a laydown or production area. A great example of a just-in-time production process is ready mix concrete (Tommelein and Li, 1999).

Successful implementation of the Just-in-time technique could be capable of reducing numerous elements, such as: inventory level, which is an important factor for any construction firm that increases costs, reduces profitability, and requires more working capital without adding any value to the customer and organization, apart from that JIT reduces storage space and rectification work so that it will lead to an improvement in quality. Therefore, it's very important for everyone involved in a construction project to understand the objective and the fundamental principles of the Just-in-time method in order to ensure a successful implementation of the JIT system (Patil and Dhawale, 2018).

In Ethiopia, the construction industry's poor performance has negatively affected the industry's development. In terms of technological advancement, the sector generally lags behind. Thus, to improve the industry's performance and competitiveness, rapid technological development is essential (MoUDC, 2012).

Generally, to advance the construction industry in Ethiopia and also overcome the challenges, it is essential to adopt new important concepts like the just-in-time philosophy. Therefore, this thesis aims to investigate the benefits and challenges of implementing the just-in-time concept for the reinforcement bar production and delivery system.

1.2. Statement of Problem

Reinforcement bar is one of the expensive materials used in the construction industry. However, there is a problem with using reinforcement bar efficiently, right from the designing stage to the construction stage. Inefficient use of steel reinforcement in concrete results in unnecessary costs, which have an impact on the project's overall cost (Nigussie and Chandrasekar, 2020).

Most construction projects that take place in urban areas have no storage space. Due to this lack of space, the construction sites are very congested. Same for most construction sites in Addis

Ababa; they are very crowded and lack storage space, making it difficult to manage the reinforcement bars properly. At some project sites, the reinforcement bars are stocked on the sides of roads. This results in the materials being exposed to theft and corrosion, and it also obstructs the free flow of pedestrians. In other ways, some contractors temporarily rent space for rebar storage and production; this incurs an extra cost. Koskela (2000) argues that the consequences of working in suboptimal conditions are decreased productivity and quality, increased material waste, and an increased risk of accidents.

In the construction industry, there is a large amount of material wastage, which contributes to the increment of the project cost. Reinforcement bar is one of these materials. Wastage of rebar can be realized even at the design stage and can propagate through every stage of the construction process. Un-optimized and inefficient working techniques in cutting and bending process, wrong rebar quantity estimation, design changes, and a shortage of qualified workmanship are the main causes of rebar wastage in Ethiopia, according to Fantahun, 2020; Girma, 2016; Nigussie and Chandrasekar, 2020.

Additionally, in most construction projects, reinforcement bars are purchased in huge quantities without a clear estimation of the amount and size of rebar. These will be stocked for a long period of time without proper management. According to Low and Choong (2001), excess inventory is regarded as waste since no value is added by stockpiling inventory. This unnecessary inventory ties down the capital, utilizes storage space, thus incurring unnecessary costs (for handling, storing, and securing these materials), and also generates additional risks associated with storage, such as those relating to damages and obsolescence.

Concepts such as waste and value are not well understood by construction personnel. They often do not realize that most of the activities performed during the construction process do not add value to their project (Ismail and Yusof, 2016). Activities such as waiting, rework, unnecessary movement, overproduction, delay, defects, lack of quality, and inventories are waste because they add no value to the process (Alwi et al., 2002). These hidden, non-value-adding activities incurred unnecessary cost and time. For this reason, to successfully execute design and construction projects, construction participants should pay attention to minimizing the amount of NVAAs (Han et al., 2007).

Therefore, with these driving problems, this thesis aims to increase value and minimize the current site-intensive rebar work activities, unnecessary inventories, and other issues related to site reinforcement bar production by introducing the concept of just-in-time philosophy.

1.3. Objective of the study

1.3.1. General Objective

The main objective of the study is to assess the current rebar production practices and analyze how the implementation of the JIT concept on rebar production and delivery systems will increase the efficiency of production by minimizing non-value-adding activities.

1.3.2. Specific Objectives

- To assess and analyze the reinforcement bar production flow and categorize activities based on the production concept of flow and value.
- To evaluate the on-site and off-site rebar production systems using the concept of Ohno's seven wastes.
- To identify the motivating and the challenging factors for the implementation of JIT on rebar production and delivery.
- To develop a discrete event simulation model for on-site and off-site rebar production systems to check their production performance.

1.4. Significance of study

As stated in the statement of the problem, there are problems related to reinforcement bar work. In order to reduce these problems, a proper study is needed. Hence, this study has mutual benefits for both the construction industry and the research group.

Construction firms that have issues related to a lack of working and storage space, unnecessary inventory, traditional and inefficient working techniques, and wasteful onsite activities have to find ways to reduce these issues. Therefore, the study is significant for the construction firms in many ways, such as: It helps them understand concepts of waste and value in order to prepare an effective improvement plan for minimizing non-value-adding activities; consider the JIT approach as one of the strategies to reduce issues related to reinforcement bar works; and understand the benefits and challenges of implementing the JIT approach to reinforcement bar works. On the other hand, this research is significant for the research group; it will be used as exploratory research for other future research.

1.5. Scope and Limitation of the study

The main focus of the study is to conduct a case study on reinforcement bar work, which is one of the upstream activities that is labor-intensive and comprises many sub-activities and movements. The activities included rebar cutting, bending, straightening, and delivery to the fixing area, and the study excludes the fixing part since the aim of the study is to improve the production system. With this study scope, two contractors for the case study were chosen to the first one uses an on-site rebar production approach, while the second uses an off-site system. The other study's focus was using time as a measuring tool to compare the two production systems performance by developing a simulation model.

Since JIT rebar production and delivery system is not widely known in Ethiopia, the availability of data on this production and delivery system is relatively scarce. Therefore, the limitations of the study are mainly the lack of documented information and data.

1.6. Organization of the thesis

This thesis contains five chapters as described below;

- Chapter one is an introductory part containing discussions on background, statement of problems, objectives of the study, significance of the study, scope of the study and finally organization of the Study.
- Chapter Two presents a review of the literature on the concept of production theory; just-in-Time philosophy, non-value-adding activities, and experience with off-site JIT rebar production and delivery.
- Chapter Three describes the research methods and methodology of the study, including data collection and data analysis methods.
- Chapter Four presents the results and discussion of the research findings.
- Chapter Five contains conclusions and recommendations based on what has been discussed in the previous chapters.

2. LITERATURE REVIEW

2.1. Introduction

This chapter presents a review of the literature to provide relevant information about the scope of the study. The literature review is structured into three major focus areas. The first part provides an explanation of the basic theories of production, such as transformation, flow, value, and the integration of the three concepts. The second part discussed the basic concept behind the study, which is the just-in-time concept. The concept will be assessed and overviewed in order to have a clear understanding of the starting point, how it was translated from manufacturing to the construction industry, particularly rebar work, its advantages and challenges, as well as the experiences of other countries. Finally, the third part discussed simulation modeling in order to have a clear understanding of the basic features of the simulation model system.

2.2. Main concept of production philosophy

The theory of production was investigated to identify wastes in production and construction processes. Even though there is no commonly accepted theory of production, there are mainly three concepts in the theory of production: transformation, flow, and value (Koskela, 2000; Wu and Low, 2013).

2.2.1. Conventional/transformation view of production

During the 20th century, production has mostly been conceptualized as a transformation of inputs to outputs. The conventional template of production has been based on this transformation concept. One of the principles of this concept is decomposing the total transformation hierarchically into smaller transformations, called tasks, and minimizing the cost of each task independently of the others (Koskela, 2000; Koskela et al., 2002).

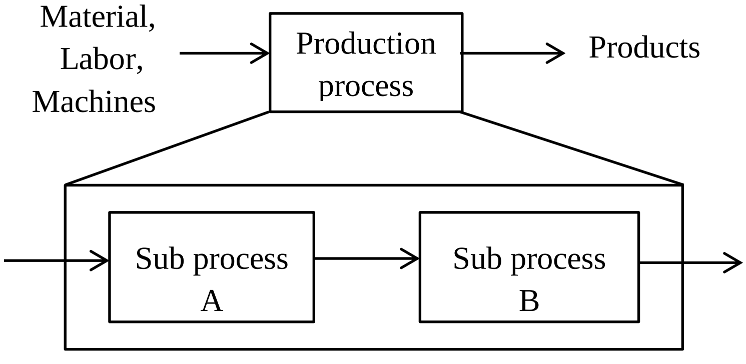

Figure 1: The view of a production as a transformation (Adapted from: Koskela, 2000).

There are two major drawbacks to the transformation concept of production: First, it ignores the fact that production processes involve phenomena besides transformations, and second, it ignores the fact that the value of an output is not determined by the transformation but rather by how well it complies with the requirements of the customer (Koskela et al., 2002).

The transformation model abstracts away physical flows between transformations. These flows consist of moving, waiting and inspecting activities. In a way, this is a correct idealization; from the customer point of view these activities are not needed since they do not add value to the end product. The model has been interpreted so that these non-value-adding activities can be left out of consideration or all activities are transformation activities which are treated as value-adding. These wrong interpretations are present in conventional production. Generally, this view is not helpful in figuring out how to avoid wasting resources or how to ensure that customer requirements are met in the best manner. Therefore, production, managed this view, tends to become inefficient and ineffective (Koskela, 2000).

2.2.2. The Flow view of production

The early framework of industrial engineering introduced another view on production, namely that of production as flow. Gilbreth first proposed the flow concept of production in 1922, and Henry Ford later adopted it. However, the Ford implementation was misunderstood and the flow view of production was further developed only from the 1940s onwards in Japan, first as part of war production and then at Toyota Motor Corporation. The flow view has provided the basis for JIT and Lean production. The basic thrust of the concept is to eliminate waste from flow processes (Koskela, 2000; Koskela et. al., 2002). According to Koskela (1992) the flow view production model can be defined as: Production is a flow of material and/or information from raw material to the end product. Thus, the task is to develop a model covering all important features of production, especially those that are lacking in the transformation model.

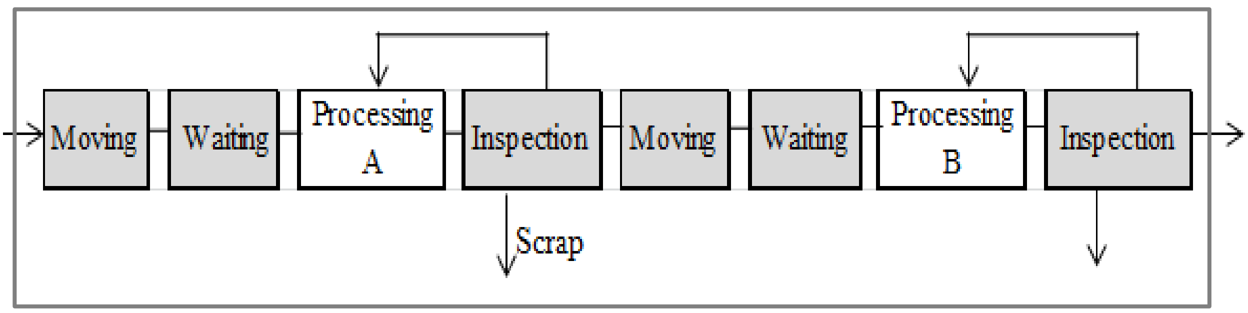

Figure 2: Production as a flow process (Adapted from: Koskela, 2000).

As it is shown in the above figure, in the production flow, the material is processed (converted), it is inspected, it is waiting, or it is moving. These activities are inherently different. Processing represents the transformation aspect of production, whereas inspecting, moving, and waiting represent the flow aspect of production. Every activity costs money and takes time, but only transformational activities add value to the final product. Therefore, non-value-adding activities should be reduced or eliminated as a priority for improving flow activities, whereas transformation activities need to be made more effective (Koskela, 2000).

2.2.3. Value generation concept of production

The third view of production was initiated by Shewhart in the 1930s, namely that of production as value generation. This concept views production as a means for the fulfillment of customer needs and the basic goal is to reach the best possible value from the point of the customer. Furthermore, the concept refined in the framework of the quality movement and translated into methods and practices useful in the industry (Koskela, 2000; Koskela et. al., 2002).

Levitt and Drucker argue that the value of a product can be determined only in reference to the customer, and the goal of production is satisfying customer needs. This is in stark contrast to the very internally oriented managerial model, based on the transformation concept, where internal production matters were emphasized rather than the customer. In value generation transformations and flows are controlled for the sake of the customer, attributes of transformations and flows impact directly on the resultant value (Koskela, 2000).

According to Womack and Jones (2003) value can only be defined by the ultimate customer. And it's only meaningful when expressed in terms of a specific product (a good or a service, and often both at once) which meets the customer's needs at a specific price at a specific time.

The processes may be characterized by their cost, duration and the value for the customer. Value has to be evaluated from the perspective of the next customer and the final customer. Cost and duration depend on the efficiency of value-adding activities and the amount of non-value-adding activities. Therefore, Production improved continuously with respect to waste and value, and periodically with respect to efficiency by implementing new technology (Koskela, 1992; 2000).

According to Koskela (2000), the whole cycle of value generation structured into five principles which, more or less, cover the cycle as shown in the following Figure.

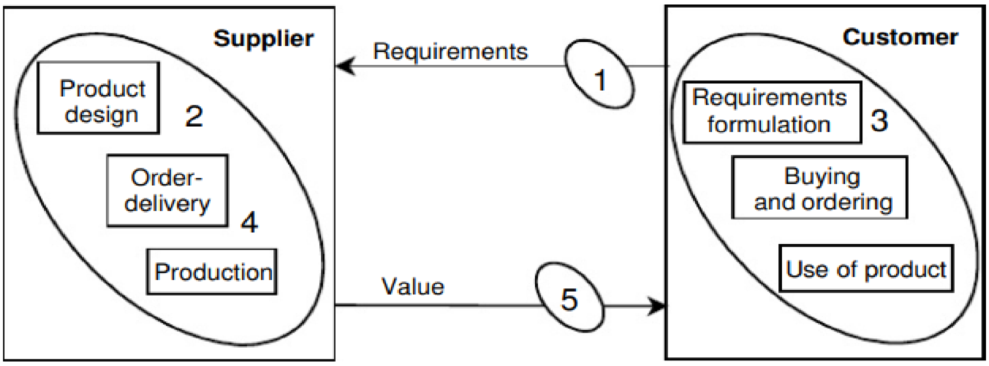

Figure 3: principles of value generation concept (Adapted from: Koskela, 2000).

The numbers in the above figure refer to principles which are described below;

1. **Requirements capture:** ensure that all customer requirements, both explicit and latent, have been captured.
2. **Requirement flow-down:** ensure that relevant customer requirements are available in all phases of production, and that they are not lost when progressively transformed into design solutions, production plans and products.
3. **Comprehensiveness of requirements:** ensure that customer requirements have a bearing on all deliverables for all roles of the customer.
4. **Capability of production subsystems:** ensure the capability of the production system to produce products as required.
5. **Measurement of value:** ensure by measurements that value is generated for the customer.

2.2.4. The Integrated Transformation-Flow-Value view of production

The three concepts of production are thus not alternative, competing theories of production, but rather partial and complementary. Each of them focuses on certain aspects of the production phenomenon: the transformation concept on the value-adding transformation; the flow concept on the non-value-adding activities; and the value generation concept on the control of production from the customer's point of view. What is needed is a production theory and related tools that fully integrate the three concepts of production (Koskela, 2000; Koskela et. al., 2002).

The goals of production could be achieved by "getting production realized efficiency", which was generated from the transformation view. These could also be achieved through the elimination of waste which originated from the flow view. In addition, elimination of value loss in the flow of value could help to achieve the goals of production. However, the three aspects of production should be balanced because their contributions to the production process were different (Koskela 2000; Wu and Low, 2013).

The construction is mainly managed according to the concept of transformation; principles regarding the flow and value generation concepts are mostly ignored. This results in uncertain flow processes, an increase in non-value-adding activities, and a decrease in output value. Hence, the conventional project management in construction is inefficient because it does not rest on a TFV theoretical framework. A reform of project management will be driven by theories from production management that adds the management of workflow and the creation and delivery of value (Howell and Koskela, 2000; Alwi et. al., 2002; Koskela and Howell, 2002).

The integrated TFV theory has the potential of stimulating major changes of performance in the construction industry. In order to effectively improve construction through these new foundations, it is necessary that the discipline of construction engineering and management, having progressed in relative isolation, be reintegrated with the generic disciplines that focus on operations, design, production and projects. Major development efforts, like industrialized construction and use of information technology in construction, have to be redirected in accordance with the new foundation (Koskela, 2000).

Table 1: Integrated TFV view of production (Adapted from: Koskela, 2000)

	Transformation view	**Flow view**	**Value generation view**
Production concept	A process of converting inputs into outputs	A material flow that includes transformation, inspection, movement, and waiting	A process where value is generated for the client by fulfilling his requirements
Main Principles	Getting production realized efficiently	Elimination of non-value adding activities/waste	Elimination of Value loss (achieving best possible value)
Practical contribution	Taking care of the necessary tasks	Taking care that what is unnecessary is done as little as possible	Taking care that customer requests are met in the best possible way
Suggested name	Task management	Flow management	Value management

2.3. Overview of just-in-time and Lean approach

The conventional transformation concept was challenged mostly by supporters of just-in-time philosophy, viewing production as a flow. The starting point of JIT production philosophy was in Japan in the 1950's by Mr. Taiichi Ohno, the chief developer of the Toyota production system (TPS) (Low and Mok, 1999; Low and Ang, 2003). Just-in-time refers to a flow process in which the appropriate parts for assembly arrive at the assembly line only when and in the quantity required (Ohno, 1988).

The driving idea in the JIT approach was reduction or elimination of inventories that manufacturing firms have no room to store and other waste (Koskela, 1992; Im and Lee, 1989). Land costs in Japan are high due to its scarcity. Inventory takes up space and ties down capital. In this philosophy, raw materials are not stockpiled. Instead, they are delivered in the right quantities, in the right condition, to the right place and at the right time for production (Low and Choong, 2001).

Similarly, lean thinking also originated from the automobile industry and developed from Taiichi Ohno's notion of reducing cost by eliminating waste'. It is defined as initiatives that focus on improving production efficiency and productivity by concentrating on waste elimination and value creation from the customers' perspective (Holweg, 2007).

According to Womack and Jones, (2003) the critical starting point for lean thinking is value. Correspondingly, Melton (2005) stated that the implementation of lean thinking concentrates on value recognition and waste elimination, thus the clients and contractors are able to attain the goal of zero waste. Just in Time (JIT) is one of the tools used for cost reduction by eliminating non-value-added activities (Abdulmalek and Rajgopal, 2007).

Just in Time (JIT) approach has been utilized in procurement activities worldwide, especially within the manufacturing industry. The approach is proven to smooth the production process and to provide its users with the benefits of eliminating waste (Low and Choong, 2001; Im and Lee, 1989). The aim of Just-in-time (JIT) was to reduce inventory and its associated costs. Nowadays, JIT is associated with efficiency, continuous improvement, quality, and optimal flow. JIT started in industries but it quickly attracted the interest of the researchers since its implementation involves difficult problems that have been, and will be, challenging the scientific community (Yasmin and Roger, 2012).

According to Mahmoud (2015) the objectives of JIT are producing products with; perfect quality, minimum lead time, only those features the customer wants, no waste of labor, material or equipment, every movement must have a purpose so that there is zero idle inventory and produce with methods that allow for the development of people.

2.3.1. Key JIT Management Concepts and Principles

One of the dominant thrusts behind the JIT philosophy is `stockless' production, i.e., reducing inventories in both raw materials and work in-progress. In JIT production everything is ordered, made and delivered just when it is needed with the right quality, in the right quantities and in the right place. To achieve this goal, the JIT system is equipped with the following seven broad principles which are very intertwined and related to one another: (Low and Mok, 1999; Low and Choong, 2001).

1. **Elimination of Waste**

The fundamental principle of the JIT philosophy is to eliminate waste (Low and Ang, 2003). It highlights the elimination of waste in any kind of resources. According to Low and Choong, (2001), under the JIT environment, the perception of waste is not only associated with waste of materials in the production process, but also other activities that does not contribute to the value of the product.

The 7 wastes identified by Ohno (1988) are; waste of (1) overproduction, (2) correction, (3) material movement, (4) processing, (5) inventory, (6) waiting and (7) waste of motion. The first 5 refer to the flow of material, the 2 last ones to work of men. Elimination of these seven wastes will reduce the cost of production, thus increasing profit (Koskela, 1992).
According to Formoso et al. (1999) the seven wastes are described as follow;

i. **Overproduction:** It is the practice of producing more or earlier than required, thereby wasting resources like labor hours, equipment, and material.
ii. **Waiting time:** This type of waste is associated with idle time caused by an inability to organize and level material flows and the rate of work by various workers or equipment.
iii. **Transportation:** concerned with the internal flow of materials at the worksite. Poor layout and an absence of material flow planning are often the causes. The primary consequences of this are the loss of man hours and energy and the possibility of material loss during transportation.

iv. **Processing:** this one has to do with the processing activity itself, which could only be prevented by modifying the construction technology.

v. **Inventories:** this is a result of having too much or unnecessary inventory, which results in material waste (due to deterioration, losses from poorly maintained stock on-site, and theft), as well as financial losses due to capital being tied up.

vi. **Movement:** concerned about workers' unnecessary or ineffective movements while performing their jobs. This could be caused by inadequate tools, inefficient work practices, or a disorganized workspace.

vii. **Defect:** It occurs when an intermediate or finished product does not fulfill the quality requirements. This could result in extra work (rework) or the addition of unnecessary materials to the structure (indirect waste).

In the Toyota Production System (TPS), the seven wastes presented by Ohno have provided understanding on the foundations of production management and guidance for action for more than half a century. This list has been widely used also when the Toyota Production System and its derivatives, like lean production, have been adapted and diffused into other industries, such as construction (Koskela et al., 2013).

2. Kanban or Pull System

“Kanban” is a Japanese term for “card” which was derived from the card system used to signal the delivery of components from one workstation to another. The idea behind this system is to provide material or resources for production only in the required amount at the required time. "Kanban" systems are developed to avoid overproduction and assure that elements are transferred from one process to the next in reverse order. Through the use of this system, production is “Pulled” by the demand side; instead of “Pushed” out before it is needed and then stored. Hence, an established relationship between the supplier and the customer is important to implement this principle (Tommelein and Li, 1999; Low and Choong, 2001; Mahmoud, 2015).

3. Uninterrupted Work Flow

The rationale behind this principle is to keep the production process smooth and the continuous flow of activities as scheduled. Hence, the production process has to be rationalized and simplified as much as possible by reducing unnecessary functions such as inspection and rework. Since the JIT concept encourages the provision of resources only at the required time following the pull system, any interruption in the production process may impact the entire process. Thus, it is essential to ensure that the production process is uninterrupted (Low and Choong, 2001; Low and Ang, 2003).

4. Total Quality Control (TQC)

To accomplish the principle of eliminating waste which will also occur due to defective components and to maintain uninterrupted work flow, a TQC system must be incorporated for a successful JIT system to materialize. Inspection will be carried out to first ensure that the product is defect-free before passing the part to the subsequent work station. Rejection of materials due to poor quality will critically disrupt the whole production workflow and schedule. Hence, the JIT concept must also encompass the total quality control concept for a smooth, just-in-time execution of the work processes (Low and Choong, 2001; Low and Ang, 2003).

5. Employee Involvement

The JIT concept comprises of a set of principles that requires practical implementation throughout the entire production process. Top management's efforts and time commitments are necessary to ensure that disciplined and correct operations are carried out in accordance with the JIT concept. Also, the involvement and motivation of employees at all levels in the organization is critical for its success. As a result, the implementation is dependent on the level of their involvement. The awareness of employees, their understanding and knowledge of the JIT concept and their ability to work quickly and as multi-functional workers would consequently be more beneficial (Low and Choong, 2001; Low and Ang, 2003).

6. Supplier Relations

Suppliers are entities external to the organization but are highly related to the production processes. As described under the principle of pull system, the material or resources in the production will be delivered only in the required amount at the required time. Therefore, careful selection of suppliers and effective coordination with suppliers are crucial in order to ensure that the right materials come at the right time. Mutual trust will encourage long term agreements between them (Low and Choong, 2001; Low and Jayawickrama, 2012).

7. Continuous Improvement

The JIT philosophy is a never-ending process which provides the means to an end and not an end in itself. Visibility management, which includes simplification, organization, discipline, cleanliness and participation, is adopted to provide an environment for continual improvement (Low and Ang, 2003). The organizations can develop their own internal systems to encourage continuous improvement of the JIT system by motivating and leading the employees to do so. All the employees should collectively implement this continuously and should strive to develop this mindset and habit in their organizations. Low and Choong, (2001) described employee involvement, which is led and guided by top management commitment, as an essential factor for "continuous improvement".

Generally, all JIT principles have tighter bonds with one another. For example, elimination of waste cannot be achieved without coordination with other principles. "The pull system" is necessary to reduce inventory, while "uninterrupted work flow" ensures that there are no waste of waiting time and waste of motion. In addition, "the total quality control concept" guarantees that there are no wastes from product defects, while "employee involvement" makes sure that no waste due to human resources happen on site. Furthermore, "supplier relations" lead to less time spent on communications with suppliers and subcontractors as well as leading to higher quality standard materials. A JIT environment can therefore be created, as long as all the aspects above are considered on a "continuous improvement" basis (Wu and Low, 2013).

2.4. Activities in the view of value generation

Womack and Jones (2003) focused on developing a guideline of waste elimination and value improvement by classifying and quantifying the activities from customers' perspective. According to their classification activities are categorized activities into three: value adding (VA), necessary but non-value adding (NNVA), and non-value adding (NVA) or waste.

1. Value adding (VA): are those activities which actually create value as perceived by the customer;
2. Necessary non-value adding (NNVA): are those activities which create no value but are currently required by the product development, and so can't be eliminated just yet;
3. Non-value adding (NVA) or waste: are those unnecessary activities which don't create value as perceived by the customer and unnecessary and so can be eliminated immediately.

Jorgensen and Emmitt (2008) argued that in the context of lean (as first proposed by Ohno, 1988), Value is viewed narrowly as only being what the end customer considers to be valuable to him or her, and waste is defined as anything that does not directly increase this value. Consequently, any process is wasteful, so it is appropriate to distinguish the two waste categories: type 1 waste, which cannot be avoided but should be reduced as much as possible, and type 2, which should be removed because it is inherently unnecessary for providing the value desired.

In Lean perspective, every activity is categorized as either a value added or non-value added activity. However, it should be noted that even some perceived NVA activities which may be necessary to comply with certain requirements. Such activities are termed as Essential Non-Value Added (ENVA) activities. Thus, activities are classified into value added (VA), non-value added (NVA) and essential non-value added (ENVA) activities (Eswaramurthi and Mohanram, 2013).

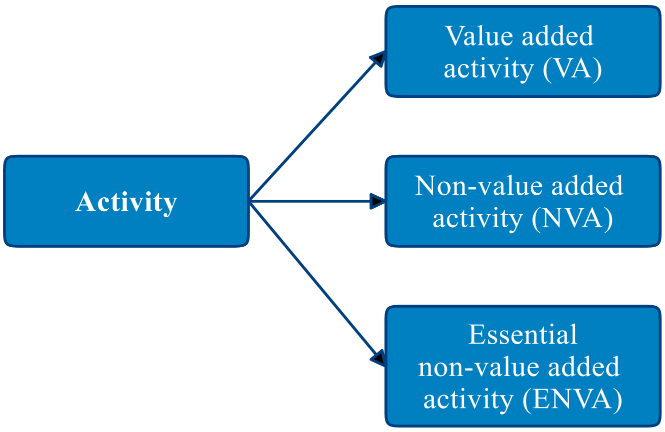

Figure 4: Classification of activities (Adapted from: Eswaramurthi and Mohanram, 2013)

Han et al. (2007) also categorized construction activities into value-adding activities (VAAs), value-supporting activities, and non-value-adding activities based on their ability to generate project value.

1. Value-adding activities (VAAs): are operational efforts that realize project requirements defined by contract.
2. Value-supporting activities (VSAs): are supportive efforts that do not directly add value; however they indirectly support other VAAs.
3. Non-value adding activities (NVAAs): are wasted efforts that consume time and/or resources but do not directly or indirectly add value or progress to the project requirements.

Lee et al. (1999) divided construction activities into six groups, including, any operations that (1) alter the shape or other characteristics of materials or products are grouped and considered as VA; (2) volume inspection, (3) quality inspection, and (4) transportation are the three groups that are considered as NNVA; finally, the activities that are relevant to (5) storage and (6) delay are the two groups of NVA/ waste in the process.

According to Diekmann et al. (2004) NNVA is the activities required for project operation although these activities do not have effects on the finished product. Some typical NNVA activities include material positioning, in-process inspection and temporary work and support activities.

2.4.1. Non-Value Adding activities/waste

Womack and Jones, (2003) define non-value adding activity/waste as any activity that does not add value to the product as defined by the customer. Similarly, Alarcon (1994) and Koskela (1992) argued that activities that produce costs, and take time, resources or require storage but do not add value or progress to the product can be called non-value-adding activities or waste. The term non-value-adding activity is used to differentiate between physical construction waste found on-site and other waste which occurs during the construction process (Alwi et al., 2002; Ralph and Iyagba, 2012).

According to Koskela (1992) in a production flow the cycle time can be represented by the addition of processing time, inspection time, wait time and move time. However, identifying and progressively reducing the cycle time by eliminating non-value-adding activities indicates another important issue which is continuous improvement.

Han et al., (2007) argue that non-value-adding activities are the major reason behind schedule delays, cost overruns, and other related problems in construction. According to the result of their simulation model, 26.1% of the assigned efforts were wasted, resulting in 171 working days of schedule delay in the case project.

Han et al., (2007) argue that non-value-adding activities are the major reason behind schedule delays, cost overruns and other related problems in construction. According to the result of their simulation model 26.1% of the assigned efforts were wasted resulting in 171 working days of schedule delay in the case project. The inherent recommendation of the new philosophy to construction practitioners is clear: the share of non-value-adding activities in all processes has to be systematically and persistently decreased and increasing the efficiency of value-adding activities has to be continued in parallel (Koskela, 1992).

2.4.1.1. Categories of Non-Value-Adding Activities

Industry researchers and practitioners acknowledge that construction activities are not always efficient. There are many wasteful activities during the design and construction process with the majority of these consumes time and effort without adding value for the client (Lee et al. 1999; Alwi et al. 2002). In order to prepare an effective management plan for minimizing NVAAs, these activities should be first identified and quantified (Han et al., 2007).

The study done by Alwi et al. (2002) that focused on the incidence of non-value adding activities within Australian and Indonesian construction companies classified variables into two groups: waste variables that contributed to a reduction in the value of construction productivity and waste causes variables that could be defined as factors producing waste. Waste variables are grouped into five categories: repair, waiting periods, materials, human resource and operations.

1. **Repair:** Repair on structural works, Repair on foundation works, Repair on finishing works, Repair on formwork/false work.
2. **Waiting Periods:** Waiting for instructions, waiting for materials, waiting for equipment repair, waiting for equipment to arrive, Waiting for labor.
3. **Materials:** Waste of raw materials on site, material does not meet specification, loss of materials on site, too much material inventory on site, unnecessary material handling, damaged materials on site.
4. **Human Resource:** Lack of supervision/ poor quality, tradesmen slow/ineffective, idle tradesmen.
5. **Operations:** Excessive accident on site, equipment frequently breakdown, unreliable equipment, delays to schedule.

The five major categories of non-value adding activities in production management are materials, cycle time, finished products, operations and human resources (Wu and Low, 2013).

1. **Materials:** Waste of raw materials in the production process, raw materials do not meet specifications, materials damages during transportation, unnecessary materials handling, too much inventory and loss of materials in factory.
2. **Cycle time:** Wait time for inspection, wait time for the delivery of materials, wait time for labor and wait time for equipment.
3. **Finished products:** Repair due to damaged products during inventory, repair due to damaged products when handling double-handling or delivery due to unsatisfied quality or specifications.

4. **Operations:** Inappropriate site layout, equipment breakdown, inappropriate selection of equipment.
5. **Human resources:** Inadequate work crews, inexperienced employees, lack of supervision.

2.4.1.2. Causes of Non-Value Adding Activities

Koskela and Sharpe (1994) indicated that there are three root causes of NVAAs, which are designed in hierarchical organizations, ignorance, and nature of production. Every time a task is divided into two subtasks executed by different specialists, non-value-adding activities increase: inspecting, moving and waiting. The nature of production contributes to an expansion of non-value-adding activities: work-in-process has to be moved from one conversion to the next, defects emerge, accidents happen. With respect to all three causes for non-value-adding activities, it is possible to eliminate or reduce the amount of these activities.

A study that focused on waste in the Turkish construction industry discovered that the origins of NVAAs in construction in terms of material or time can be categorized with respect to design, procurement, material handling, site operation, and other construction related activities (Polat and Ballard, 2004).

In addition, a study done by Alwi et al. (2002) grouped the sources of non-value adding activities into six categories: people, professional management, design and documentation, materials, site operations and external/physical factors**.** The waste cause variables linked to these categories are;

1. **People:** inadequate trades skills, poor distribution of labor, late supervision of work, shortage of skilled supervisors/foremen, inadequate subcontractor skills, and inexperienced inspectors.
2. **Professional management:** poor planning and scheduling, poor coordination among project participants, poor information management, a slow decision-making process.
3. **Design and documentation:** poor quality site documentation, unclear site drawings, unclear specification, slow response to requests for information, poor design, and design changes.
4. **Material:** Poor quality of materials, delay of material delivery, poor material handling on site, inappropriate/misuse of material, poor storage of material, poorly scheduled delivery of material to site.

5. **Site operations:** poor site layout, outdated equipment, equipment shortage, inappropriate construction methods, and too much overtime for labor in order to execute work timely.
6. **External/Physical factors:** Site condition, weather, damage by other participants.

Furthermore, Rajkumar and Biswas (2016) mentioned some variables related to non-value-adding activities in the Indian construction industry such as; waiting for raw materials, labor and equipments idle for long time, lack of available space on site, overproduction, too early fabrication of rebar, poor design and specifications, frequent drawings and specifications changes, lack of planning and control, unnecessary movements of workers on job site, poor site layout, deterioration of stocked materials, ordering materials and resources more than requirement, inadequate stock conditions on site and robbery.

Ralph and Iyagba (2012) conduct a comparative study on non-value-adding activities in Nigeria and Indonesia, and from the result of their study; repairs on finishing works, waiting for instruction, waiting for materials and materials not meeting specifications were identified as the key waste variables, while site condition, weather and lack of subcontractors' skill were identified as key waste causing variables.

2.4.1.3. The Extent of non-value adding activities in construction

There is strong empirical evidence showing that a considerable amount of waste and loss of value exists in construction. A large part of this waste has been hidden, and it has not been perceived as actionable (Koskela, 1992).

Horman and Kenley (2005) in their study they quantified the levels of wasted time in construction using meta-analysis and their analysis reveals that an average of 49.6% of construction operative time was devoted to wasteful (non-value adding) activity. It indicates the potential performance improvements that are possible through waste minimization initiatives like those advocated by lean construction.

A study by Serpell et al., (1995) that focused on waste was conducted to identify the most relevant factors that produce waste of productive time in building construction projects found on metropolitan region of Chile, from 1990 to 1994. Then the study concluded that around 53% of the total working time is dedicated to non-productive activities. From this 28% are contributory works and the rest 25% is non-contributory. Waiting time, idle time and travelling time, indicated as the main subcategory of non-contributory work (waste).

A study presented by Arbulu et al. (2003) assessed the supply chain for pipe supports used in US power plants. The analysis shows that about 3.6% of the total time a pipe support needs to flow through the system represents value-added time. The remaining 96.4% of the time reflects non-value-added time, or waste. The study also described various strategies that industry leaders in supply chain management are implementing to improve the supply chain performance.

The study conducted by Ayalew et al. (2018), characterize the seven types of wastes (Ohno's waste) in Ethiopian construction industry based on the subject of lean construction. The main focus of the study was on the extent of waste and their frequency of occurrence in Ethiopian building construction projects. Accordingly, the study confirmed that close to 40% of the project time is wasted in performing NVAAs such as; over production, over processing, transport, motion and waiting related wastes.

The case study by Sahlu (2017), focused on construction wastes based on the concept of lean philosophy on selected construction sites in Addis Ababa is conducted. One of the focuses of the study was rebar fixing process for slab section. Two companies were compared with different work methodologies and the result showed that the working hours which spent on NVAAs in the time of fixing is 45.82% and 29.59% respectively. From this result waiting time takes the biggest share among the NVAAs.

Assefa (2020) conducted a study that focused on improving labor productivity using value stream mapping and discrete event simulation. The main focus of the study was analyzing the slab reinforcement bar and hollow concrete block (HCB) operations. Thus, the study reveals that 99.96% of the slab reinforcement bar and 99.7% of the HCB operations are constituted by NVAA. NVA activities that are found in both operations are: overproduction, unnecessary transportation, defects, over-processing, inventory, waiting, and unnecessary movement of employees.

2.5. JIT Approach to Construction Industry

The Just-in-Time (JIT) philosophy originated from the Toyota production system (TPS) and has been used in the manufacturing industry for many decades. It has helped to increase the productivity of the industry and has also increased the quality of its products. In recent years JIT is introduced in the construction industry to gain similar benefits. Even though it originated in the manufacturing industry and the nature of the construction industry is distinctively different in many aspects from the manufacturing industry, studies have identified that the JIT philosophy is applicable in the construction industry with some modifications (Low and Mok, 1999; Low and Gao, 2011). In manufacturing, the new production philosophy improves competitiveness by identifying and eliminating NVAAs. Construction also could realize improvements simply by identifying and eliminating non-value-adding activities (Koskela, 1992).

2.5.1. Characteristics of construction industry

The construction industry is very complicated industry in nature due to various levels of management, complex design, lot of process and labor intensive (Ismail and Yusof, 2016). The construction industry comprises of multi-disciplinary tasks and parties that are inherently complex in nature. It also produces unique products according to specific client requirements. Client involvement is high in construction projects which may lead to variations during the construction process. Apart from this, construction projects are highly influenced by the external environment such as inclement weather, safety hazards and many other unforeseeable conditions such as shortages of building materials. Due to the often-large scope of works operating over an extended time frame, construction projects are highly vulnerable to adverse effects of wide economic fluctuations and unstable political situations (Low and Jayawickrama, 2012).

Furthermore, the problems of construction are well-known. Construction productivity lags that of manufacturing. Occupational safety is notoriously worse than in other industries. Due to inferior working conditions, there are work force shortages in many countries' construction sector. The quality of construction is considered to be insufficient (Koskela, 1992, 2000).

Generic procedures for material acquisition in construction include material inspection, delivery, handling and storage before installation. Some of these activities have been described as waste; they do not add value and hence should be minimized. One of the concepts in the manufacturing industry developed to address similar complex communication, coordination and waste minimization is Just-in-Time (Akintoye, 1995).

The most basic solution to alleviate the site problems is to configure the material flows so that a minimum number of activities are carried out on site. The rationale of prefabrication, modularization and preassembly is partly based on this principle. Likewise, in more site oriented construction some activities such as inspection, storage, sorting etc., can be pushed upstream in the material flow (Koskela, 1992).

2.5.2. Benefits of JIT in construction

The application of JIT philosophy in construction, in relation to material inventory, aims to minimize all waste. Practically, the ultimate goal is to have direct receipt of materials into construction work-in-process, replacing the traditional receiving, inspection and storage functions. These traditional procedures for material acquisition do not add value and should be minimized to achieve inventory reduction in the construction process (Akintoye, 1995).

By applying the JIT concept, in the pre-design stage, all the deliveries of the materials, construction and installation activities were taken into consideration, so that no unnecessary movements would happen on site. Only the amount that was required of the proper parts was supplied to the site at the right time (Ohno 1988).

Safety is one of the chronic problems in construction. The application of the new production philosophy can also contribute in this area. Standardized, systematized and regularized production can be expected to lead to better safety as a side effect (Kobayashi 1990). There are several mechanisms for this: There is less material in the work area, the workplace is orderly and clean, the work flows are more systematized and transparent and there are fewer disturbances which are prone to cause accidents (Koskela, 1992).

The Just-in-Time technique is an effective management technique which manages the flow of materials, components, tools and associated information regarding ongoing project. In various construction projects, the use of this technique will improve project's productivity, improve work flow, and project durations will shorten. Successful implementation of just-in-time technique will maintain quality of the entire project, increase efficiency of the workers and it will reduce a few elements such as stock level, capacity space and generation costs (Patil and Dhawale, 2018).

Labor, materials and plant are the main types of resources involved in construction projects therefore eliminating idling labor, material wastage, idling plant, and wasting resources on un-related activities are one of the important waste elimination JIT principles. Quality is one of the major aspects of a construction project in which the contractor ensures that all the client requirements are achieved. Hence, Total Quality Control (TQC) principle is of immense importance for the construction industry (Low and Choong, 2001).

Generally, the benefits gained from JIT application in the construction industry according to (Akintoye, 1995; Low and Mok, 1999; Mahmoud, 2015) include:

- Enhancing the competitive advantage of firms in terms of meeting customer requirements
- Improving quality of construction materials and components
- Productivity enhancement
- Cost reduction in terms of minimizing the levels of inventory
- Improving relationships with suppliers
- Completing work ahead of schedule
- Improving the tidiness of construction sites and
- Eliminating site congestion and inconveniences caused to neighborhoods.

2.6. Application of JIT to Reinforcement bar Production

Many organizations throughout the world have successfully adopted the Just-In-Time (JIT) idea in various construction-related applications, such as project management, precast concrete component (Low and Choong, 2001), construction site management (Low and Ang, 2003), ready-mix concrete production (Tommelein and Li, 1999), building materials management (Akintoye, 1995), reinforcement bar work (Hussin and Ismail, 2014), site layout (Low and Mok, 1999), and so on. The reinforcing bar work, which was chosen from among these application areas, was the major focus of this study.

Reinforcement bar work is one of the essential elements in construction process which affect the project performance. The supply system of this material is a critical factor in meeting the budget and schedule goals of a construction project for the production of reinforced concrete. Any inefficiency in the supply chain of rebar may result in substantial delays and significant cost overruns. Thus, rebar supply system needs to be well managed in order to enhance efficiency (Polat and Ballard, 2003). The JIT approach is better to be utilized to manage the issues faced in undertaking the reinforcement works in the construction industry (Hussin and Ismail, 2014).

2.6.1. On-site rebar production

In the on-site production practice, the contractor procures straight reinforcement bar from the rolling mill and takes responsibility for producing and installing them. In the on-site production operations, contractors frequently work with huge lot sizes (Polat and Ballard, 2003). The basic characteristic of this rebar preparation system is that cutting and bending of rebar are performed at the construction site, occupying a large space and sometimes producing a significant amount of waste it can also cause accidents to rebar workers. Additionally, this method characterized by excessive number of on-site operations related with transport, storage and inspections of rebar, this fact demands more use of manpower throughout the process.

In Ethiopia, in most building construction sites reinforcement work is still carried out by means of manual method which is labor intensive to a considerable extent, mainly using simple tools and aids. The reinforcement bar is delivered in lengths of 12 m then bar benders will cut and bend the rebar on site (Nigussie and Chandrasekar, 2020).

2.6.1.1. Problems related to current rebar production

According to different researchers, the site reinforcement bar work practice is vulnerable to many problems, including inefficient rebar cutting, cut and bend errors, design changes, over-design, corrosion, rework, unnecessary inventories, damages during handling, transportation, and installation (Asmara, 2015; Fantahun, 2020; Formoso et al. 2002; Poon et al. 2004; Tam et al. 2006; Girma, 2016).

i. Design problem

The structural design that is poor in terms of standardization and detailing is one of the causes of steel reinforcement waste (Formoso et al., 2002; Chandrasekar and Nigussie, 2018). Additionally, Asmara, 2015; Girma, 2016; Fantahun; 2020; Mulualem et al.; 2015 argued that design change is one of the problems which are mostly encountered in construction projects due to the information gap or miscommunication between a client, consultant and contractor. The design change made by client and the designer while construction period may cause the previous work done have to be aborted and also resulted wastage (Wan, 2011). Therefore, to reduce rebar waste first working more at the design stage is best and also practicing highly off-site construction by adopting different technologies like prefabrication is recommended (Girma, 2016).

ii. Ordering errors/ incorrect quantity estimation

According to Kim et al. (2004) during the pre-construction waste rate can be estimated as high as 3 to 5% in the material ordering phase. The study shows that the highest rate of waste is observed when the purchase order with redundancy is made to reinforcing steel without an accurate understanding of structural drawings and bar bending schedules (BBS). Similarly, Chandrasekar and Nigussie, 2018 mentioned main causes of rebar wastage is the bar bending schedule is not properly supplied from design office and Poor software usage for bar bending schedule preparation.

Ordering greater quantities of materials such reinforcement and floor, pipes, electrical cables and tiles are also a major problem in Ethiopian context (Ayalew et al., 2018). The excess of material that needs to be purchased tends to increase stocks, the demand of the transportation system, and the effort necessary to remove debris from site. These problems might also negatively affect health and safety conditions (Formoso, 2002). Therefore, before ordering careful analysis should be done about the amount of material required for the project (Kim et al. 2004).

In reinforcement work rebar schedule is one document whose importance and significance is often underestimated. As a result, drawing up a reinforcement schedule has come to be regarded generally as a job with a low status. Lists are sometimes drawn up by inexperienced individuals, frequently resulting in incorrect notations. Errors of this type can give rise to major and serious disturbances in production (Hjort, 1982).

iii. Un-optimized Cutting method

For concrete construction, one problem that a construction firms often encounters is that there is a large amount of wastes of reinforcing steel caused by cutting. There are different lengths of reinforcing steels used in construction but there are only few standard lengths of reinforcing steels produced depending on countries standard. Therefore, it is necessary to cut the steels from the standard lengths, this causing a large amount of unusable pieces of reinforcing steels remain at the job site due to un-optimized cutting procedure (Formoso et al., 2002; Shen et al., 2000; Fantahun, 2020; Nigussie and Chandrasekar, 2020; Asmera (2015). They recommended pre-bending in the factory could reduce cutting waste.

Reinforcing bars (rebar), which have the most embodied carbon dioxide (CO_2) per unit weight in built environments, generate a significant amount of cutting waste during the construction phase. Excessive cutting waste not only increases the construction cost but also contributes to a significant amount of CO_2 emissions (Lee et al., 2020)

iv. Improper rebar handling and storage

According to Indian standard (IS: 2502-1963) the reinforcement bars should not be left in direct contact with the ground but they should be stacked on top of an arrangement of timber sleepers or the like and also. Because of its weight and shape, it is difficult to control and manage steel reinforcement on construction sites (Formoso et al, 2002). Problems related to poor handling of materials were resulting in large disorganized stocks, which often caused damages and rusting during storage (Shen et al., 2000; Formoso et al, 2002; Asmara, 2015; Mulualem et al., 2015; Fantahun, 2020). Rusts in the form of scales are peeled off from the swelled surface of iron. It is serious problem as the surface becomes rough with rusted iron projections. This may injure users. Also, the loss of steel sectional area may cause failure of structural elements.

The inefficiency of inventory management is one of the frequent causes of waste of rebar (Ugochukwu et al. 2017). This type of waste is observed in urgent and large-scale construction projects. Any material that arrives early before it is needed time has a chance of deterioration, being stolen, and taking up too much storage space. This is especially true for materials such as reinforcement bar and cement that require extra care for storage and require large storage space. Material that arrives late than planned will result in a schedule delay (Fantahun, 2020).

v. Workmanship

According to Chandrasekar and Nigussie, (2018) unskilled manpower, poor supervision and mistake in cutting are some of the causes of rebar waste. The quality of labor provided by the subcontractor can significantly influence the waste rate (Wan, 2011).

2.6.2. Off-Site Reinforcement Bar production

The tradition of the construction industry has long been to deliver rebar from a rebar supplier or the warehouse of a contractor to the construction site in large batches; cut and bend rebar on-site and position it for assembly. The traditional rebar supply system requires large on-site yard and holding costs. Since people recognized the holding costs including yard space requirements, a new method has gained industry attention especially in construction projects in urban areas. A new rebar supply system uses off-site cut and bend with a frequent delivery to the job site when it is needed (Kim, et al., 2013).

Therefore, in the construction process of reinforced concrete structures, one potential way of streamlining rebar supply chains and ultimately maximizing efficiency is off-site fabrication of reinforcing steel bars (Formoso et al., 2002). In this production system the contractor acquires cut and bent reinforcement bar from the fabricator with just-in-time (JIT) deliveries and does the installation in the off-site fabrication practice (Polat and Ballard, 2003).

The off-site rebar fabrication has become increasingly popular in industrial construction projects over the past decade due to advantages of higher productivity, better quality, better safety and improved time and cost effectiveness (Azimi, 2011).

The supply chain of reinforcement bar was considered as the activities associated with the flow of materials supply to site and the on-site work flow. In this view, main participants in the supply chain of reinforcement bar include contractors, rolling mills and reinforcement bar fabricators.

2.7. Advantages of JIT off-site rebar production

Several previous studies showed that off-site rebar production and supply system offers several significant advantages such as: reduction of rebar waste, reduction of NVAAs, reduction of cost, reduction of space at the construction site, reduction of cycle time, and improves productivity according to (Low and Mok, 1999; Formoso et al., 2002; Polat and Ballard, 2005; Low and Choong, 2001; Arbulu and Ballard, 2004).

2.7.1. Reduction of rebar waste

According to Bossink and Brouwers (1996) and Formoso et al. (2002), between 16 and 26 percent by weight of the entire amount of rebar purchased is lost during construction. Bae and Kim (2009) compared the On-site and off-site rebar fabrication; thus, the result revealed that a rebar loss rate of 10% for On-site fabrication, and a 2% loss rate for Prefabrication with JIT supply chain which means that on-site fabrication generated five times of more rebar loss than the rebar loss in off-site production.

Off-site fabrication is expected to have significantly lower waste because production is largely computerized and incorporates more standardized quality control systems (Polat and Ballard, 2005; Low and Mok, 1999; and Low and Choong, 2001). The goals of the rebar processing plant are to reduce the on-site rebar loss rate/waste caused by disorganized cuttings, and the stockpiling of rebar on construction sites which often results in rust and theft of rebar Bae and Kim (2009). In off-site production the supply is made by the nominal weight, which means the client receives exactly the meters that will consume; therefore, there is no waste the ordered quantity is strictly equal to the amount consumed.

2.7.2. Reduction of NVAAs

According to, Koskela (1992) one potential means of minimizing waste and maximizing value in construction is eliminating, or at least significantly reducing, on site activities through off-site production of the components used in construction process. Therefore, implementing off-site rebar production is advantageous in reducing or eliminating non-value adding activities in the rebar production life cycle.

By separating rebar bending and cutting places from actual working site, wastes that arise out of unnecessary inventory, waiting time, unnecessary movement and unnecessary transportation of workers can possibly be reduced (Sahlu, 2017). Similarly, Bae and Kim (2009) stated that on site waste due to processing and maintaining of rebar will be minimized.

2.7.3. Reduction of cost

According to Low and Mok (1999), Polat and Ballard (2005), Low and Choong (2001), and Formoso et al. (2002), the following are the key benefits of producing rebar off-site:

- **Reduces investment cost:** for the on-site production of rebar, contractors use manual cutting and bending machines. Although these machines have a long working life and a high initial cost, their continued use depends on whether or not there are any upcoming new projects. However, the investment cost per unit of rebar produced is lower for the automated machinery used in off-site fabrication because it is employed continuously for mass manufacturing.
- **Reduces labor cost:** In a rebar production procedure that takes place on site, employees transport rebar from storage to the cutting machine, cut it, and then transport the cut rebar to the bending machine and bend it. However, as the process is automated in off-site fabrication, labor costs are reduced.
- **Reduces inventory cost:** holding inventory while producing rebar on site raises storage, finance, and handling costs. The contractor can reduce inventory costs by using just-in-time (JIT) to receive supplies in small batches from off-site fabricators.

2.7.4. Reduction of space at the construction site

The off-site fabrication of reinforcing steel reduces the space needs for inventory storage and for rebar workshop (i.e. for cutting and bending activities on sites). Thus, the resulting advantages includes; the spaces that are corresponding to the stock of bars, bending machines, table benders and beds will be used for other purposes or saved when they are few, like happens in urban areas. There will be neater site with more space for workers to work in, and clear space for mobile plant to move about on site. It would also facilitate better housekeeping as rubbish arising from leftover cuttings of reinforcement bars (Low and Mok, 1999; Arbulu and Ballard, 2004; Bae and Kim, 2009).

2.7.5. Reduction of time

The off-site rebar fabricators produce cut and bent rebar using computerized machinery. Compared to the cutting and bending machines used for on-site production, the productivity of these automated machines is significantly higher. As a result, the off-site approach significantly reduces the amount of time needed for fabrication. Project durations are also decreased since off-site production can be completed simultaneously with the installation of previously supplied materials. Additionally, cycle time will decrease as the extent of non-value-adding tasks decreases.

2.7.6. Quality of product

- Bending angle, tensile strength, steel classification etc. Those terms are fundamental to guarantee the quality of rebar, but are often neglected in the execution on-site due to the pressure caused by deadlines and working conditions. In this system, quality issues are guaranteed.
- A rebar prefabrication yards operate under an effective quality management system, including the establishment of a traceability system in relation to the handling of rebar materials and prefabricated rebar products. The yards concerned shall also satisfy the stipulated requirements on probity, technical and quality assurance (GEO, 2021)
- The goals of the rebar processing plant are to minimize the amount of loss due to rebar waste, meet the exact specifications of the reinforcing process (Bae and kim, 2009).

2.7.7. Reduction in accidents and ill health

Transferring much of the construction work from an open site to a controlled factory environment reduces on-site time for workers and reduces the potential for site-based accidents and ill health (Taylor, 2015).

2.8. Other countries experience on JIT off-site rebar production

Some countries that experience the off-site rebar production with JIT delivery are;

2.8.1. United Kingdom

Construction on confined urban spaces presents developers with various challenges such as; the lack of working and storage space, the need to minimize the impact of construction work on local residents and the shortage of skilled labor for site construction. These challenges can be met by the use of off-site construction methods to replace site intensive work activity and delivery on a just-in-time basis to suit local conditions without the need to store on site. There will also be reduction of labor and quantity of site-generated waste through the use of off-site fabrication when compared to traditional onsite fabrication methods (Taylor, 2015).

The fabrication of reinforcing steels, into shapes suitable for fixing the concrete formwork, is normally performed “off-site” in the UK, by specialist reinforcement fabricators. Very little reinforcement is cut and bent on-site in the UK today. Although the cutting and bending of reinforcement appears relatively straightforward, the specialist reinforcement fabricator is well equipped to do so in a consistently accurate manner and, by working within a defined set of quality management criteria, as provided by the CARES scheme, provide an important link in the reinforcement supply chain. The accuracy of cutting and bending operations is vital to ensure proper fit on site, and to maintain required lap lengths, anchorage lengths and cover (UK CARES, 2011).

Within the UK and abroad, BS 8666, specification of rebar for concrete, specifies requirements for scheduling, dimensioning, bending and cutting of reinforcing steels. It is of vital importance that the standard being used. Under CARES approval, all approved reinforcement fabricators are required to fully understand the requirements of their customers and to provide reinforcement to the specified standards and related bending schedule.

2.8.2. Hong Kong

The Geotechnical Engineering Office (GEO) of the Civil Engineering and Development Department (2021) stated that the construction industry in Hong Kong is facing the challenges of high construction costs, an ageing workforce and labor shortage. To overcome such challenges and to enhance cost-effectiveness and productivity the Government committed to adopt the new technology and innovative construction methods. One of such important initiatives is to promote the use of prefabricated rebar products (cut and bent rebar) produced by highly automated off-site rebar prefabrication yards.

The automated rebar processing in a factory-like setting helps enhance productivity, uplift -built quality, improve construction safety and promote environmental friendliness. The off-site rebar prefabrication yards operate in a factory-like setting, deploying advanced computer systems and highly automated machinery for production. Such a rebar processing mode has been proven effective in enhancing productivity, improving performance in the contexts of safety, quality and promotes environmental friendliness. When compared with the conventional practice of the on-site rebar processing, the automated off-site rebar processing enjoys a number of advantages.

Table 2: Off-site vs. on-site rebar production (Adapted from: GEO of the CEDD, 2021)

	Off-site rebar processing	**On-site rebar processing**
Productivity	• Efficient production with the use of advanced computer systems and highly automated machinery	• Manual processing with lower efficiency
Storage	• Pre-tested products ready for use, saving valuable storage spaces on site	• Rebar materials occupying valuable storage space on site
Quality	• Better product quality on account of automated production and effective monitoring in a factory-like setting	• Product quality undermined by human errors and failure of close monitoring on account of congested site conditions
Environment	• Computer-monitored production with high precision and reduction in material wastage	• Manual processing with errors and high material wastage
Safety	• Adoption of standard working procedures and highly automated machinery to provide a safer working environment	• Manual processing, as well as congested site conditions, increase injury hazards • Labor intensive
Traceability	• Computerized product tags detailing the materials' traceability information to facilitate the management by sites	• Manual processing without computerized product tags

2.8.3. Malaysian

According to Hussin and Ismail (2014) the implementation of JIT approach in reinforcement bar works in Malaysian construction industry is seen as a tool to address construction's site issues of late delivery of material, storage space and labor requirement, which if successfully implemented, could ultimately improve project management and benefit the company.

CHRB and its group of company is one of the largest suppliers of building material, especially steel bar, in Malaysia. The company services the Malaysian construction industry with off-site produced reinforcing steel. The reinforcement bars are fabricated in their plant and will be delivered to site on just-in-time basis and the company gives the following advantages:

- Provides more value adding to clients by adopting a highly integrated approach in meeting their needs e.g., from the preparation of bar bending schedules to delivery and management on site
- No stock lengths need to be stored on construction sites. This offers major savings in cash flow management, storage space utilization and area required for site operations.
- The client only pays for what is designed, detailed and delivered. No allowance needs to be made for material wastage.
- Cut and bent reinforcing steel bars are delivered in a just-in-time manner to site based on clients' requirements.
- Crane-age time on site can be significantly minimized as fabricated bars can be offloaded at the actual locations of installation.
- Steel is cut and bent to a high degree of accuracy and consistency using sophisticated high quality of fabricated steel, which facilities faster installation on site.

2.8.4. Turkey

The practice of JIT approach in reinforcement bar work in Turkey can help to reduce the cost of construction. The nature of off-site fabrication will also reduce waiting time and delay significantly and therefore, improvise the possibility of delay in the construction. The study done by Polat G. (2008) on Turkish construction compared the economics of on-site and off-site rebar fabrication practices using a simulation-based efficiency assessment approach. Thus, the study reveals that fabricating rebar off-site is more economical than fabricating it on-site when storage and waiting costs are taken into account in the current state of the construction industry. In addition, by making improvements to the production method used on-site, the lowest possible rebar total cost can be obtained.

Furthermore, Polat and Ballard (2005) in their study they identified the driving and the restraining forces for the deployment of off-site fabrication practices in the Turkish construction industry. The driving forces are; major reductions in initial investment costs, worker costs, waste encountered throughout on-site fabrication practice, carrying costs, project duration and substantial enhancements in productivity, quality and work process. The restraining forces encompass nationwide obstacles (Turkish Social Security Law, great fluctuations in the unit price, high shipping cost), industry wide obstacles (low wages of workers, high cost of implementing technology) and companywide obstacles (uncertainty in the procurement process, low productivity of workers unethical behaviors and resistance to change). The off-site fabrication of reinforcement bar will be more preferable in a project environment in which most of those restraining forces were reduced or eliminated.

2.8.5. Brazil

The study in Brazil shows that the sources of waste indicated that a large proportion of material waste occurs because flow activities, such as material delivery, inventories, and internal transportation and handling. So that one obvious strategy for reducing the waste in the Brazilian industry seems to be to encourage the use of precut, preassembled components, instead of producing materials such as mortar, concrete, and steel reinforcement on site. In recent years many companies in Brazil have decided to purchase off-site steel reinforcement. One of the advantages of this alternative is that it drastically reduces waste mainly by optimizing the cutting of bars (Formoso, et al., 2002).

2.9. Challenges that need considerations on JIT application

One of the challenges of JIT is of unexpected changes from the original plans. There could be sudden shortages of materials arising from uncontrollable external factors like bad weather condition. Thus JIT, being a highly regularized program, could be affected and may be blamed for being inflexible, unresponsive and possibly disrupting of work flow (Low and Mok, 1999). The Kanban" or Pull System is one of the principles of the JIT concept, the risks associated with this principle is unforeseeable conditions, late deliveries and shortages of resources are stated as limitations for the implementation of this principle in the construction industry (Low and Choong, 2001).

According to Oral et al. (2003) the six common characteristics of developing countries that affect the JIT implementation are; implementation costs, costs of technology and maintenance, labor productivity and labor costs, inflation and the supply conditions, the demand conditions and culture.

Furthermore, Akintoye (1995) argued that for successful JIT implementation in building construction, the following bottlenecks should get consideration.

1. **Production planning**

Construction work is characterized by poor planning and associated project time overrun. JIT requires an accurate work program. It must show clearly the specific time that material is needed. The construction schedule needs to be developed by providing only the quantities of material required for a specified time period. This means that contractors need more discipline and that they must strive to achieve an accurate construction plan and to ensure that construction is carried out as planned.

2. **Design planning**

The interaction between design and construction process is important to the total JIT effort. The contractor can provide vital input to project simplification, standardization of specification, design easy to build and building quality into the design. JIT philosophy performs efficiently when a production process is standardized. Designing products with commonly accepted and uniform techniques, dimensions, or materials is known as standardization. The current level of building waste output might be significantly reduced by standardization. For the production process to be standardized, the design input is paramount.

3. **Construction process output and material quantities**

The construction process output and quantities of materials delivered to construction site must conform to JIT system. The level of the process output determines the quantity of and the rate at which materials are delivered. The quantity of material must be exact and delivered in small and variable finite quantities to ensure zero or near zero inventory on construction sites. Therefore, it is essential, for the contractor to maintain stable productivity so that material can flow smoothly into the production system and also the contractor needs to determine the exact quantities of construction materials in relation to production plan and schedule, and communicate this information to suppliers.

4. Construction contractor and supplier's relationship

In JIT supply system the suppliers must embrace quality delivery by committing themselves to deliver the agreed-upon quantity of acceptable building materials and equipment on time, neither before nor after the agreed-upon date. This requires good delivery planning by both supplier and contractor. Apart from that trust and discipline on the part of the contractor and its suppliers is essential for successful JIT implementation.

5. Construction site layout and storage planning

Construction site layout and storage facilities need to be properly planned such that building materials and components are located at fixed positions on the site. The underlying planning strategy requires JIT suppliers to deliver all materials components and subassemblies to, or close to, the point of work in the proper sequence. This strategy will minimize material waste and damage on site which is caused by multiple handling of material and will also increase productivity due to the ease of access to the materials components and subassemblies.

6. Training and education

Construction firms and suppliers from top management to the low level employee must know the basic JIT philosophy. They need to know how and why JIT could improve efficiency in the construction process. Since JIT requires an attitude change of employees, it is important that all employees in both the contractor and the suppliers' organizations understand the JIT system before its implementation.

2.10. Simulation Modeling

A simulation, according to Banks et al. (2014), is a time-based replication of how a real-world process or system might operate. It entails creating an artificial history of a system and observing that history to derive conclusions about the operational features of the actual system. A system is a set of entities that interact and communicate with each other in order to achieve a certain goal (Law, 2013; Banks et al., 2014). By creating a simulation model, the behavior of a system as it changes over time could be analyzed.

A model is a visualization of a system created with the goal of understanding the system. This model often takes the form of a list of presumptions about how the system will operate. The model needs to be accurate enough to allow for appropriate conclusions about the real system. A model could be used to research a wide range of "what if" questions concerning the real-world system once it has been created and validated (Banks et al. 2005, 2014).

Through the provision of a tool that enables the analysis and comprehension of a system's present behavior, simulation modeling is used to support decision-making. It can also aid in forecasting how that system will perform in a variety of scenarios chosen by the decision-maker (Greasley, 2008).

One of the effective tools for assisting in decision-making in construction management is simulation. The development of improved solutions and resource optimization are both aided by an accurate model of the building process (AbouRizk and Mohamed, 2000).

Construction simulation is the use of software applications to simulate the behavior of a model created to represent a construction system in order to depict the dynamic characteristics of the system. An abstraction of the construction system is represented by a simulation model, which is a set of objects that is used to define, analyze, and simulate the behavior of the system (AbouRizk et al., 2016).

Construction projects can benefit from the use of a variety of simulation tools for project planning, operations bottleneck detection, productivity analysis, resource utilization enhancement, and easy comparisons of different construction scenarios. In general, construction simulation enables professionals in the construction industry to experiment with various construction technologies and predict potential outcomes and effects on budgeting and scheduling (Ruwanpura et al., 2001).

2.10.1. Types of Simulation models

According to Banks et al. (2005, 2014), Kin and Chan (2011), and Law (2013), the simulation models are classified into 3 different dimensions and described as follows:

1. **Static vs. Dynamic Simulation Models**

A static simulation model is a representation of a system at a certain point in time, or one that might be used to describe a system in which time is purely irrelevant. Some Monte Carlo models are examples of static simulations. A dynamic simulation model, on the other hand, depicts a system as it changes over time.

2. **Deterministic vs. Stochastic Simulation Models**

A simulation model is termed "deterministic" if it does not contain random variables. A known set of inputs and a specific set of outcomes are the basis of deterministic models. Stochastic simulation models are a result of the necessity to model many systems as having at least some random input components. A stochastic simulation model's inputs can include one or more random variables. Random inputs produce random results. The outputs can only be viewed as estimations of a model's actual properties because they are random.

3. **Discrete vs. Continuous Simulation Models**

Discrete-event simulation is the modeling of a system as it changes over time using a representation in which the state variables change instantly at different points in time. On the other hand, continuous simulation models simulate systems with continually changing state variables. The exact goals of the study will determine whether to adopt a discrete or continuous model for a given system.

2.10.2. Discrete-Event Simulation (DES)

Modeling systems in which the state variable changes only at certain points in time is known as discrete-event simulation. These moments in time, also known as "event times," show the occurrence of certain events that change the system's state. When no events are occurring between event periods, the system state doesn't change (Kin and Chan, 2011; Law, 2013; Banks et al., 2014). This unique feature of DES simplifies modeling and analysis by allowing the modelers to focus on the events, their connections, and their durations. Simply creating a DES model requires identifying these elements and putting them together in the correct manner (Kin and Chan, 2011).

Discrete event simulation models especially belong to the category of dynamic simulation models. These models are handled by discretely advancing the time in accordance with significant model occurrences. The simulation model often begins with a certain event, which then causes further events to occur until a termination point is reached. The CYCLONE model is an illustration of such a model (AbouRizk et al., 2016).

2.10.3. CYCLONE Simulation Model

To accomplish the many operations that make up the construction process, several resources are required, and numerous interactions take place. The statistical analysis of the data may be used to study the behavior of the key variables in each of the processes, which enables the prediction of new scenarios that enhance or optimize the initial situation (Maria et al., 2020).

Halpin first presented CYCLONE, an acronym for CYCLic Operations Network, as a construction simulation language in 1977. Halpin's strategy is based on the idea that construction processes can be abstracted as cyclic networks of modeling components that depict the flow of resources between two states: an active state and an idle state. A resource's active state is represented by the task element, while its idle state is represented by the queue element. CYCLONE models are effective for repetitive processes (AbouRizk et al., 2016).

According to AbouRizk et al. (2016), the fundamental concepts for developing models in the CYCLONE simulation are:

- Models are made up of modeling components and virtual entities that move from one element to the next until a certain condition is satisfied to stop the simulation.
- Models are constructed by outlining the systems in real life that they reflect and then tracking the path that virtual entities take between the modeling elements.
- The modeling elements manage the virtual entities as they enter in and release them to subsequent elements once their processing is finished.

There are various methods to model a system. However, one of the most common approaches is to first consider identifying the key elements and then presenting those elements in some form using a computer. One of the simulation software developed in academic institutions is Simphony, which was developed in 1998 by AbouRizk and Hajjar; its successor, Simphony.NET, was also developed by AbouRizk and Hague (AbouRizk et al., 2016).

Simphony is an integrated environment for developing special purpose simulation tools. Simphony's simulation service supports discrete-event simulation and includes features like queue management, next-event polling, and event scheduling. Simphony provides a very flexible yet simple to use environment for the simulation modeling process. It supports both general-purpose modeling structures like process interaction and CYCLONE as well as specialized templates for specific construction methods like earth moving and aggregate production (AbouRizk and Mohamed, 2000).

2.10.4. Basic Elements of CYCLONE Simulation Modeling

According to AbouRizk et al. (2016), the basic elements that adjust the resource flow in CYCLONE simulation model are: Queue, Combi, Normal, Function, Counter, and Branch. Their description and rules are discussed below.

1. **Queue element (Queue)**

In CYCLONE, a queue element serves two purposes. First, at the start of the simulation, it initializes model entities; all CYCLONE entities start their life cycles inside queue elements. Second, it gives entities a place to queue up as they wait to be released to Combi elements. The waiting entities are directed to the next element through the connecting arrows in a first-in-first-out (FIFO) order after the requirements for their release have been satisfied.

2. **Combination task (Combi)**

The Combi element is a constraint task, limited by the availability of resources required for the transformation or movement in each individual process (Maria et al., 2020). As long as each previous queue holds at least one entity, the resource or entities may flow into the Combi from those queues. Therefore, the entities wait in their own queues until every queue that comes before the Combi element has one entity in it. Entities are released to every element following the Combi as soon as this condition is satisfied and the specified time period has passed.

3. **Normal task (Normal)**

The Normal element is an unconstrained task because it can manage an infinite number of objects at once. The only prerequisite for routing entities into a Normal element is for them to arrive at the Normal element. When an entity arrives, it is held for the time period determined by the user before it is released.

4. **The Function Element**

The Function element in CYCLONE allows users to control entities that are passing through the model to produce specific effects. Specifically, this element makes it easier to generate and consolidate entities based on the values assigned to its properties. Until the number given in its Divide By property is reached, the Function element holds onto entities that are coming. Then, it generates entities equal to the number specified in its Multiply By property and simultaneously releases them.

5. **The Counter Element**

A Counter element has three main functions in CYCLONE. First, it measures production in a CYCLONE model by recording the time an entity passes through it. Second, it monitors things taking place in a simulation during execution. Third, it terminates the simulation and provides the termination time of the simulation.

6. **The Branch Element**

The Branch element is used to model uncertainty associated with events in the systems being modeled. When an entity enters the element, a random number between 0 and 1 is sampled and utilized to determine whether the entity should be sent out by the top branch or the bottom branch.

7. **The Composite Element**

Every Simphony modeling element, including the CYCLONE template, uses the Composite element. Though it does not participate in the simulation, it serves as a container for sub-models. Therefore, it can be used to enhance the model presentation by creating neat and readable models.

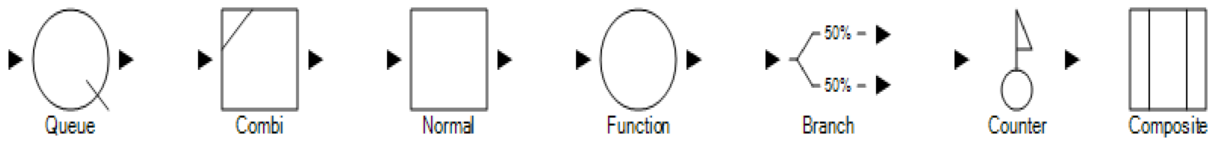

Figure 5: The graphical modeling elements of CYCLONE

The direction of flow for entities or arrows that connect elements is based on the following rules:

- **Queue:** A queue element's input point can be attached to any other element type except another queue. The output point of a Queue element can only be connected to Combi elements.
- **Combi:** Only Queue elements are able to be connected to a Combi element's input point. A Combi element's output point can connect to any other type of element except another Combi.
- **Normal:** The input point of a Normal element may be connected to any type of element except a Queue. The output point of a Normal element may be connected to any type of element except a Combi.
- **Function:** The input point of a Function element may be connected to any type of element except a Queue. The output point of a Function element may be connected to any type of element except a Combi.
- **Branch:** The input point of a Branch element may be connected to any type of element except a Queue. The output points of a Branch element may be connected to any type of element except a Combi.

- **Counter:** The input point of a Counter element may be connected to any type of element except a Queue. The output point of a Counter element may be connected to any type of element except a Combi.

2.11. Summary and Research Gap

The purpose of this literature review was to provide a better understanding of the concept of production theory and the JIT philosophy, as well as the relevance of JIT in increasing productivity and eliminating NVAAs (waste) in the construction industry.

Though there is no commonly accepted theory of production, there are mainly three concepts in the theory of production: transformation, flow, and value. These three concepts of production are thus not alternative, competing theories of production but rather partial and complementary. Each of them focuses on certain aspects of the production phenomenon: the transformation concept focuses on the VA transformation; the flow concept focuses on the NVAAs; and the value generation concept focuses on the control of production from the customer's point of view.

The transformation concept abstracts away physical flows between transformations. It views all activities as value-adding and doesn't consider non-value-adding activities like moving, waiting, and inspecting. Thus, it was challenged mostly by advocates of JIT, who view production as a flow. Toyota was the first company to implement this system, which has since been utilized in procurement activities worldwide, especially within the manufacturing industry.

Even though the JIT philosophy originated in the manufacturing industry, it is applicable in the construction industry with some modifications. Many organizations throughout the world have successfully adopted the Just-In-Time idea in various construction-related applications, such as project management, precast manufacturing, ready-mix concrete production, rebar production, site layout, and so on. The reinforcing bar, which was chosen from among these application areas, was the major focus of this study. Studies showed that implementing JIT in the rebar production and supply system offers several significant advantages, such as reductions in cost, waste, storage space, and cycle time. It also improves productivity.

However, so far, there has been no study conducted on the implementation of the JIT approach for rebar production and delivery in the Ethiopian construction industry. It indicated that there is a gap in this application area. Therefore, this study tried to fill the gap by contributing a better knowledge of JIT rebar production and delivery systems to improve the current site-intensive rebar production practice in the Ethiopian construction industry.

3. RESEARCH METHOD AND METHODOLOGY

3.1. Introduction

Research methods refer to all the methods or techniques that are used by the researcher during the course of studying his research problem. Research methodology is a way to systematically solve the research problem. It may be understood as the science of studying how research is done scientifically. It is necessary for the researcher to know not only the research methods but also the methodology (Kothari, 2004; 2019).

Therefore, this chapter aims to describe the methods and methodology that were used for this study. It includes information about the research design, population, and sampling method. It also describes the data collection methods and analysis methods. Furthermore, the chapter presents the verification and validation of the study.

3.2. Research design

The research design refers to the overall strategy that one may choose to integrate the different components of the study in a coherent and logical way. This was done in order to ensure that the research problem was effectively addressed (Kothari, 2004). Research design can also be considered as plans and procedures for research that span the decisions from broad assumptions to detailed methods of data collection, measurement, and analysis. The basic approaches which are applied in designing research are quantitative, qualitative, and mixed research approaches (Creswell, 2009).

Quantitative research is a means for testing objective theories by examining relationships among variables. Here the variables are described in terms of measured quantities that will be subjected to rigorous quantitative analysis in a formal way. The qualitative approach to research is concerned with subjective assessment for exploring and understanding attitudes, opinions, and behavior. It is non-numerical, descriptive, and uses words. Its aim is to get the meaning and describe the situation. The last one, which is the mixed research approach, is an approach to inquiry that combines or associates both qualitative and quantitative forms (Creswell, 2009; Goundar, 2012; Kothari, 2019).

The research approach that has been used for this research is a mixed research approach, which is a combination of both qualitative and quantitative forms. The selection of this research approach is based on the study objectives and the nature of the research problem, which contains both qualitative and quantitative data. Qualitative data is data that are expressed in the form of words and sentences, whereas quantitative data is data that are measured and analyzed using statistical procedures.

3.2.1. Types of Research

Research can be classified as descriptive, explanatory, and exploratory depending on the specific purpose or objectives that the research tries to address. A descriptive research type tries to describe a certain problem, phenomenon, or situation systematically simply to provide information about the current living condition. Explanatory research aims to clarify why and how there is a relationship between two or more aspects of a situation. Exploratory research is conducted when there are few or no earlier studies to which references can be made for information. It focuses on gaining background information and helps with a better understanding (Goundar, 2012).

Based on the objectives of the research, the research type is both a descriptive and an exploratory research type. Describing the rebar production practices showed it is descriptive research, and investigating the NVAAs from the rebar production flow and analyzing whether or not the implementation of JIT philosophy to rebar production would be advantageous and increases efficiency this showed the exploratory part of the research.

3.2.2. Research Process

The research process consists of a series of actions or steps necessary to effectively carry out research and the desired sequencing of these steps (Kothari, 2004). The chart presented in the below figure shows the research process that has been followed in this research.

Figure 6: Research process flow chart

As it is shown in the above figure, the first step was identifying the research problem, which has been done through an unstructured literature review, observation, and informal discussion with colleagues. Once the problem is formulated, a literature review that is related to the problem was conducted, and after that, the research design or the whole research structure was formulated. Then the relevant data were collected through case studies and analyzed by using descriptive analysis and by a simulation model analysis method. Finally, based on the study findings, conclusions and recommendations were forwarded.

3.3. Research Population and Sampling

3.3.1. Research Population

The collection or group of all the units being studied and to whom the research's conclusions will be applied is referred to as the "population" (Shukla, 2020). Determining which population is truly crucial is significant because a smaller population may be investigated more thoroughly at a fixed cost than a bigger population.

In order to assess the current reinforcement bar production and delivery system the study population should be identified first. Thus, the targeted population for this study was grade one contractors who were legally registered under the building and general contractor’s categories in Addis Ababa. Those contractors are selected because they have experience, effectiveness, and managerial and financial capability that are advantageous to achieving the research objective.

3.3.2. Sampling technique

Sampling is the process of selecting a number of study units from a defined study population. Due to time or resource limitations, it is doubtful that researchers will be able to examine the whole population, so they use the sampling technique to minimize the number of participants (Taherdoost, 2016). Therefore, from those targeted populations, samples were taken by using purposive sampling method. Based the following criteria two contractors were selected.

For case study one:

1. Contractor who executes the rebar production process on-site and doesn’t have working space
2. Contractor who uses the cutting and bending machine to avoid variability from the case study two production

For case study two:

1. Contractor who executes the rebar production process off-site and delivers it on time to project sites only for assembly.
2. Contractor who uses the cutting and bending machine.

3.4. Data Collection method

Based upon the approaches to information gathering, data is categorized into two types: primary data and secondary data. The primary data is that which is collected for the first time and thus has a unique character. Secondary data, on the other hand, is data that has already been collected by someone else and has gone through the statistical process. The primary data could be obtained through the use of questionnaires, interviews, observations, experiments, and surveys. Books, earlier research, journals, internet articles, records, biographies, newspapers, published censuses or other statistical data, etc. are some ways of collecting secondary data (Kothari, 2004; Kumar, 2011; Kabir, 2016). Both primary and secondary data were collected in this study. And the method that was conducted to gather the necessary data for this research was a case study data collection method.

3.4.1. Case Study

A case study is taken as one of the important and reliable methods for legal research. It is a method of studying in-depth rather than breadth, and it focuses on the comprehensive examination of a small number of events or conditions and their interrelationships (Kothari, 2004; Kabir, 2016). Detailed information for the case studies was gathered through direct observation and interview.

- **Direct observation:** In this method, the information is sought by way of the investigator's own direct observation without asking the respondent (Kothari, 2004). The methods used to record the observed information during the site visit are taking photographs and taking field notes. The data included in the field notes of observation will be: the way reinforcement bars are stored and handled; the working condition; overall the rebar production flow; and the general working techniques and duration of activities on both case studies.
- **Interview:** An interview is a way in which the researcher asks questions and gets answers from research participants in verbal form. Greasley (2008) stated that an interview with the process owner can assist in the analysis of system behavior which

may not always be documented. Thus as a supplementary source of information unstructured interviews was carried out to gather relevant information from employees which have good knowledge and experience.

3.5. Data Analysis method

After the data have been collected, it has to be processed and analyzed in accordance with the research approach chosen for the study. According to Kothari (2004), the term "analysis" refers to the computation of certain measures along with searching for patterns of relationships that exist among data groups. The analysis of data requires a number of closely related operations, such as the establishment of categories and the application of these categories to raw data through coding, tabulation, and then drawing statistical inferences.

Data analysis in mixed-method research occurs both within the quantitative (descriptive and inferential numeric analysis) and the qualitative (description and thematic text or image analysis) approaches and often between the two (Creswell, 2009). As the research approach is mixed, both quantitative and qualitative analyses were employed in the data analysis process.

The collected numerical data was analyzed using DES simulation model and the qualitative data obtained from interviews and observation were analyzed using description and thematic text or image analysis. After the analysis, the results were presented in tables and figures based on the result of the study conclusions and recommendations were drawn from the results of the study.
The data collection and analysis for the two case studies were carried out according to the following procedures:

1. Examine the process of rebar production and identify the flow.
2. Activities in the flow were analyzed and classified into value-adding, necessary non value adding, and non-value-adding activities.
3. The non-value activities that could be minimized by changing the work methodology will be identified.
4. The qualitative data obtained from interviews and observations were analyzed using description and thematic text or image analysis.
5. Finally the two rebar production systems were analyzed by using the simulation model to check their productivity.

3.6. Simulation model

Modeling and simulation techniques are becoming an important research method for investigating operational and organizational systems, in addition to their success in physical system design, manufacture, analysis, and improvement (Yin and McKay, 2018). The steps that are followed in simulation modeling development is shown in the below diagram.

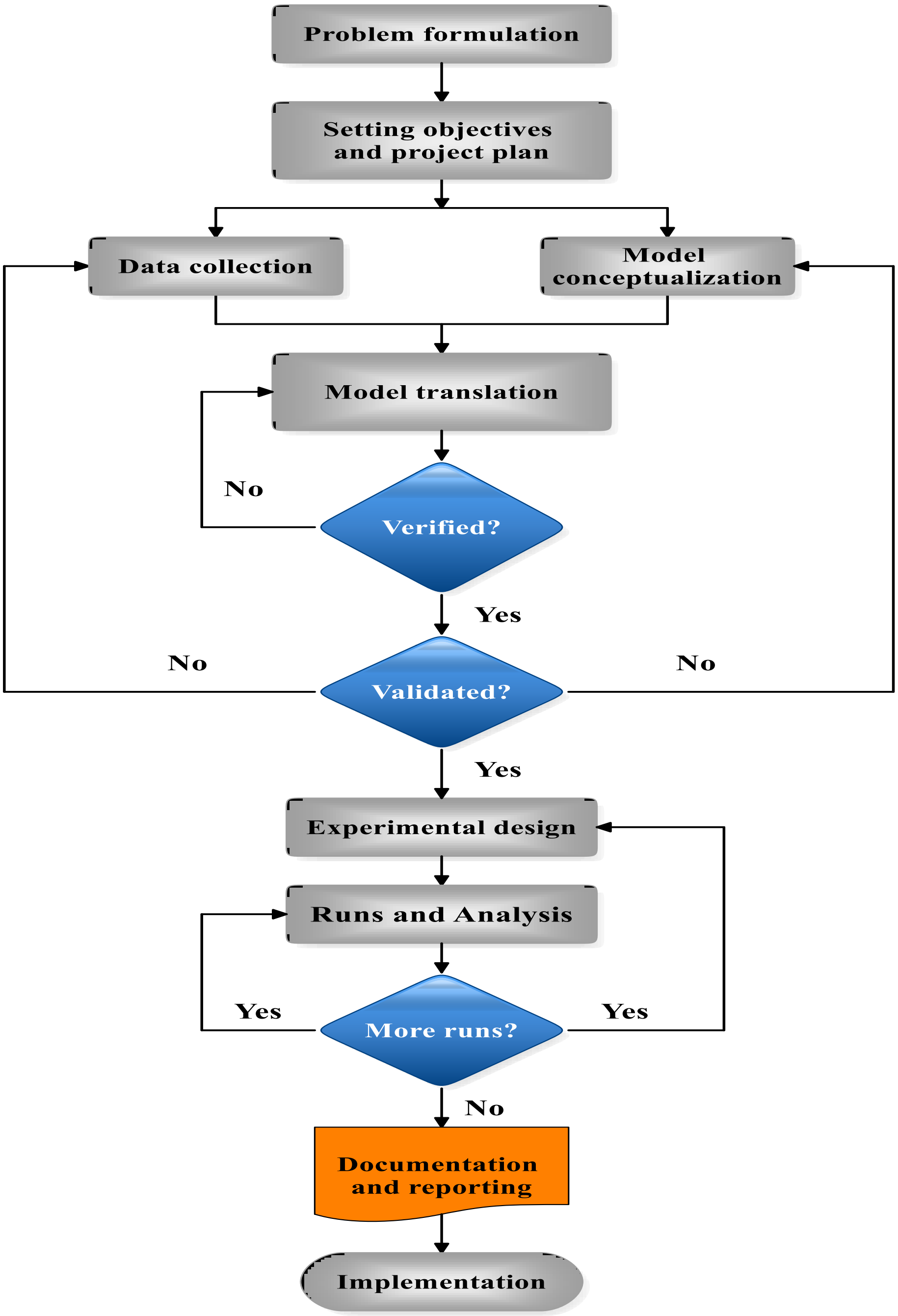

Figure 7: Simulation model development steps (Adapted from: Banks et al., 2014)

In this study, it has been tried to model on-site and off-site reinforcement bar production using discrete event simulation modeling. The aim of developing this simulation model was to compare the performance of the two rebar production systems and identify the effect of non-value-adding activities on production time. To achieve this, the rebar production process was first investigated, then relevant data were collected for each entity through a case study; based on this, the conceptual model was formulated, and finally an appropriate simulation model was developed using the Simphony.NET simulation software.

3.6.1. Input modeling

The development of a valuable model of input data involves four steps, according to Banks et al. (2005, 2014); AbouRizk et al. (2016):

Step 1: Data collection

Data collection is one of the most important and challenging issues in simulation modeling. This often requires considerable time and commitment. Without proper input data collection and analysis, even a model that precisely depicts a process won't produce reliable final output (Greasley, 2008). The main focus of input modeling is on the statistical characteristics of fitting probability distributions to the data distributions that will later be used as the main inputs for the simulation. However, precise and significant input data must be available before the fitting process can begin.

Step 2: Identifying probability distribution

Following the data gathering, a probability distribution will be established that accurately represents the data. Finding a family of distributions to utilize as an input model is a smart strategy for choosing distributions. There are several methods for choosing a distribution to represent a sample of data. The form of the underlying distribution is frequently shown by plotting the frequency distribution or histogram. A family of distributions is selected based on the frequency distribution and basic understanding of the process.

Step 3: Choosing distribution's parameters

Once a family of distributions has been selected, the next step will be determining the distribution parameters that most closely fit the data. In order to achieve this, one can estimate the parameters of the underlying distribution using least squares, maximum likelihood, moment matching, percentile matching, or other methods (AbouRizk et al., 2016).

Step 4: Testing for the goodness of the fit

After estimating a distribution's parameters, one should compare the fitted distribution to the empirical distribution and evaluate the fit's quality to see if the distribution is a good fit (AbouRizk et al., 2016).

Testing for goodness-of-fit is a useful tool for determining whether a proposed input model is appropriate. Statistical goodness-of-fit tests, such as the chi-square test, the Kolmogorov-Smirnov (K-S) test, Q-Q plots, and visual inspection of the quality of the fit between the empirical cumulative distribution function and the fitted theoretical CDF are frequently used to assess the accuracy of the fit.

1. **Pearson's Chi-Squared Test**

The Pearson Chi-Squared test measures the discrepancy between the fitted probability density function and the histogram of the sample. When the discrepancy is large enough, the test rejects the fitted model.

2. **Kolmogorov-Smirnov (K-S) Test**

The Kolmogorov-Smirnov (K-S) test measures the biggest difference between the fitted cumulative distribution function and the empirical distribution function determined by the samples. It is especially useful when there are small sample sizes and no parameters that have been estimated from the data.

3. **Visual Assessment of the Quality of the Fit**

One of the most popular methods for determining how well a theoretical distribution fits an empirical one is to evaluate its quality visually. It is typically done in combination with statistical tests to ensure the accuracy of the test results. In general, the approach consists of comparing how closely the fitted CDF matches the empirical CDF by plotting both the empirical and fitted CDFs on the same plot.

3.6.2. Output Analysis

Analyzing the data produced by a simulation is known as "output analysis," and its goal is to evaluate the performance of several alternative system strategies or to anticipate how well the system will operate (Banks et al., 2014).

The simulation experiment can start after a suitable input analysis of the duration data for the process under study. One simulation run is sufficient to establish the result for simulation models when every element is deterministic. On the other hand, a stochastic simulation will not yield the same results when performed repeatedly with different random seeds. To verify that the system under examination is accurately depicted, it is necessary to do many runs with different seeds for the random-number-generating streams (AbouRizk et al., 2016).

3.6.3. Model Verification and Validation

Simulation models are being employed more often to help people make decisions and find solutions. The question of whether a model and its findings are "accurate" is one that should worry not just the creators and users of these models but also the decision-makers who use the information gained from these models' results and the people impacted by such decisions. Model verification and validation are used to overcome this issue (Sargent, 2007).

3.6.3.1. Model Verification

Model verification is a process of demonstrating that the model is accurately changed from one form to another. It focuses on accurately developing the model. In model verification, the correctness of converting a problem statement into a model specification or a model illustration from a flowchart into an executable computer program is assessed (Sargent, 2000; Banks et al., 2014).

3.6.3.2. Model Validation

One of the challenging things in the simulation modeling process is trying to figure out whether a simulation model is a correct depiction of the actual system being investigated, which means whether the model is valid (Law A., 2013). Model validation confirms if the model acts accurately and in accordance with the goals of modeling and simulation within the scope of its applicability. It concentrates on developing the right model (Sargent, 2000).

4. ANALYSIS AND DISCUSSION

4.1. Introduction

This chapter presents the data analysis along with a discussion on the results of the analysis according to the study objectives. As it was discussed in the previous sections, the construction industry faces some challenges, and one of the challenges encountered in construction is due to reinforcement bar work. Mostly reinforcement bar production in construction sites is challenged by space constraints, workmanship, wrong quantity estimation, activities that do not add value to the work, and other factors. To gain a clear understanding of the problem and to achieve the study objectives, a case study data collection method was conducted.

The case study focused on two contractors. These contractors were selected based on their rebar production approaches. The first one uses the on-site rebar production method, while the other contractor uses off-site rebar production with JIT delivery. Through direct observation and unstructured interviews, the necessary data were collected and analyzed in both case studies. In general, this chapter provides an overview of the two rebar production and delivery systems, as well as an analysis of their production flow and categories, simulation model analysis, case study result discussion, and JIT implementation challenges.

4.2. Case Study One

4.2.1. Overview of the Case Study contractor

The contractor selected for this case study was a grade 1 General Contractor (GC1) who was constructing 2B+G+20 apartment buildings for a real estate company, and the production system used on this project site was on-site reinforcement bar production. The reinforcement bars were transported from the factory to the project site with a standard length of 12 meters, and the overall rebar production takes place on site. The site observations and overall results of the collected data about the rebar production at this site will be described in the following sections.

4.2.2. Storage and Handling of Rebar

Reinforcement bars should be handled and stored properly; they should be arranged in such a way that the various sizes and lengths can be quickly and easily identified (IS: 2502-1963). In this case study site, the client stored the reinforcement bars on the ground, covering a huge area for a long period of time. In contrast, the contractor doesn't have enough storage space, so he stored the reinforcement bars on the pathway. The excess cut and bent rebars due to overproduction were also improperly stored. Different diameter bars were stored together and mixed, which increased the non-value-added activities while identifying the needed rebar diameter. Additionally, the reinforcement bars that are stored on the pathway create bad conditions for workers to transport the reinforcement bars from one place to another safely and comfortably. Besides, small diameter rebars will be damaged or deformed while they walk on them.

Figure 8: Improper rebar storage on the pathway

4.2.3. Method of rebar cutting and bending

According to several scholars, rebar cutting and bending is one of the most important activities in construction work. Thus, special care should be taken to ensure that the rebar is cut and bent in accordance with the bar bending schedule as well as in an optimized way.

At this project site, the rebar cutting order was prepared in the office using optimization software and given to the rebar production foreman, as shown in the below figure. The bar benders then produced the rebars based on this cutting order. The process of cutting and bending reinforcement bars was done by using a cutting and bending machine. There are 3 bending and 3 cutting machines. The two cutting machines cut rebar with diameters less than 14 and one with diameters greater than 14.

Length	Material	Quantity	Label	Waste	Graphic: 1D
12	Rebar 14	2		0.36	3.88 / 3.88 / 3.88
12	Rebar 14	37		0.75	5.02 / 3.88 / 2.35
12	Rebar 14	112		1.54	5.23 / 5.23
12	Rebar 14	15		1.4	5.3 / 5.3
12	Rebar 14	206		1.24	5.38 / 5.38
12	Rebar 14	270		1.22	5.39 / 5.39
12	Rebar 14	6		0.1	5.4 / 3.25 / 3.25
12	Rebar 14	3		0.8	5.6 / 5.6
12	Rebar 14	37		0.04	5.98 / 5.98
12	Rebar 14	75		0.07	6.33 / 5.6

Figure 9: Sample of optimized rebar cutting order

4.2.4. Site Lay Out

According to Sanadet et al. (2008), a good site layout is fundamental to ensuring the safety of the working environment and effective operations. Proper site layout planning is required to remove unnecessary inventories that take up space and use the site space efficiently.

As can be seen from the storage and production area layout, the open storage is a place where the client stores bundles of reinforcement bars that would be used for all the blocks. Most of the project site space was covered by this rebar storage, which confined the site. This led to poor rebar handling and unnecessary transportation.

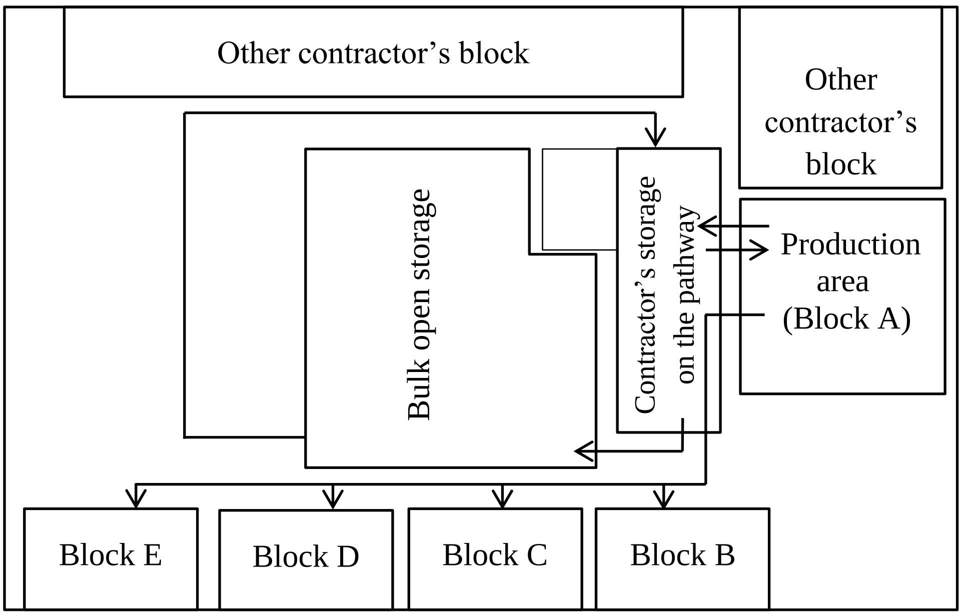

Figure 10: Storage and production area layout

Despite the fact that the rebar inventory takes up a huge amount of space on the site, the contractor doesn't have enough space for storage and production. Due to this, the rebar production takes place in the basement of Block A. After production, the rebars will be transported to the fixing blocks. Sometimes the production process was challenging because of the columns and shear walls inside the basement, especially when bending long bars.

4.2.5. Working condition and safety

According to Abrey and Smallwood (2014), site working conditions are one of the factors that affect productivity in the construction industry. Poor working conditions decrease productivity and endanger workers' safety.

The working environment and the safety of workers at this project site were not good. As shown in the below figure, workers were transporting the reinforcement bars by walking on stored rebar without wearing personal protective equipment (PPE). As was discussed previously, the production process takes place in the basement of the building, which is under construction. Thus, it is not safe because materials might fall while they are transporting the rebar from outside to inside and vice versa. In general, working in this condition decreased their productivity, morale, and motivation.

Figure 11: Laborers working on uneven condition

4.2.6. On-site rebar production on the view of Ohno's 7 wastes

The current status of the on-site reinforcement bar production according to the seven Ohno's wastes is described as follows:

1. Overproduction

According to Ohno (1988), overproduction is the practice of producing more or earlier than necessary. On this site, the production system they follow is the push system, which is one of the causes of overproduction. The reinforcement bars were produced as much as they could in a day, not only for the needed work quantity. Since they left the remaining rebar on the cutting area, there would not be enough space to store the next rebar production. Due to that, they store the cut bars in any available free space without considering the location of the bending machine. This results in extra transportation of reinforcement bar and the searching and identification of rebar, which are both non-value-added activities.

Figure 12: Rebar overproduction

2. Transportation

As it was described in the previous sections, the reinforcement bars are stored on the pathway while the production is inside the basement of the building. This increased non-value-adding activities, such as unnecessary material transportation and the movement of workers from place to place. Additionally, the fixing area is a little far away from the production area, and the transportation was carried out by laborers. This requires a lot of workers and results in a waste of time and energy.

The flow of transportation shows that there are four transportation cycles: transportation of rebar (1) from storage to the straightening area; (2) from the straightening area to cutting; (3) from cutting to bending; and (4) from bending to fixing. All these transportation cycles take time and resources.

Table 3: Flow of transportation

Storage	⇄	Straightening area
Straightening	⇄	Cutting
Cutting	⇄	Bending
Bending	⇄	Fixing

Figure 13: Rebar transportation

3. Over processing

One of the common practices at construction sites that does not add any value but increases the number of activities is straightening. Straightening is the process of making the reinforcement bar straight and suitable for cutting. Basically, the reinforcement bars are fabricated straight, but in order to deliver them to the site easily, they will be bent. After the rebars are dumped at the site, they will be straightened again in the straightening process. This activity takes space, resources, and time but does not add value, so it should be removed from the production process by changing the current practices.

Figure 14: Rebar Straightening

4. **Inventories**

Ohno (1988) claims that having large or unnecessary inventories results in waste of material due to deterioration, poor stock conditions on site, theft, vandalism, and financial losses due to capital being tied up.

On this site, there was a lot of rebar stock that had been stored for more than three months. This caused poor working conditions, congestion, and increased holding costs. In general, the space occupied by this rebar inventory is large, which prevents them from properly utilizing the site space.

Figure 15: rebar inventory on the site

5. Defect

One of the causes of rework in rebar production is straightening defects. During the time of straightening, some rebars didn't straighten properly, which affected the bending activities in the production flow. The bar bender stops the bending work and makes a correction for this defect.

Figure 16: Straightening defect

6. Movement

Workers made unnecessary movements to do their job due to a lack of space and a poorly organized working environment. These unnecessary movements increased the rebar production time and could be reduced by proper site layout and organization. If there is no working space on site, separating the production area from the site will be another way to reduce this unnecessary movement.

7. Waiting time

In this case study, this type of waste is related to idle time caused by a crew's lack of a working area at the same time. During transportation, one crew may wait for the other until they pass. Furthermore, due to poor working conditions and a lack of motivation, workers stop working, take breaks, and talk to each other in the middle of the work.

4.2.7. Rebar wastage

As was described in the literature review, different factors, including poor rebar handling, inefficient cutting, unnecessary inventories, design changes, and so on, contribute to the waste of reinforcement bars. In this case study, the trim loss in the cutting process reduced by computing favorable cutting patterns using optimization software. However, there is wastage due to improper reinforcement bar handling and rebar leftovers. Sometimes, after computing optimized cutting patterns, depending on the required lengths there will be leftover rebar that could be re-used. But due to improper waste management, the leftover rebars might not be used again and will remain as waste.

Additionally, the cut and bent rebars were transported to the fixing area in more than the needed quantity, and after fixing, the remaining rebar will be left there. While transporting the cut and bent rebar to the fixing area, laborers dump and store the rebars randomly without sorting them by type. At this time, the rebar will be mixed up, and some rebars will be missed. The missed rebar will then be produced again, resulting in yet another source of rebar waste.

Based on the optimized cutting order the utilized amount and the leftover rebar/waste are shown in the below table. In this case study the waste percentage of rebar diameter 12 and 14 are greater than the other rebar diameter this is due to the leftover rebar length were not mostly reused for that project site.

Table 4: Rebar waste percentage

	Total Kg	**Utilized (kg)**	**Waste(Kg)**
12	6105.89	5724.71	381.17
		93.76%	6.24%
14	21112.08	18799.39	2312.69
		89.05%	10.95%
16	4266.00	4203.46	62.54
		98.53%	1.47%
20	8921.64	8828.55	93.09
		98.96%	1.04%

4.3. Case Study Two

4.3.1. Overview of the Case Study Project/contractor

The contractor selected for this case study was a grade 1 General Contractor (GC1) who was constructing different projects, including buildings, road overpasses, and a concrete retaining wall. The rebar production system the contractor adopted is an off-site production system. The reinforcement bars were produced off-site at the central rebar processing plant and delivered on time to project sites only for assembly.

4.3.2. Storage and Handling of Rebar

In this rebar production area; reinforcement bars are stored in a proper and organized way. Each rebar diameter has its own proper place so that they can be identified easily without unnecessary activity. Furthermore, the reinforcement bars were stored on a raised masonry platform, as shown in the figure. On the other hand, the project sites are free from storage and production of reinforcement bars since the reinforcement bars are delivered to the site only for assembly.

Figure 17: Rebar storage on masonry

Storage for left-over rebar was also provided, and they manage it properly. The rebars that are stored in the minimize storage were left over from the current work and will be used again for the next work, while the rebars that are stored in the scrap storage are waste and will not be used again. Thus, due to proper rebar storage and management, the working area is good and clean.

Figure 18: Scrap and Minimize storage

4.3.3. Method of rebar cutting and bending

In this case study, the project sites prepared the rebar cutting order using optimization software and sent their orders with shop drawings to central rebar production. The rebar production is carried out in the central rebar processing area and delivered to job sites just in time. The process of cutting and bending reinforcement in the central rebar production area takes place using cutting and bending machines. There are 3 bending and 2 cutting machines. Following the completion of the cutting and bending work, the cut and bent rebars are stored in the correct types, sizes, and lengths to simplify the transport process.

Figure 19: Off-site rebar cutting and bending

The sample optimized cutting order that the project sites prepared and sent to the central rebar production is shown in the below figure.

Length	Material	Quantity	Label	Waste	Graphic: 1D
12	Dia -12	20	FB	0	9 / 3 S13 / S4*
12	Dia -12	37	FB	0.03	3.67 / 3.67 / 3.67 / 0.9 / 0.0 G5-2 / G5-2 / G5-2 / P3
12	Dia -12	6	FB	0.02	7.77 / 3 / 1.2 / 0.0 S7 / S4* / G7
12	Dia -12	77	FB	0.04	3.67 / 3.57 / 3.57 / 1.1 / 0.0 G5-2 / G5-4 / G5-4 / G8
12	Dia -12	4	FB	0.04	3.67 / 3.57 / 3.57 / 1.1 / 0.0 G5-2 / G5-3 / G5-4 / G8
12	Dia -12	4	FB	0.04	3.67 / 3.57 / 3.57 / 1.1 / 0.0 G5-2 / G5-4 / G5-3 / G8
12	Dia -12	31	FB	0.01	3.87 / 3.57 / 2.8 / 1.15 / 0 / 0.0 G5-1 / G5-3 / P1 / G8 / D3-1
12	Dia -12	16	FB	0.01	3.87 / 3.57 / 2.8 / 1.15 / 0 / 0.0 G5-1 / G5-4 / P1 / G8 / D3-1
12	Dia -12	8	FB	0.01	5.93 / 2.8 / 1.15 / 1.15 / 0.9 / 0.0 S6a* / P1 / G8 / G8 / P3

Figure 20: Sample of optimized rebar cutting order

4.3.4. Site Lay Out

In this production site, the reinforcement bar storage is near the cutting and bending area, so there is not much material and human movement and transportation. The reinforcement bars, which have close rebar diameters, were not stored next to each other since they are similar. Workers may select the incorrect diameter by mistake. To avoid this confusion, they arrange the storage properly so workers can identify it easily.

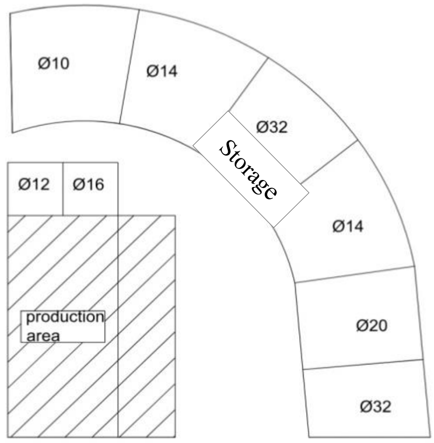

Figure 21: Rebar storage and production layout

4.3.5. Working Condition and Safety

The working conditions and safety at this central rebar production area are comparatively good. Workers wear some personal protective equipment while doing their job. And due to the clean and organized area, workers were free to do their jobs. Furthermore, the project sites were free from risk due to the production of rebar. A sample of the safety cautions posted in the production area is shown below.

Figure 22: Posted Safety Cautions

4.3.6. Off-site rebar production on the view of Ohno's 7 wastes

The current status of the off-site reinforcement bar production according to the seven Ohno's wastes is described as follows:

1. Overproduction

According to the principle of JIT, the production system they follow is a pull system. The reinforcement bars were produced based on demand from the project site and when they were needed, and then all the produced rebar was checked and delivered to the site. Thus, the pull production system prevents overproduction.

2. Transportation

The reinforcement bars are stored near the production area, so the laborers didn't have to travel as far to do their work. The main transportation is the transportation of reinforcement bar from central production to project sites; others are small internal transportation. Based on their storage location, some rebars are transported by crane near the straightening and cutting area, which minimizes transportation cycle time. In general, the production site arrangement reduces unnecessary transportation. Since the production takes place at the central reinforcement bar processing plant, the project sites are free from unnecessary transportation.

3. Over processing

In this case study, large-diameter rebars are delivered straight to the production area by using a low-bed truck, while small-diameter rebars are delivered bent. These bent bars will be straightened in the production area. This adds some steps to the process.

4. Inventories

The reinforcement bars are purchased for all project sites based on the quantity needed, and they won't be stored for a long period of time. Since these rebars are stored on the provided space in the production area, there is no rebar inventory at the project sites.

5. Defect

In order to reduce rework, rebars are checked to see if they have defects or not before they are delivered to the site. Sometimes a straightening defect will occur, and they will make corrections at the time of bending.

6. Movement

The production area is clean and organized, the storage area is near the production area, and the positions of the cutting and bending machines are suitable for work. Thus, unnecessary movements are greatly reduced.

7. Waiting time

In this case study, this type of waste is related to waiting for an order or instruction. If there is no order, they will be idle. Sometimes it is related to idle time due to taking rests and talking to each other in the middle of the work.

4.3.7. Rebar wastage

In this case study, the rebar cutting waste was minimized by computing optimized cutting patterns using optimization software. After computing the best cutting pattern, there might be remaining waste (usable leftovers). These leftovers were also used for the upcoming demands in different arrangements instead of cutting standard bars. In the cutting process, priority was always given to leftovers, which were stored and managed properly in the production area. The remaining rebar from one project site will be used for the other project site, and there is proper organization and cleanliness at the site. Because of these reasons, rebar waste in this production area has significantly decreased.

Table 5: Rebar waste percentage

	Total Kg	Utilized (kg)	Waste(Kg)
12	5903.424	5873.30	30.121
		99.49%	0.51%
14	11746.68	11594.66	152.02
		98.71%	1.29%
16	12930.72	12609.02	321.70
		97.51%	2.49%
20	16539.12	16097.83	441.29
		97.33%	2.67%

4.4. Rebar Production Flow Analysis

Eliminating or minimizing the non-value-adding activities from the rebar production flow was one of the objectives of the study. To attain this objective, first observing and understanding each activity in the rebar production process was required. After observing the production process, non-value-adding activities were identified and analyzed.

Several scholars agreed with the classification of activities into value adding (VA), necessary but non-value adding (NNVA), and non-value adding (NVA)/waste (Womack and Jones, 2003; Diekmann et al., 2004; Eswaramurthi and Mohanram, 2013). Based on this classification, the rebar production and delivery activities are categorized.

4.4.1. On-site rebar production flow

The production process began with manually carrying the reinforcement bars from storage to the straightening area. The rebar was then straightened using a hand tool, locally called a bega. After the reinforcement bars are straightened, they will be transported to the cutting area. The rebar cutting crew then received and cut the reinforcement bars, which were then randomly stored on free available space. Next, the cut bars were delivered to the bending area, where they were bent by the rebar bending crew. After this, the bent steel bars were stored until they were delivered to the fixing area. Finally, the transport crew transported the bent bars to the fixing area by carrying them on their shoulders.

All of the activities discussed above were carried out on site, required a lot of workers, and took time to complete. Activities that do not add any value to the final product are identified as non-value-adding and should be minimized. Activities that are supportive and necessary but do not add value are categorized as necessary but non-value-adding, while activities that create value are categorized as value-adding, as shown in the following table.

Table 6: Main activities on site rebar work and their categories

No.	Activity	Activity Category
1	Taking order	NNVA
2	Transporting from storage to straightening area	NVA
3	Rebar positioning for straightening	NVA
4	Straightening	NVA
5	Transporting after straightening to production area	NNVA

No.	Activity	Activity Category
6	Measure and mark at the cutting point	NNVA
7	Put and set the rebar to the cutting point	NNVA
8	Cutting process	VA
9	Transporting and store randomly on free available space	NVA
10	Measure and mark at the bending point	NNVA
11	Transporting from store to bending area	NVA
12	Put and set the rebar to the bending point	NNVA
13	Bending	VA
14	Rotating the rebar bending sides	NNVA
15	Storing the bent bars	NNVA
16	Rework due to defect in the time of straightening	NVA
17	Select and carry the rebar	NNVA
18	Transport to the fixing area	NNVA
19	Dumping the rebar in the fixing area	NNVA

4.4.2. Off-site rebar production flow

The production process starts when the project sites send their demand to the central rebar processing plant. The reinforcement bars are only produced when there is an order from the project sites. Then the production began with straightening activity. The crane moved the bundle of rebar near the straightening area according to their storage location, and then an average of three laborers picked it up and gave it to the person who is doing the straightening work. Following rebar straightening, the rebar cutting crew will transport, cut, and store the cut bar at the bending machine, where the bending crew will bend the bars and store them according to their size and type. The project site engineer will check the quantity of the rebar before transporting it to the site, and after that, the rebars will be tied together to prepare them for transportation. Depending on the number of rebars, the loading activity will be carried out by a half crane or by humans. Finally, they will be delivered to the project site.

Since all the rebar production is carried out in the production area, there are no non-value-added activities performed on the project site due to the rebar production.

Table 7: Main activities on off-site rebar work and their categories

No.	Activity	Activity Category
1	Taking order	NNVA
2	Transporting from storage to straightening area	NVA
3	Rebar positioning for straightening	NVA
4	Straightening	NVA
5	Measure and mark at the cutting point	NNVA
6	Transport and put to the cutting machines	NNVA
7	Cutting process	VA
8	Transporting and store to bending machine	NNVA
9	Measure and mark at the bending point	NNVA
10	Put and set the rebar to the bending point	NNVA
11	Bending	VA
12	Rotating the rebar bending sides	NNVA
13	Storing the bent bars	NNVA
14	Checking and tying the rebars	NNVA
15	Loading the rebar in the truck	NNVA
16	Transport to the fixing site	NNVA
17	Dumping the rebar in the fixing sites	NNVA

Having looked at the main activities involved in the production of rebar, in both cases, most of the activities fall under the third category, which is necessary but not value-adding (NNVA). The main non-value adding activity is straightening. The straightening process can be immediately eliminated, and when straightening activity is eliminated, related activities like transport and rework are also removed from the process. In order to eliminate the straightening activity, consider using low-bed trucks for transporting straight rebar or improving the production methodology, like producing in factories. Unnecessary internal transportation could also be minimized by proper site layout, making the location of storage near the production area. On the other hand, proper planning is essential in order to reduce sudden orders in the middle of the work.

4.5. Simulation model using Simphony

The objective of developing simulation models is to simulate and compare the two rebar production systems, which are on-site and off-site. The simulation model takes into consideration the various activities and resources that are part of the reinforcement bar production processes.

In the production of reinforcement bar, there are a lot of scenarios. Due to the design and complexity of construction projects, the required diameter, length, and shape of rebar at project sites vary. Therefore, when designing a simulation model, it is difficult to consider all of the scenarios. For this study, to compare the two production systems, four models were developed with different scenarios based on their overall production.

The first step in model building consists of observing and understanding the real systems and the interactions among their various components, as well as collecting data on their behavior.

4.5.1. Data Collection

All relevant data for the development of the reinforcement bar production simulation model was gathered through direct observation and unstructured interviews from both case studies. Real-time data were collected at the time of production and include the following:

- **Process layout:** A flow diagram of the production process that shows the sequence of each activity that can be used to develop the conceptual model
- **Process time:** Durations for all activities in the production processes (e.g., cutting time, transporting time, bending time, straightening time, etc.)
- **Available resources:** Manpower needed for each activity; available cutting and bending machines
- **Overall production type:** The rebar diameter, length, shape produced in both case studies.
- **Cutting and bending capacity:** The average amount of rebar that the cutting machine can cut and the bending machine can bend at once

Table 8: Available resources and machine capacity at a time

No.	Resource	On-site	Off-site	Average machine capacity at a time (bars)			
				Ø8, 10	Ø12, 14	Ø16, 20	Ø24, 32
1	Cutting machines	3	2	5	4	2	1
2	Bending machines	3	3	5	4	2	1
3	Manpower	20 - 25	8 - 12				

Table 9: Rebar workers crew on the site vs. off-site production area

On-Site			Off-Site		
Crew	Activity	Average No of workers	Crew	Activity	Average No of workers
1	Transport for storage	3	1	Transport from storage	3
2	Straightening	1	2	Straightening	1
3	Transport for cutting	4	3	Cutting	4
4	Cutting	4	4	Bending	4
5	Transport for bending	2			
6	Bending	4			
7	Transport to fixing	6			
	Total	24		Total	12

4.5.2. Process Mapping

A process map, also known as a conceptual model, should be created in accordance with the scope and level of detail of the project specification. A key component of this activity is creating a flow diagram, which is a diagrammatic depiction of the process. This is important because it demonstrates how different process steps interact with one another and provides a framework for comprehending and describing processes (Greasley, 2008).

Reinforcement bar production is a repetitive process that involves four main steps: transporting, straightening, cutting, and bending. As a result, a flow diagram based on the actual rebar production operations in both case studies has been created to provide a better understanding of the details of the rebar production process.

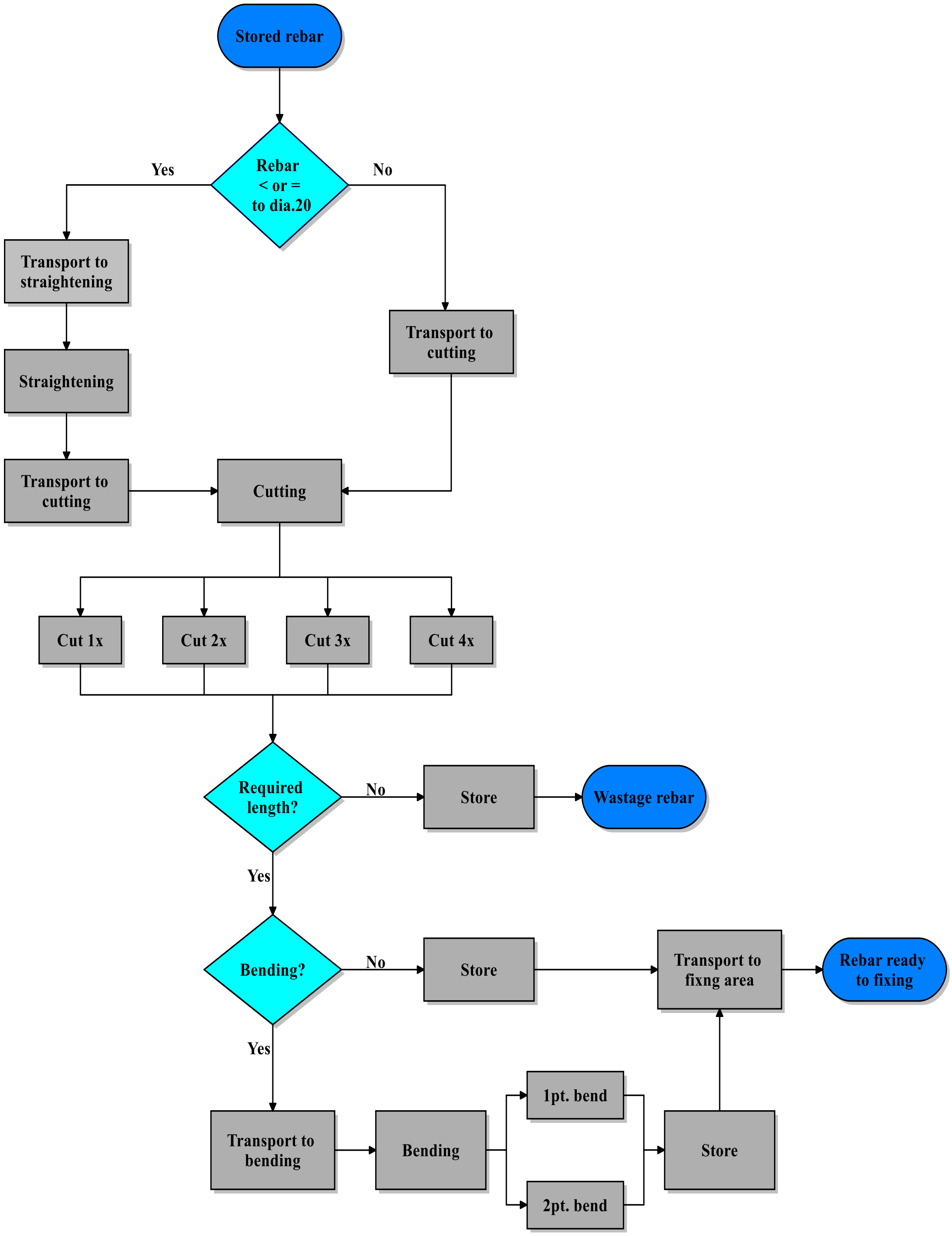

Figure 23: Flow diagram of the on-site reinforcement bar production process

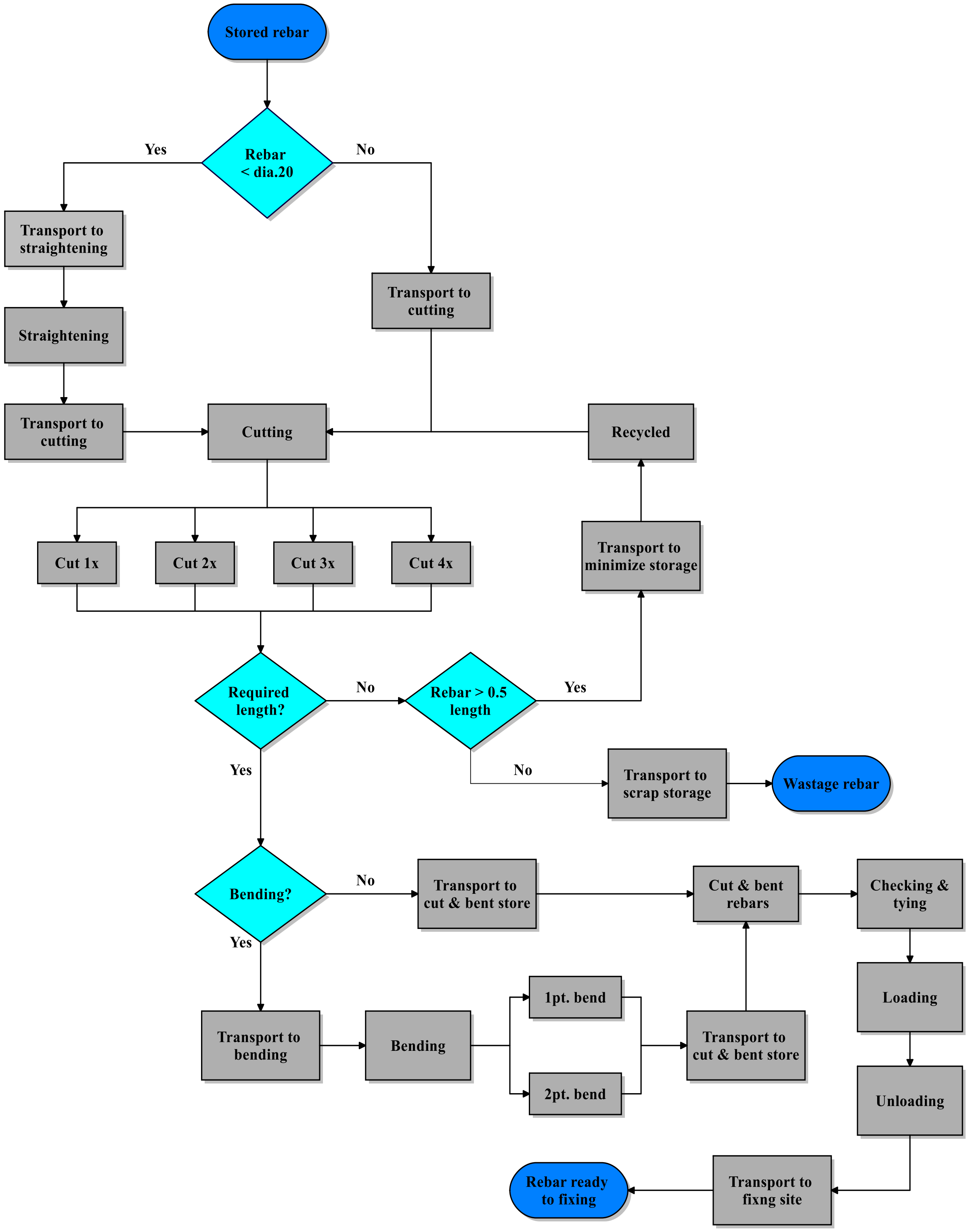

Figure 24 : Flow diagram of the off-site reinforcement bar production process

4.5.3. Input Data Analysis

4.5.3.1. Choosing distribution's parameters

Following the data collection, the next step was to select the distribution parameter that best fit the collected duration data. There are many distribution parameter estimators, but the Simphony simulation software computes the following: least squares, maximum likelihood, and moment matching. According to Abourisik (2016), different parameter estimation techniques give different parameter estimates, so he recommends selecting the parameters that produce the best fit.

According to Law (2011), the maximal likelihood estimation technique is preferable to others such as least-squares and the method of moments for three reasons: (1) the fundamental concept of maximum-likelihood estimation has a strong intuitive appeal; (2) the use of MLEs turns out to be crucial in validating the chi-square goodness-of-fit test; and (3) MLEs offer a number of desirable qualities that are frequently not possessed by alternative methods of estimation. The basis for MLEs is most easily understood in the discrete case. Choi and Kang (2013) also stated that the maximum likelihood estimator (MLE) is the preferred choice for parameter estimation.

4.5.3.2. Goodness of fit

According to Low (2007), the K-S tests are more powerful than chi-square tests against many alternative distributions. The K-S tests do not require grouping the data in any way, so no information is lost; this also eliminates the troublesome problem of interval specification. Another advantage of K-S tests is that they are valid (exactly) for any sample size n (in the all-parameters-known case), whereas chi-square tests are valid only in an asymptotic sense.

Therefore, for this study, the distribution parameter estimation method used is maximum likelihood, while the Kolmogorov-Smirnov (K-S) test is used to test the goodness of the fit. In addition, visual inspection of the input modeling is used to check the goodness of fit for theoretical vs. empirical distributions. The fitted distribution parameter for each activity and the graph that shows the empirical vs. theoretical distribution are shown in the below tables and figures.

Table 10: Fitted Distributions for corresponding activities (On-site rebar production)

No.	Activity	Fitted distribution	Duration
1	Transport from storage	Beta	Beta (1.241, 0.888, 0.57, 0.71)
2	Return to the storage	Beta	Beta(1.082, 1.022, 0.425, 0.512)
3	Straightening	Triangular	Triangular (0.180, 0.436, 0.271)
4	Transport to cutting	Triangular	Triangular (1.054, 1.841, 1.229)
5	Return to the straightening area	Beta	Beta(0.845, 1.368, 0.55, 0.97)
6	3x cut	Beta	Beta (0.985, 1.305, 1.25, 1.51)
7	4x cut	Beta	Beta(0.919, 1.262, 1.63, 2.1)
8	Store the cut bars	Beta	Beta (1.02, 2.05, 0.203, 0.324)
9	Transport rebar to bending	Beta	Beta (1.091, 0.914, 0.8, 1.1)
10	Return	Beta	Beta (0.722, 0.804, 0.406, 0.495)
11	1pt. Bend	Beta	Beta (1.724, 1.566, 0.18, 0.33)
12	Store/ make it ready to transport	Beta	Beta (1.782, 1.734, 0.209, 0.332)

Table 11: Fitted Distributions for corresponding activities (Off-site rebar production)

No.	Activity	Fitted distribution	Duration
1	Transport from storage	Beta	Beta (1.38, 0.71, 0.449, 0.674)
2	Return to the storage	Beta	Beta (0.736, 0.988, 0.246, 0.356)
3	Straightening	Triangular	Triangular (0.144, 0.377, 0.314)
4	Transport to cutting	Beta	Beta (0.805, 1.254, 0.486, 0.72)
5	3x cut	Triangular	Triangular (1.196, 1.702, 1.529)
6	4x cut	Beta	Beta (1.292, 1.804, 1.56, 2.01)
7	Store to bending area	Beta	Beta (0.885, 0.922, 0.171, 0.246)
8	Return to the straightening area	Beta	Beta (1.095, 1.239, 0.288, 0.46)
9	1pt. Bend	Beta	Beta (0.746, 0.760, 0.204, 0.327)
10	Store/ make it ready to transport	Triangular	Triangular (0.117, 0.272, 0.130)

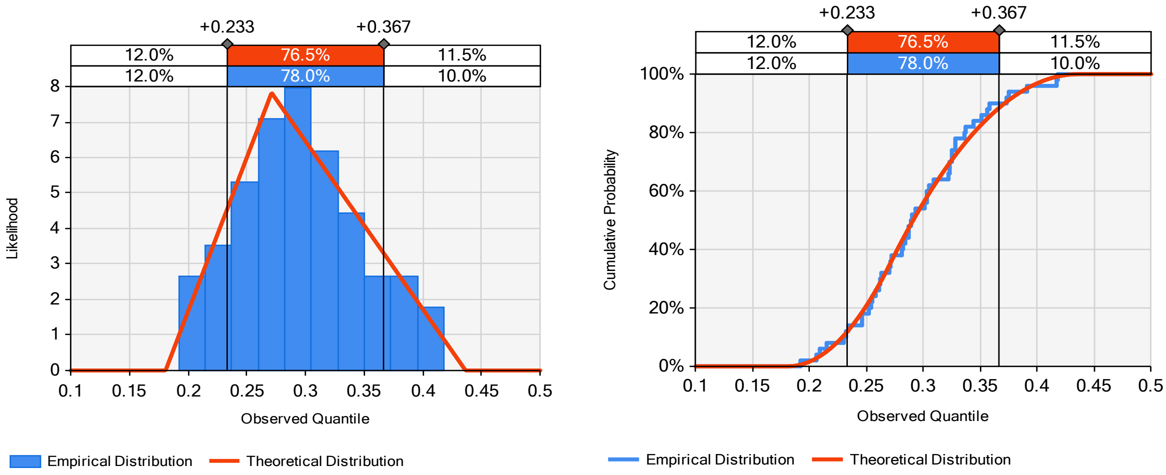

Figure 25: Empirical vs. Theoretical distribution for transporting activity (On-site)

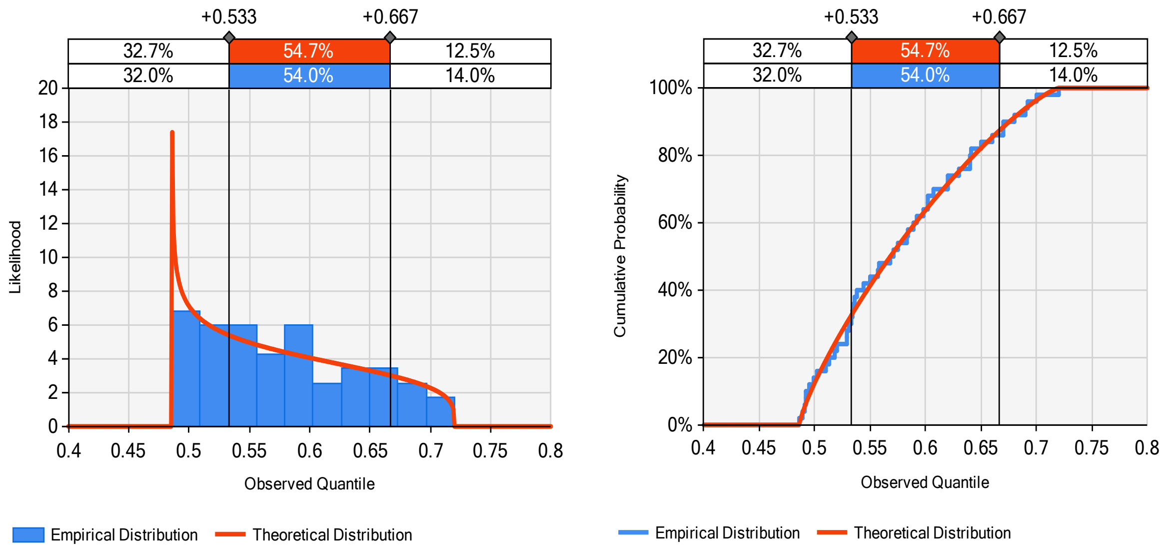

Figure 26: Empirical vs. Theoretical distribution for transporting activity

4.5.4. Simulation Model and Output Analysis

The four simulation models were developed with different scenarios for both case studies, as shown in the below table. For each scenario, the input rebar quantity was 2500 bars of standard 12m rebar. To obtain satisfactory results for analysis, the Simphony simulation software runs a 1000-observation count for each scenario. After the simulation run is completed, the software generates a statistical report that shows the simulation termination time, production rate, average waiting times, inter-arrival time, and others. To determine the production performance of the two-rebar production system, mainly the final simulation time to finish the overall process, the production rate, and the average waiting time were selected.

Table 12: Simulation model scenarios for both case studies

Scenario	Diameter	No of cut (%)		Rebar type (%)		Bending type
				Bent bars	Straight bars	
1	**12**	3x	55	53	47	**1pt bent**
		4x	45	61	39	
2	**14**	2x	64	75	25	**1pt bent**
		3x	36	56	44	
3	**16**	1x	30		100	
		2x	55	24	76	**2pt bent**
		3x	15	51	49	
4	**20**	2x		2	98	**2pt bent**

4.5.4.1. Case study one (On-site rebar production)

Scenario 1: Analysis of simulation model for diameter 12 rebar production

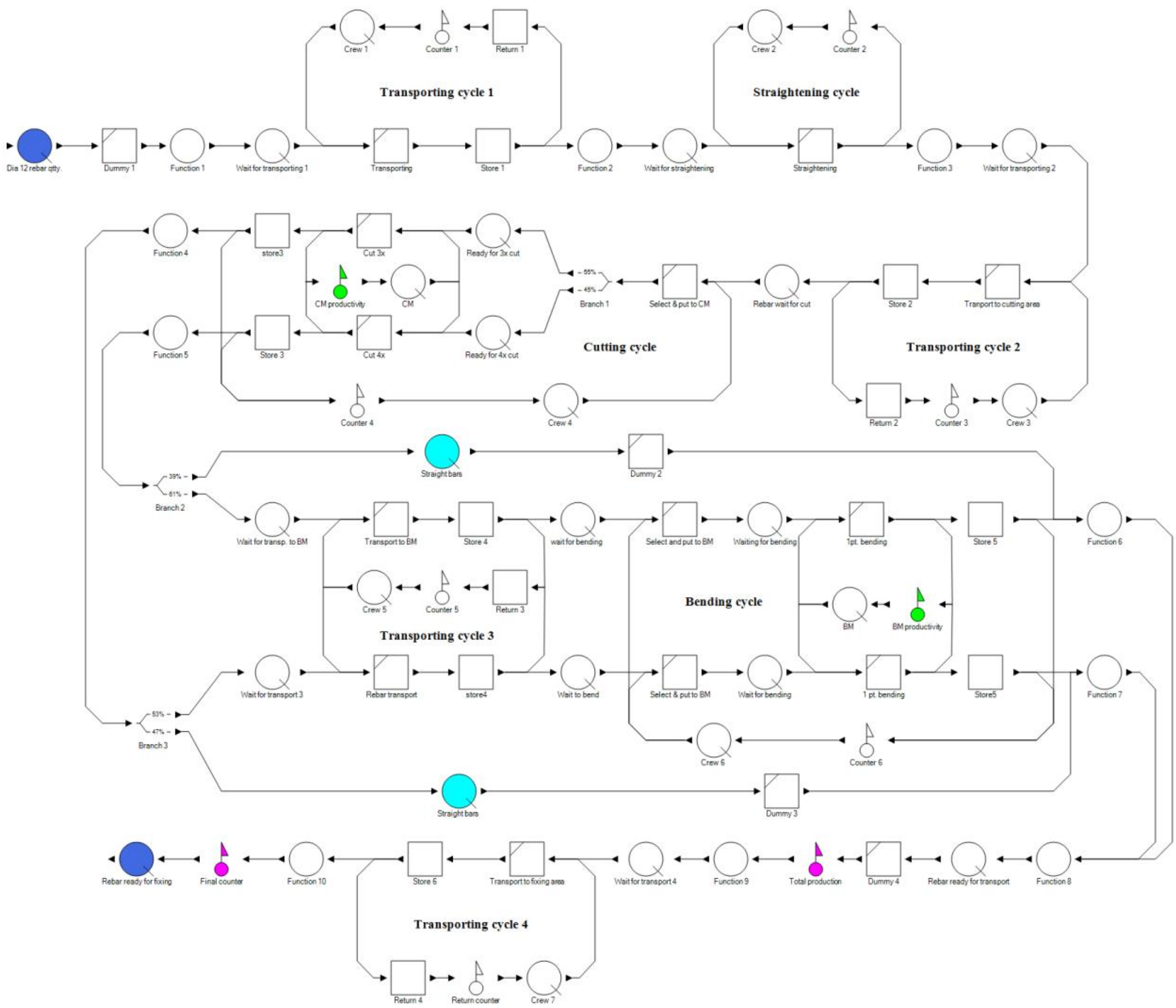

Figure 27: On-site reinforcement bar production model for diameter 12

Table 13: Simulation output result for rebar diameter 12 production (On-site)

Non-Intrinsic Statistics

Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
Dia. 12 (On-Site) (Termination Time)	2,324.203	48.837	1,000.000	2,176.610	2,442.909

Intrinsic Statistics

Element Name	Mean Value	Standard Deviation	Minimum Value	Maximum Value	Current Value
BM (Percent Nonempty)	0.823	0.001	0.821	0.826	0.824
CM (Percent Nonempty)	0.577	0.007	0.555	0.597	0.580
Crew 1 (Percent Nonempty)	0.749	0.004	0.732	0.761	0.752
Crew 2 (Percent Nonempty)	0.682	0.006	0.660	0.698	0.686
Crew 3 (Percent Nonempty)	0.427	0.010	0.387	0.459	0.434
Crew 4 (Percent Nonempty)	0.482	0.008	0.453	0.505	0.485
Crew 5 (Percent Nonempty)	0.006	0.000	0.005	0.009	0.006
Crew 6 (Percent Nonempty)	0.562	0.001	0.559	0.566	0.563
Crew 7 (Percent Nonempty)	0.579	0.025	0.499	0.650	0.593

Counters

Element Name	Final Count	Production Rate	Average Inter arrival	First Arrival	Last Arrival
BM productivity	1,586.860	0.674	1.456	6.659	2,316.295
CM productivity	625.000	0.465	2.131	4.965	1,334.611
Counter 1	500.000	0.855	1.166	1.164	583.165
Counter 2	2,500.000	3.369	0.296	0.993	740.532
Counter 3	625.000	0.467	2.131	4.016	1,333.521
Counter 4	625.000	0.465	2.131	5.209	1,334.854
Counter 5	1,586.860	0.673	1.456	6.735	2,316.373
Counter 6	1,586.860	0.673	1.456	6.931	2,316.566
Final counter	2,500.000	1.362	0.924	12.569	2,321.237
Return counter	1,250.000	0.677	1.848	15.498	2,324.203
Total production	2,500.000	1.380	0.924	8.178	2,316.566

According to the above statistical report, by using one cutting machine and one bending machine, the total simulation time it took to finish the rebar production process for diameter 12 was 2,324.203 minutes, or 38.74 hours. And the productivity of the production system was 64.53 bars per hour.

The average waiting time or idleness of crew 1 is 74.9% of the time; crew 2 waits on average 68.2% of the time; crew 3 waits on average 42.7% of the time; crew 4 waits on average 48.2% of the time; crew 5 waits on average 0.6% of the time; crew 6 waits on average 56.2% of the time; and crew 7 waits on average 57.9% of the time. The idleness of the bending machine was 82.3%, and the cutting machine was idle on average 57.7% of the time. The production rate for bending and cutting machines is 0.674 and 0.465, respectively. The production rate for the total production activities is 1.38.

Scenario 2: Analysis of simulation model for diameter 14 rebar production

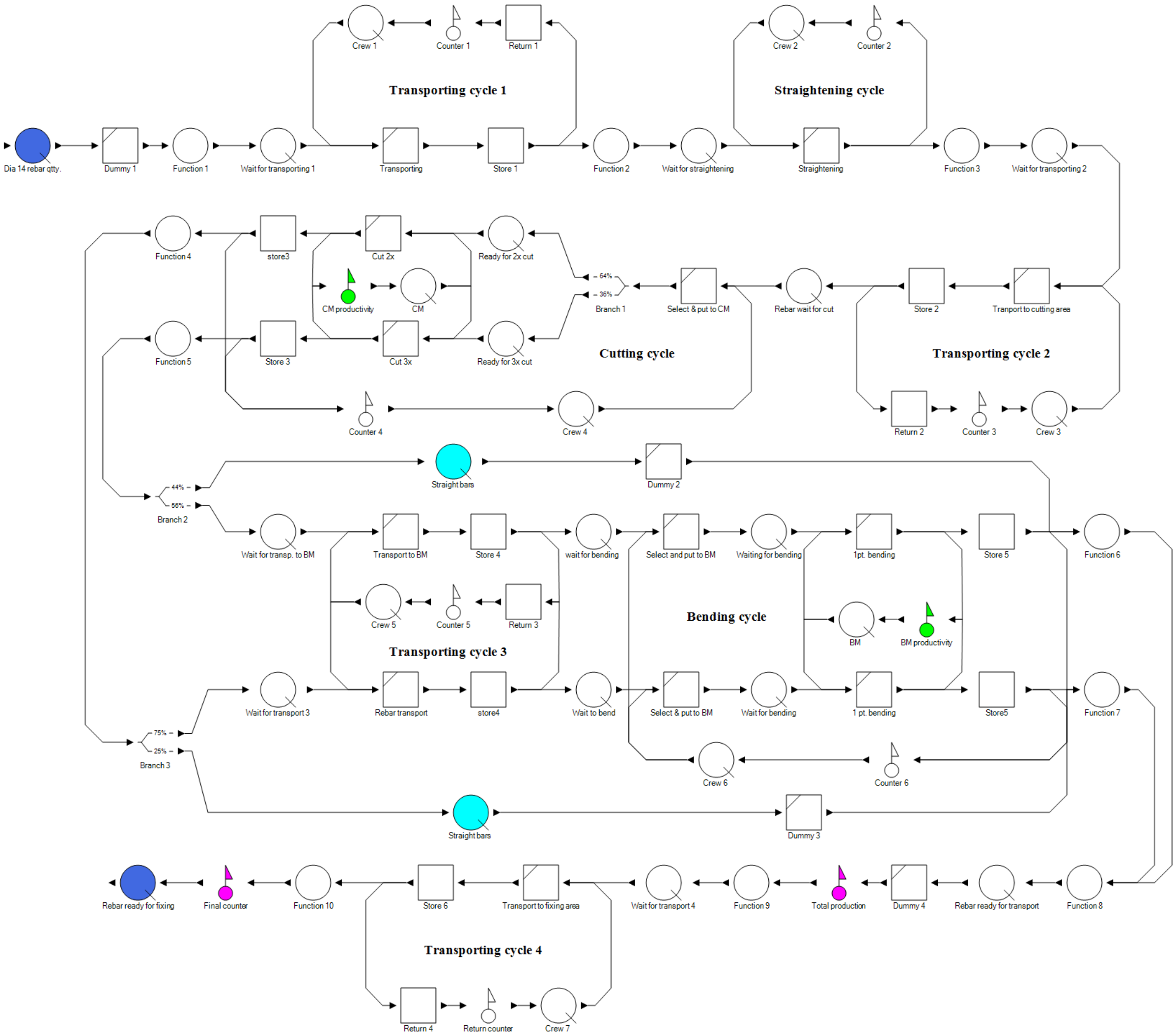

Figure 28: On-site reinforcement bar production model for diameter 14

Table 14: Simulation output result for rebar diameter 14 production (On-site)

Non-Intrinsic Statistics

Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
Dia. 14 (On-Site) (Termination Time)	1,879.666	6.265	1,000.000	1,857.768	1,899.502

Intrinsic Statistics

Element Name	Mean Value	Standard Deviation	Minimum Value	Maximum Value	Current Value
BM (Percent Nonempty)	0.806	0.003	0.797	0.817	0.803
CM (Percent Nonempty)	0.596	0.004	0.584	0.607	0.598
Crew 1 (Percent Nonempty)	0.626	0.001	0.621	0.630	0.626
Crew 2 (Percent Nonempty)	0.613	0.002	0.608	0.618	0.613
Crew 3 (Percent Nonempty)	0.007	0.000	0.005	0.008	0.007
Crew 4 (Percent Nonempty)	0.465	0.004	0.453	0.478	0.467
Crew 5 (Percent Nonempty)	0.490	0.011	0.459	0.536	0.480
Crew 6 (Percent Nonempty)	0.522	0.007	0.500	0.550	0.514
Crew 7 (Percent Nonempty)	0.534	0.009	0.504	0.561	0.535

Counters

Element Name	Final Count	Production Rate	Average Inter arrival	First Arrival	Last Arrival
BM productivity	1,403.941	0.744	1.329	6.919	1,871.668
CM productivity	625.000	0.333	2.987	5.055	1,868.873
Counter 1	625.000	0.888	1.125	1.127	703.278
Counter 2	2,500.000	3.412	0.291	0.971	728.619
Counter 3	625.000	0.333	2.987	4.818	1,868.627
Counter 4	625.000	0.332	2.987	5.336	1,869.156
Counter 5	1,403.941	0.744	1.329	7.048	1,871.610
Counter 6	1,403.941	0.743	1.329	7.185	1,871.935
Final counter	2,500.000	1.302	0.746	12.356	1,876.695
Return counter	1,250.000	0.647	1.493	15.279	1,879.666
Total production	2,500.000	1.316	0.746	7.967	1,871.957

According to the statistical report, the total simulation time required to complete the rebar production process for diameter 14 was 1,879.666 minutes, or 31.32 hours, using one cutting machine and one bending machine. And the productivity of the production system was 79.82 bars per hour.

The average waiting time for crew 1 is 62.6% of the time; crew 2 waited on average 61.3% of the time; crew 3 waited on average 0.7% of the time; crew 4 waited 46.5% of the time; crew 5 waited 49.0% of the time; crew 6 waited 52.2% of the time; and crew 7 waited 53.4% of the time. The idleness of the bending machine was 80.6% of the time, and the idleness of the cutting machine was on average 59.6% of the time. The production rates for the bending and cutting machines are 0.744 and 0.333, respectively. The production rate for the total production activities is 1.316.

Scenario 3: Analysis of simulation model for diameter 16 rebar production

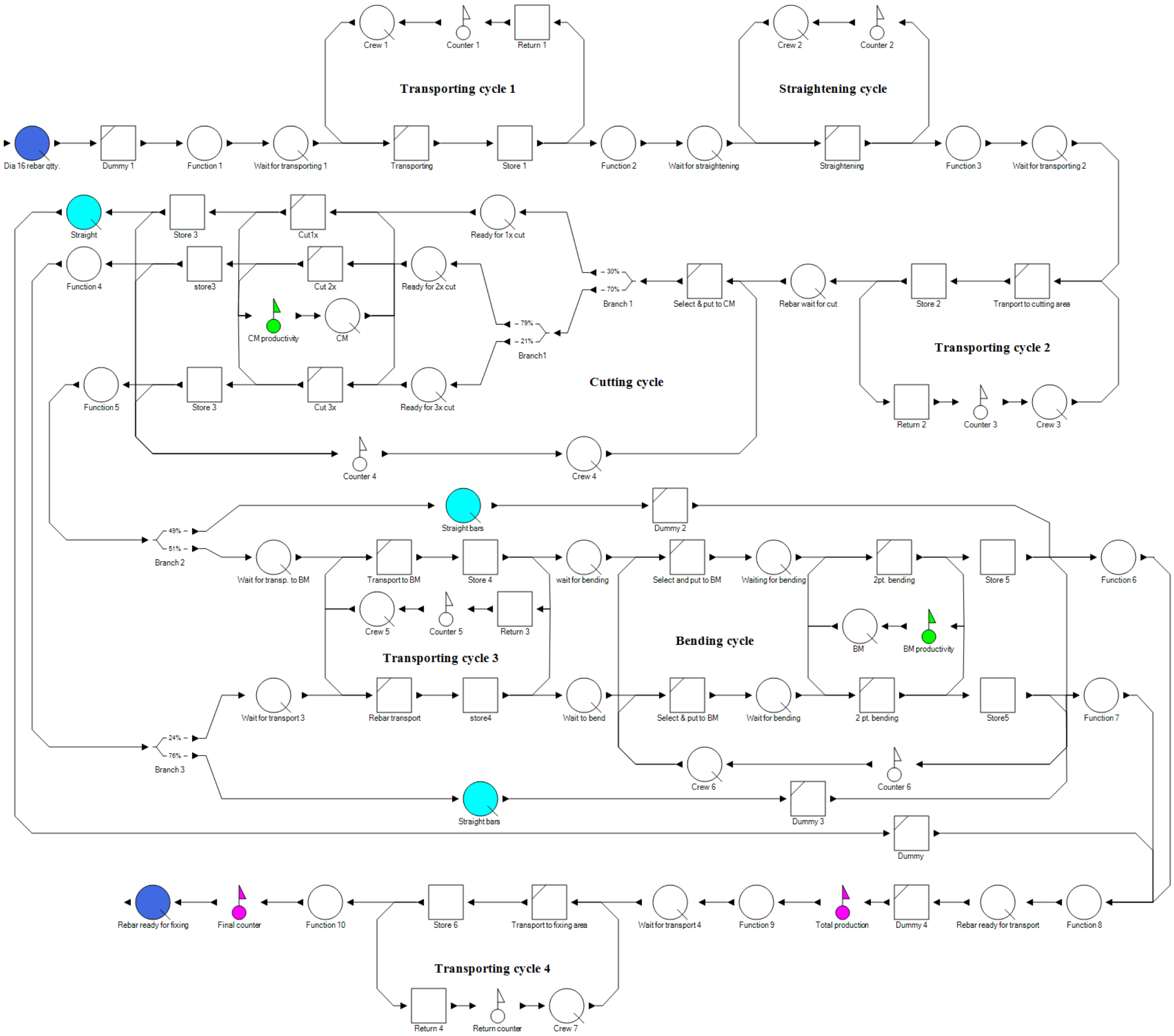

Figure 29: On-Site reinforcement bar production model for diameter 16

Table 15: Simulation output result for rebar diameter 16 production (On-site)

Non-Intrinsic Statistics

Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
Dia. 16 (On-Site)	3,372.853	7.527	1,000.000	3,345.373	3,404.498

Intrinsic Statistics

Element Name	Mean Value	Standard Deviation	Minimum Value	Maximum Value	Current Value
BM (Percent Nonempty)	0.820	0.007	0.799	0.838	0.812
CM (Percent Nonempty)	0.676	0.005	0.661	0.691	0.672
Crew 1 (Percent Nonempty)	0.581	0.001	0.577	0.585	0.580
Crew 2 (Percent Nonempty)	0.757	0.001	0.755	0.761	0.758
Crew 3 (Percent Nonempty)	0.003	0.001	0.002	0.007	0.003
Crew 4 (Percent Nonempty)	0.510	0.005	0.495	0.525	0.505
Crew 5 (Percent Nonempty)	0.550	0.016	0.497	0.596	0.527
Crew 6 (Percent Nonempty)	0.723	0.010	0.690	0.750	0.710
Crew 7 (Percent Nonempty)	1.000	0.000	0.998	1.000	1.000

Counters

Element Name	Final Count	Production Rate	Average Inter arrival	First Arrival	Last Arrival
BM productivity	871.735	0.260	3.857	10.052	3,363.753
CM productivity	1,250.000	0.371	2.689	4.151	3,362.830
Counter 1	1,250.000	0.884	1.132	1.130	1,414.383
Counter 2	2,500.000	1.765	0.566	1.008	1,414.586
Counter 3	1,250.000	0.371	2.689	4.032	3,362.730
Counter 4	1,250.000	0.371	2.689	4.486	3,363.167
Counter 5	871.735	0.260	3.857	9.773	3,363.475
Counter 6	871.735	0.260	3.857	10.318	3,364.020
Final counter	2,500.000	0.734	1.344	10.142	3,369.897
Return counter	1,250.000	0.366	2.690	13.090	3,372.853
Total production	2,500.000	0.740	1.344	5.608	3,365.360

According to the statistical report, the total simulation time required to complete the rebar production process for diameter 16 was 3,372.853 minutes, or 56.21 hours, using one cutting machine and one bending machine. And the productivity of the production system was 44.47 bars per hour.

The average waiting time of crew 1 is 58.1% of the time, crew 2 waited on average 75.7% of the time, crew 3 waited on average 0.3% of the time, crew 4 waited 51.0% of the time, crew 5 waited 55.0% of the time, crew 6 waited 72.3%, and crew 7 waited 100 % of the time. The idleness of the bending machine was 82.0% of the time, and the idleness of the cutting machine was on average 67.6% of the time. The production rates for the bending and cutting machines are 0.260 and 0.371, respectively. The production rate for the total production activities is 0.740.

Scenario 4: Analysis of simulation model for diameter 20 rebar production

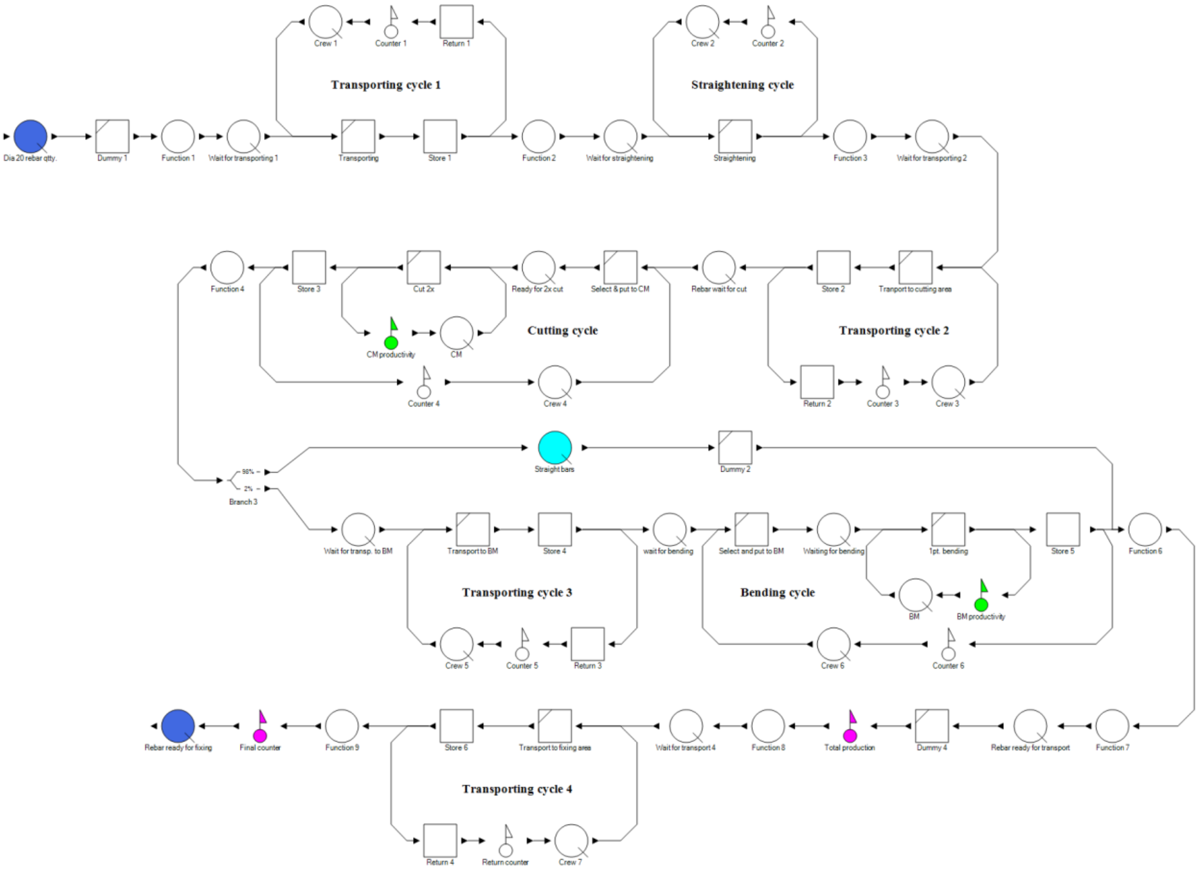

Figure 30: On-site reinforcement bar production model for diameter 20

Table 16: Simulation output result for rebar diameter 20 production (On-site)

Non-Intrinsic Statistics					
Element Name	**Mean Value**	**Standard Deviation**	**Observation Count**	**Minimum Value**	**Maximum Value**
Dia. 20 (Termination Time)	3,539.346	8.193	1,000.000	3,511.792	3,565.003

Intrinsic Statistics

Element Name	**Mean Value**	**Standard Deviation**	**Minimum Value**	**Maximum Value**	**Current Value**
BM (Percent Nonempty)	0.995	0.001	0.992	0.997	0.995
CM (Percent Nonempty)	0.630	0.001	0.626	0.635	0.631
Crew 1 (Percent Nonempty)	0.596	0.001	0.593	0.600	0.598
Crew 2 (Percent Nonempty)	0.746	0.001	0.743	0.750	0.746
Crew 3 (Percent Nonempty)	0.003	0.000	0.002	0.004	0.003
Crew 4 (Percent Nonempty)	0.482	0.002	0.477	0.487	0.483
Crew 5 (Percent Nonempty)	0.964	0.004	0.949	0.979	0.966
Crew 6 (Percent Nonempty)	0.987	0.002	0.982	0.992	0.987
Crew 7 (Percent Nonempty)	1.000	0.000	1.000	1.000	1.000

Counters

Element Name	**Final Count**	**Production Rate**	**Average Inter arrival**	**First Arrival**	**Last Arrival**
BM productivity	75.009	0.018	47.042	50.549	3,485.632
CM productivity	1,250.000	0.353	2.824	4.389	3,531.434
Counter 1	1,250.000	0.874	1.144	1.146	1,429.691
Counter 2	2,500.000	1.745	0.572	1.048	1,429.956
Counter 3	1,250.000	0.353	2.824	4.219	3,531.274
Counter 4	1,250.000	0.352	2.824	4.697	3,531.744
Counter 5	75.009	0.018	47.042	50.685	3,485.767
Counter 6	75.009	0.018	47.042	50.799	3,485.883
Final counter	2,500.000	0.699	1.411	9.343	3,536.398
Return counter	1,250.000	0.348	2.824	12.291	3,539.346
Total production	2,500.000	0.704	1.411	4.813	3,531.874

According to the above statistical report, by using one cutting machine and one bending machine, the total simulation time it took to finish the rebar production process for diameter 20 was 3,539.346 minutes, or 58.99 hours. And the productivity of the production system was 42.38 bars per hour.

The average waiting time or idleness of crew 1 is 59.6% of the time; crew 2 waits on average 74.6% of the time; crew 3 waits on average 0.3% of the time; crew 4 waits on average 48.2% of the time; crew 5 waits on average 96.4% of the time; crew 6 waits on average 98.7%, of the time; and crew 7 waits on average 100% of the time.

The idleness of the bending machine was 99.5%, and the cutting machine was idle on average 63.0% of the time. The production rates for bending and cutting machines are 0.018 and 0.353, respectively. The production rate for the total production activities is 0.704.

4.5.4.2. Case study two (Off-site rebar production)

Scenario 1: Analysis of simulation model for diameter 12 rebar production

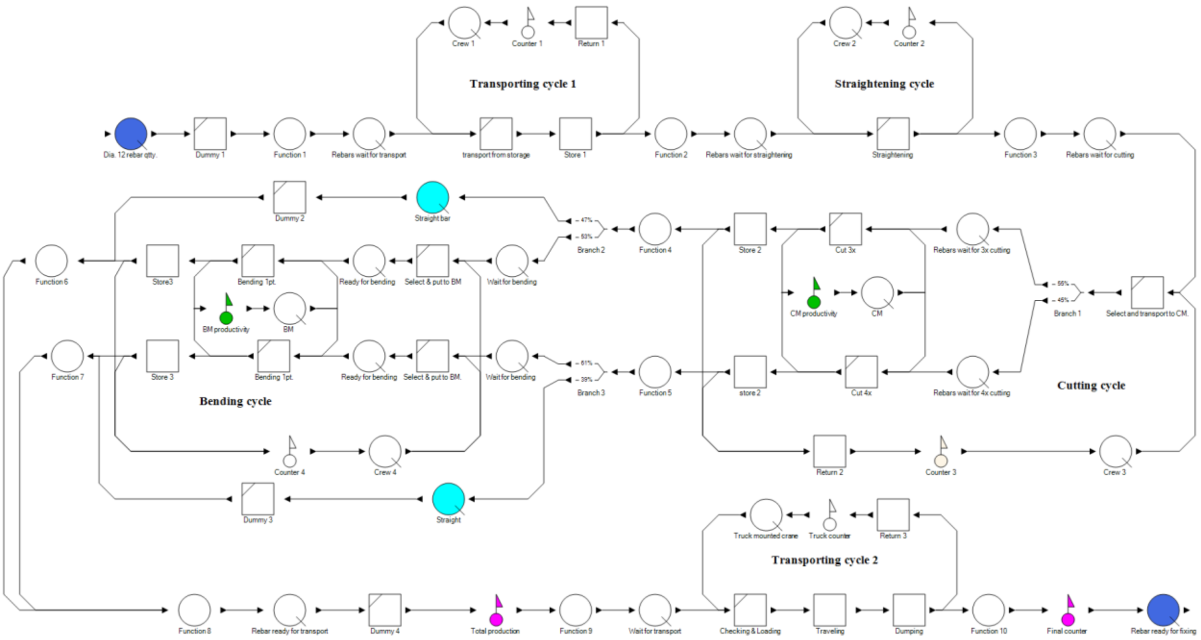

Figure 31: Off-site reinforcement bar production model for diameter 12

Table 17: Simulation output result for rebar diameter 12 production (Off-site)

Element Name	**Mean Value**	**Standard Deviation**	**Observation Count**	**Minimum Value**	**Maximum Value**
Non-Intrinsic Statistics					
Dia. 12 (Off-Site) (Termination Time)	1,775.138	5.433	1,000.000	1,757.479	1,794.814
Intrinsic Statistics					

Element Name	Mean Value	Standard Deviation	Minimum Value	Maximum Value	Current Value
BM (Percent Nonempty)	0.763	0.004	0.746	0.777	0.762
CM (Percent Nonempty)	0.437	0.002	0.433	0.443	0.437
Crew 1 (Percent Nonempty)	0.736	0.001	0.733	0.741	0.736
Crew 2 (Percent Nonempty)	0.607	0.002	0.600	0.614	0.608
Crew 3 (Percent Nonempty)	0.031	0.002	0.027	0.036	0.032
Crew 4 (Percent Nonempty)	0.515	0.009	0.481	0.544	0.515
Truck mounted crane	0.970	0.002	0.966	0.974	0.969

Counters

Element Name	Final Count	Production Rate	Average Inter arrival	First Arrival	Last Arrival
BM productivity	1,585.381	0.879	1.085	4.610	1,722.394
CM productivity	625.000	0.362	2.752	3.936	1,720.998
Counter 1	500.000	1.061	0.936	0.934	467.867
Counter 2	2,500.000	3.563	0.279	0.920	697.931
Counter 3	625.000	0.361	2.752	4.513	1,721.578
Counter 4	1,585.381	0.879	1.085	4.783	1,722.569
Final counter	2,500.000	0.710	0.000	1,762.701	1,762.701
Total production	2,500.000	1.437	0.687	5.536	1,722.607
Truck counter	1.000	0.000	NaN	1,775.138	1,775.138

According to the above statistical report, by using one cutting machine and one bending machine, the total simulation time it took to finish the rebar production process for diameter 12 was 1,775.138 minutes, or 29.59 hours. And the overall productivity of the production system was 84.49 bars per hour.

The average waiting time or idleness for crew 1 is 73.6% of the time, crew 2 waits on average 60.7% of the time, crew 3 waits on average 3.1% of the time, and crew 4 waits on average 51.5% of the time. The production rate for bending and cutting machines is 0.879 and 0.362, respectively. The production rate for the total production activities is 1.437.

Scenario 2: Analysis of simulation model for rebar diameter 14

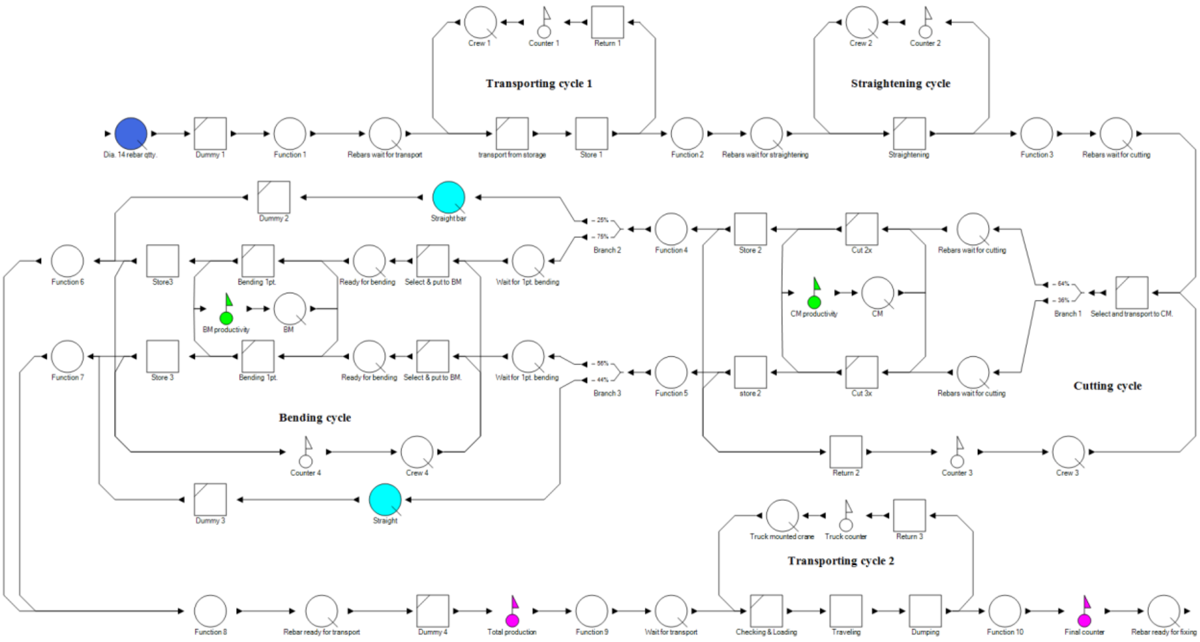

Figure 32: Off-site reinforcement bar production model for diameter 14

Table 18: Simulation output result for rebar diameter 14 production (Off-site)

Non-Intrinsic Statistics

Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
Dia. 14 (Off-Site) (Termination Time)	1,433.949	7.933	1,000.000	1,406.411	1,461.736

Intrinsic Statistics

Element Name	Mean Value	Standard Deviation	Minimum Value	Maximum Value	Current Value
BM (Percent Nonempty)	0.741	0.004	0.726	0.755	0.743
CM(Percent Nonempty)	0.514	0.003	0.506	0.523	0.510
Crew 1 (Percent Nonempty)	0.641	0.003	0.632	0.652	0.643
Crew 2 (Percent Nonempty)	0.493	0.003	0.483	0.504	0.500
Crew 3 (Percent Nonempty)	0.038	0.002	0.033	0.044	0.039
Crew 4 (Percent Nonempty)	0.468	0.009	0.436	0.497	0.470
Truck mounted crane (Percent Nonempty)	0.927	0.003	0.918	0.935	0.923

Counters					
Element Name	**Final Count**	**Production Rate**	**Average Inter arrival**	**First Arrival**	**Last Arrival**
BM productivity	1,404.231	1.013	0.982	4.054	1,381.239
CM productivity	625.000	0.445	2.206	3.420	1,380.003
Counter 1	625.000	1.211	0.824	0.821	514.862
Counter 2	2,500.000	3.424	0.291	0.844	727.204
Counter 3	625.000	0.444	2.206	3.929	1,380.513
Counter 4	1,404.231	1.012	0.982	4.228	1,381.411
Final counter	2,500.000	1.073	0.275	733.077	1,421.405
Total production	2,500.000	1.764	0.551	4.866	1,381.430
Truck counter	2.000	0.001	688.362	745.587	1,433.949

According to the above statistical report, by using one cutting machine and one bending machine, the total simulation time it took to finish the rebar production process for diameter 14 was 1,433.949 minutes, or 23.89 hours. And the overall productivity of the production system was 104.64 bars per hour.

The average waiting time or idleness for crew 1 is 64.1% of the time, crew 2 waits on average 49.3% of the time, crew 3 waits on average 3.8% of the time, and crew 4 waits on average 46.8% of the time.

The idleness of the bending machine was 74.1%, and the cutting machine was idle on average 51.4% of the time. The production rate for bending and cutting machines is 1.013 and 0.445, respectively. The production rate for the total production activities is 1.764.

Scenario 3: Analysis of simulation model for rebar diameter 16

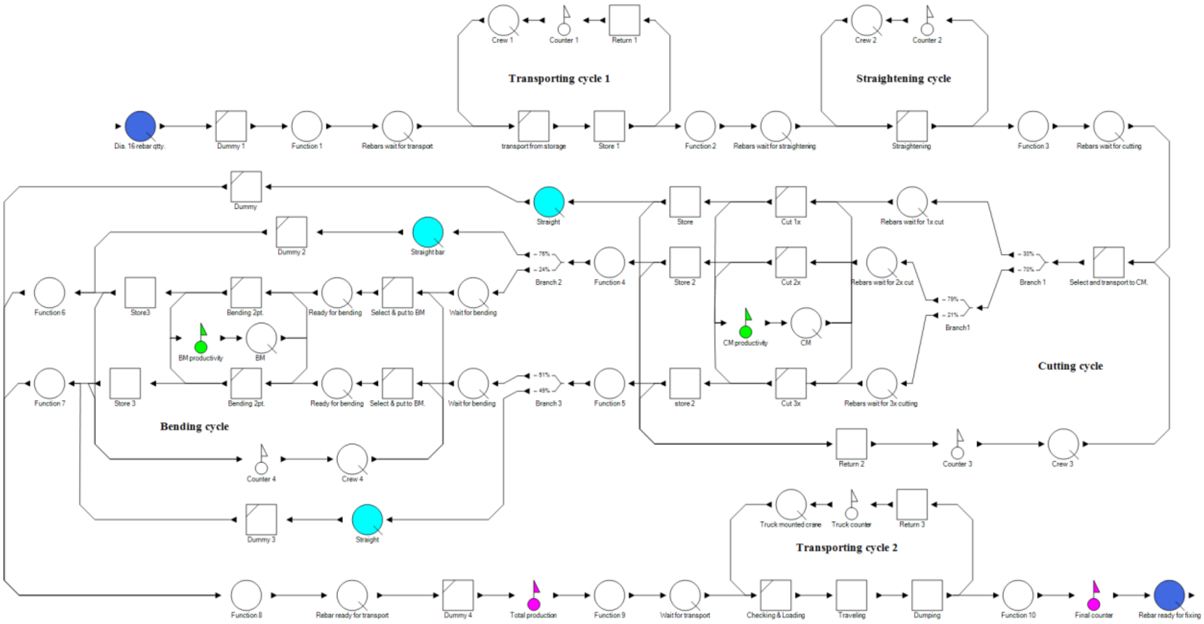

Figure 33: Off-site reinforcement bar production model for diameter 16

Table 19: Simulation output result for rebar diameter 16 production (Off-site)

Non-Intrinsic Statistics

Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
Dia. 16 (Termination Time)	2,568.452	15.539	1,000.000	2,520.392	2,613.897

Intrinsic Statistics

Element Name	Mean Value	Standard Deviation	Minimum Value	Maximum Value	Current Value
BM (Percent Nonempty)	0.775	0.008	0.755	0.803	0.777
CM (Percent Nonempty)	0.615	0.004	0.603	0.626	0.612
Crew 1 (Percent Nonempty)	0.615	0.003	0.606	0.623	0.614
Crew 2 (Percent Nonempty)	0.691	0.002	0.684	0.698	0.692
Crew 3 (Percent Nonempty)	0.021	0.001	0.018	0.024	0.020
Crew 4 (Percent Nonempty)	0.649	0.012	0.618	0.694	0.653
Truck mounted crane	0.959	0.001	0.954	0.963	0.962

Counters

Element Name	Final Count	Production Rate	Average Inter arrival	First Arrival	Last Arrival
BM productivity	874.316	0.342	2.876	6.132	2,514.417
CM productivity	1,250.000	0.498	2.011	2.585	2,514.800
Counter 1	1,250.000	1.262	0.792	0.791	989.886
Counter 2	2,500.000	2.518	0.396	0.838	990.262
Counter 3	1,250.000	0.497	2.011	3.171	2,515.387
Counter 4	874.316	0.342	2.876	6.396	2,514.682
Final counter	2,500.000	0.608	0.503	1,298.688	2,555.915
Total production	2,500.000	0.991	1.005	3.430	2,515.869
Truck counter	2.000	0.001	1,257.297	1,311.155	2,568.452

According to the statistical report, the total simulation time it took to finish the rebar production process for diameter 16 was 2,568.452 minutes, or 42.81 hours. And the productivity of the production system was 58.39 bars per hour.

The average waiting time or idleness for crew 1 is 61.5% of the time, crew 2 waited on average 69.1% of the time, crew 3 waited on average 2.1%, and crew 4 waited on average 64.9% of the time. The idleness of the bending machine was 77.5%, and the cutting machine was idle on average 61.5% of the time. The production rate for bending and cutting machine is 0.342 and 0.498 respectively. The production rate for the total production activities is 0.991.

Scenario 4: Analysis of simulation model for rebar diameter 20

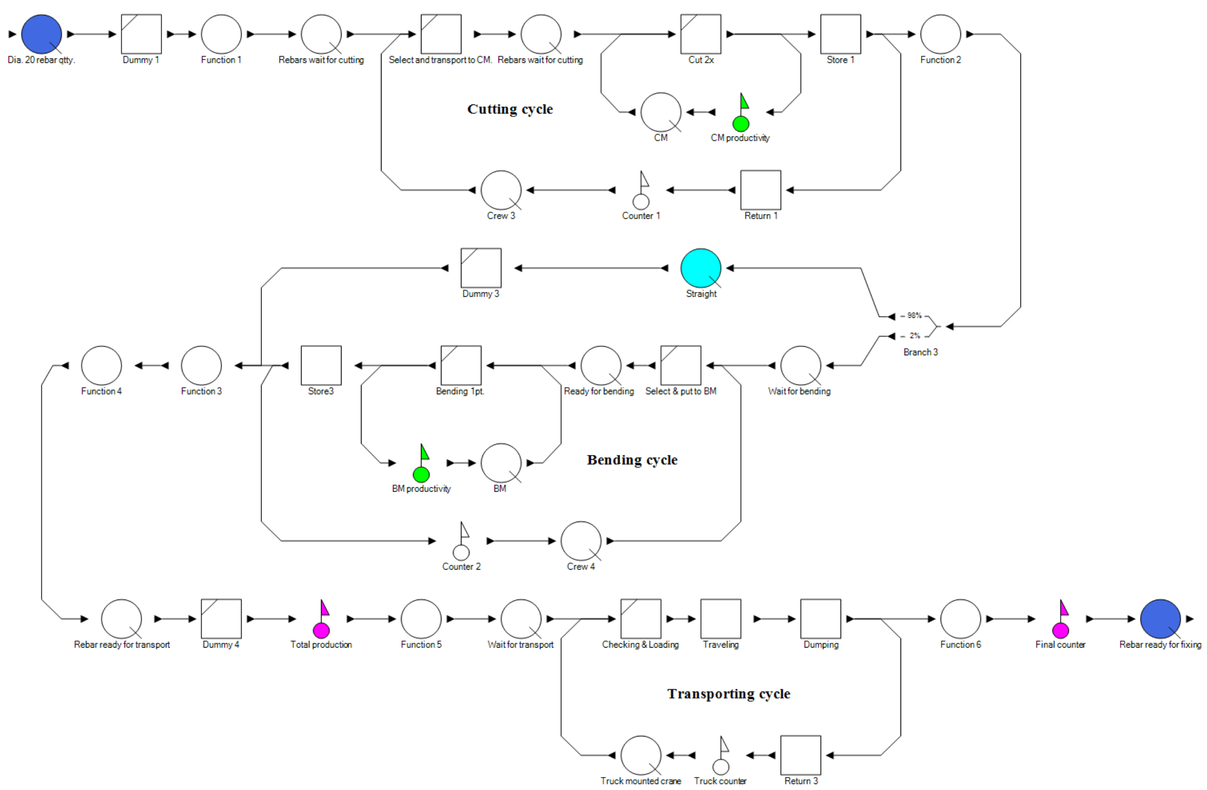

Figure 34: Off-site reinforcement bar production model for diameter 20

Table 20: Simulation output result for rebar diameter 20 production (Off-site)

Non-Intrinsic Statistics

Element Name	Mean Value	Standard Deviation	Observation Count	Min. Value	Max. Value
Dia. 20 (Term. Time)	2,586.379	6.108	1,000.000	2,567.628	2,603.962

Intrinsic Statistics

Element Name	Mean Value	Standard Deviation	Minimum Value	Maximum Value	Current Value
BM (Percent Nonempty)	0.992	0.001	0.990	0.995	0.991
CM (Percent Nonempty)	0.559	0.001	0.556	0.563	0.560
Crew 3 (Percent Nonempty)	0.020	0.001	0.017	0.023	0.022
Crew 4 (Percent Nonempty)	0.981	0.002	0.975	0.988	0.979
Truck mounted crane	0.959	0.001	0.955	0.964	0.959

Counters

Element Name	Final Count	Production Rate	Average Inter arrival	First Arrival	Last Arrival
BM productivity	74.538	0.037	34.018	34.159	2,501.776
CM productivity	1,250.000	0.492	2.027	1.523	2,533.603
Counter 1	1,250.000	0.491	2.027	2.029	2,534.107
Counter 2	74.538	0.036	34.018	34.445	2,502.062
Final counter	2,500.000	0.602	0.507	1,306.573	2,573.906
Total production	2,500.000	0.982	1.013	1.783	2,533.848
Truck counter	2.000	0.001	1,267.244	1,319.135	2,586.379

According to the statistical report, the total simulation time it took to finish the rebar production process for diameter 20 was 2,586.379 min., or 43.10 hours. And the productivity of the production system was 58.00 bars per hour.

The average waiting time or idleness of Crew 3 and Crew 4 is 2.0% and 98.1%, respectively. The idleness of the bending machine was 99.2% with a production rate of 0.037, and the cutting machine was idle on average 55.9% of the time with a production rate of 0.492. The production rate for the total production activities is 0.982.

4.5.5. Simulation output comparison and discussion

As was shown in the previous section, it has been tried to model the rebar production in both systems, which are on-site and off-site, with four different scenarios. The output result of the two production systems is summarized in the following table.

Table 21: Rebar production summary of the two production systems

Production type	Dia.	Termination time	Production Rate			Idleness (Waiting)%	
			Bending machine	Cutting machine	Total production	Bending machine	Cutting machine
ON-SITE	12	2,324.203	0.674	0.465	1.380	82.3	57.7
	14	1,879.666	0.744	0.333	1.316	80.6	59.6
	16	3,372.853	0.260	0.371	0.740	82.0	67.6
	20	3,539.346	0.018	0.353	0.704	99.50	63.0

Production type	Dia.	Termination time	Production Rate			Idleness (Waiting)%	
			Bending machine	Cutting machine	Total production	Bending machine	Cutting machine
OFF-SITE	12	1,775.138	0.879	0.362	1.437	76.3	43.70
	14	1,433.949	1.013	0.445	1.764	74.1	51.40
	16	2,568.452	0.342	0.498	0.991	77.5	61.50
	20	2,586.379	0.037	0.492	0.982	99.2	55.90

According to the result of the simulation model, the total time it took to finish the rebar production process in the on-site case for diameter 12 was 2,324.203 min, whereas in the off-site production it took 1,775.138 min. This reduced the production time by 23.62%. The productivity of the on-site and off-site rebar production systems was 64.53 bars per hour and 84.5 bars per hour, respectively. This indicates that they can produce 19.97 more bars per hour in the off-site case. The idleness of the cutting and bending machines shows that. In the onsite case, the bending machine was idle for 82.3% of the time, and the cutting machine was idle for 57.7% of the time. In the off-site case, the bending machine was idle 76.3% of the time, and the cutting machine was idle 43.7% of the time.

The second model was developed for the rebar production process of diameter 14, and the output report shows that the total time it took to finish the production process in the on-site case was 1,879.666 min, whereas in the off-site production it took 1,433.949 min. This reduced the production time by 23.71%. The productivity of the on-site and off-site rebar production systems was 79.8 bars per hour and 104.6 bars per hour, respectively. This shows that they can produce 24.8 more bars per hour in the off-site case. In the on-site case, the idleness of the bending machines was 80.6% and that of the cutting machines was 59.6%. In the off-site case, the bending machine was idle 74.1% of the time, and the cutting machine was idle 51.4% of the time.

The third model was developed for the rebar production process of diameter 16, and the output report shows that the total time it took to finish the production process in the on-site case was 3,372.853 min, whereas in the off-site production it took 2,568.452 min. This reduced the production time by 23.85%. The on-site and off-site rebar production systems had productivity rates of 44.47 and 58.39 bars per hour, respectively. This shows that in the off-site case, they can produce 13.92 more bars per hour. In the on-site case, the idleness of the bending machines was

82.0% and 67.6% for the cutting machines. In the off-site case, the bending machine was idle 77.5% of the time, and the cutting machine was idle 61.5% of the time.

The last model was developed for the rebar production process of diameter 20, and the output report shows that the total time it took to finish the production process in the on-site case was 3,539.346 min, whereas in the off-site production it took 2,586.379 min. This reduced the production time by 26.92%. The productivity of the on-site and off-site rebar production systems was 42.38 bars per hour and 58 bars per hour, respectively. This shows that in the off-site case, they can produce 15.62 more bars per hour. In the on-site case, the idleness of the bending machines was 99.5% and 63.0% for the cutting machines. In the off-site case, the bending machine was idle 99.2% of the time, and the cutting machine was idle 55.9% of the time.

Finally, based on the above four scenarios' result analysis, off-site rebar production shows better production performance in all cases. In the off-site case, the production termination time is decreased, and the productivity is higher than the on-site rebar production. In addition, the idleness of the cutting and bending machines is also less in the off-site case than on-site.

One of the factors contributing to an increase in production time is unnecessary rebar transportation from one place to another. The traveling time increases if the storage and production locations are far apart. In the off-site case, the traveling time is decreased since the storage and production areas are close. The site layout and working conditions are other factors that affect the transportation cycle time.

The number of cuts is another factor that affects the total production time. If the number of cuts increases, the number of pieces will also increase, which will increase the production time. The diameter of the rebar also has an effect on the total termination time. For example, the machine can cut four diameter 12-rebars at a time but only two diameter 20-rebars, so the termination time for diameter 12-rebars will decrease by half that of diameter 20.

In addition, the workers experience has also affected the production time. The time to do an activity will increase or decrease based on the worker's efficiency. For example, in the case of straightening, it takes less time to do it if the worker has experience. If the worker has no experience, it takes time, and there will also be defects, which result in rework at the time of cutting and bending.

In some cases, the type of rebar that is produced contributes to the idleness of the bending and cutting machines. For instance, the bending machine will be idle if the required rebar is straight and doesn't need to be bent. As a result, the idleness of the bending machine will increase and the rate of production will decrease as the proportion of straight bars increases.

Generally, the main factors for the reinforcement bar production time, productivity, and idleness are: the rebar type that needs to be done (i.e., diameter, bending shape, number of cuts); the method of cutting and bending; the site layout; the workspace; the worker's experience; and so on.

4.5.6. Model Verification and Validation

4.5.6.1. Model Verification

The conceptual model was developed based on real-world two-rebar production systems, which accurately represent the system. The total number of entities that have entered each component of the system has been checked by adding entity counters in each production process cycle. This helps to track the flow of entities and check for the presence of logical errors. The Simphony simulation software checked the model integrity and also the model input data probability distribution, which was checked for goodness of fit and verified.

4.5.6.2. Model Validation

The validation of the rebar production simulation model, including the conceptual model, input data, and operation validation, was checked and validated. The input data has been checked and validated by using the built-in tool in the Symphony simulation software. Construction professionals experienced in the rebar production process also validated the logic of the conceptual model, and the model's correctness for input-output was checked and validated.

4.6. Discussion on the two production systems

Based on the collected data, the two rebar production systems were described previously, and in this section they will be summarized by comparing the results of the two case studies. As it was discussed in the literature review, the application of off-site rebar production with JIT delivery has a lot of advantages. The contractor who applied off-site production with JIT delivery shows better performance than the contractor who used on-site production on the following points:

4.6.1. Storage and handling

In case study one, the reinforcement bar storage and production were on site, which was taking up valuable space, blocking the way, and creating congestion at the project site. Whereas in case study two, the reinforcement bars were dumped on the site only for assembly; otherwise, they would not be transported there. Since the production takes place off-site, there is no unnecessary rebar stock on the site, which avoids congestion and the storage of rebar on site.

4.6.2. Non-value-adding activities

In case study one, all activities were carried out on site, and some of them were identified as non-value-adding activities, which led to wastage of time. But in case study two, only the unloading and fixing activities were carried out on site; the other activities were carried out off-site in the production area. Therefore, non-value-adding activities that do not add value but create congestion at the site were reduced in the off-site case study.

4.6.3. Rebar production crew

In case study one, there are a lot of workers on the project site since both rebar production and fixing activities are undertaken there. The production crew and the transportation crew are the two main crews on the site. Beside the rebar fixing crew, there is an average of 20 laborers on the site for rebar production purpose. In case study two, only the rebar fixing crew was available on site since the production was off-site. There are also few workers in the production area, with an average of 10 workers producing rebar for all of the project sites. The number of workers required for off-site production is reduced by 50% compared to onsite production.

4.6.4. Production type

In Case Study one, the rebar production system was based on the idea of a push system, where rebars were cut and bent more than was needed. So there is a problem of overproduction that takes up working space and results in waste. In case study two, the contractor follows the pull production system; rebars are produced only when they are needed in the required quantity since there is no overproduction. Additionally, after production, rebars were delivered to the project site due to the fact that the working area was clean.

4.6.5. Rebar wastage

Both contractors use optimization software to minimize rebar waste, but sometimes there is leftover rebar that could be used for the next job. Thus, in case study one, these leftover rebars would be stored somewhere and forgotten, and they would not be used again. But in case study two, since the central production prepared rebars for the entire projects, the waste from one project site could be used for the other. Additionally, when they use optimization software, the left-overs are always prioritized over the standard rebar as an input quantity. Reusing the rebars is crucial to lowering the loss rate.

4.6.6. Safety and working environment

In case study one, due to lack of space and a congested working area, the safety was not good, whereas in case study two, the workplace in the central rebar production is orderly and clean, so it has a good working environment. Also, on the project sites, there is no risk for labor due to the production of rebar.

4.6.7. Production cycle time

Both contractors use cutting and bending machines, which are efficient for rebar production, but the cycle time it takes to produce rebar in case study one is higher than in case study two. Because of additional steps and the duration of transportation, the flow increased, increasing the cycle time for the case study one. But for case study two, the number of steps is simplified and minimized, which reduced the cycle time.

4.6.8. Work productivity

The production area is one of the factors for labor productivity. Labor productivity would be improved under off-site production because the working environment and available space on the job site have a crucial effect on its effectiveness. Workers spend their time doing non-value-adding activities; this takes time but decreases their productivity.

4.6.9. Economic value

As it was discussed in the previous sections, waste is not only associated with waste of material; it also includes activities that do not add value to the projects. These wastes, directly or indirectly, incur unnecessary costs. Therefore, the financial benefits and losses due to the two rebar production practices are described below.

- **Inventory cost:** If the contractors store the reinforcement bars for a long period of time, it occupies a huge space that could be used for other purposes. These rebar inventories result in financial losses due to deterioration, theft, rebar waste, and holding capital. Furthermore, if the contractors don't have space for storing and handling rebar on the project site, they need to rent space for this purpose, which also results in additional storage and holding costs. One of the JIT principles is to reduce inventories on site; therefore, costs associated with inventory will be reduced.

- **Machine purchasing cost:** To increase the efficiency of the rebar production process, it is better to use the cutting and banding machines. If the contractor has different projects, the cost of purchasing cutting and bending machines for each project is not economical. But if the production is off-site in the factories or in the central rebar production area, the machines will be used for all projects.
- **Cost related to resource utilization:** In site rebar production, there is less resource utilization since the cutting and bending machines are for one specific project. The inefficient utilization of resources causes a financial loss due to idleness. But in off-site production, the resources could be utilized effectively for all projects.
- **Labor cost:** The labor needed in site rebar production is greater than that needed off-site due to many activities that might be value-adding or non-value-adding on the site. Thus, the cost related to labor increased in the on-site production system. If the production is off-site, the labor required on site is only for fixing activities, so the labor needed and the cost related to it decrease.
- **Delivery cost:** In on-site production, the reinforcement bars might be transported to the site in bulk or in small lots at any time. After site production the reinforcement bars are transported from production to fixing area is mostly carried by labor. However, in the off-site case there will be frequent delivery at the required time this might increase site delivery cost in the off-site case.
- **Overproduction cost:** When rebars are produced in more than the required quantity or earlier than the needed time, there will be excess cut and bent rebars due to overproduction. This results in financial loss due to wastage of rebar, wastage of manpower, and wastage of time. But in the JIT system, reinforcement bars are only produced based on customer demand and requirements at the appropriate time.
- **Rebar waste loss:** The rebar waste on the construction sites due to inefficient cutting patterns caused financial losses. But in the off-site production, the rebars are produced based on the customer's requirements, which will be optimized. Also, if there are leftovers after cutting, they will be used for another customer.

4.7. Motivating and Challenging factors of JIT implementation

According to the current on-site rebar production practice and other countries experiences, the study identified the motivating and challenging factors for the implementation of off-site rebar production with JIT delivery in the Ethiopian construction industry.

4.7.1. Motivating factors

- Reduction of space on the construction sites. Since the rebar production is off-site, there is no need to store the reinforcement bars on site. This also reduces inventory costs related to storage and holding.
- It creates a clean and organized working environment on construction sites. When the rebar production activities are undertaken off-site, the site intensive activities related to rebar production will be minimized. Therefore, there will be free working space for other work by reducing congestion.
- It reduces the rebar waste on the construction site due to an inefficient cutting pattern and leftovers. In the off-site rebar production, the rebars will be produced by using an optimized cutting pattern. When the reinforcement bars are produced at one place, the leftovers from one project will be used for the other.
- It reduces overproduction. In JIT off-site production, the reinforcement bars are produced based on the customer's requirements and delivered at the needed time.
- It reduces the responsibility and burden for workers at the construction site. If the rebar production is outsourced to rebar factories, the project site will no longer be responsible for rebar production; instead, the construction project will only be in charge of fixing work.
- It improves the labor-intensive, traditional, and inefficient site rebar production practices. If the production process is improved, the rebar production time will be reduced.
- It reduces financial loss caused by wastage of rebar (due to handling, overproduction, inefficient cutting, etc.), wastage of labor, and time (due to unnecessary activities and waiting time).

4.7.2. Challenges factors

- **Adopting new system**

One of the challenging things about the implementation of the just-in-time concept for rebar production and delivery in Ethiopia is accepting or adopting a new system by overcoming the current production and delivery practices. Because of the benefits of bulk discounts and the risk of a supply shortage and price fluctuation, reinforcement bars are purchased and stored on site before their required time. Thus, it will be challenging for the construction industry to adopt this system.

- **Availability of production area**

Reinforcement bar is a huge material that requires a very large space for storage and production. After production, storage space is also needed for storing cut and bent rebars. Therefore, if the production is carried out in one place, in factories or in central production, there should be enough space with a proper site layout. Site layout is one of the causes of non-value-adding activities; hence, the rebar production place should be organized properly.

- **Uncertainty issues**

The pull system is one of the JIT principles under which the production and delivery instructions come from the downstream customer to the upstream supplier. Some of the problems in the construction industry that affect or interrupt the work flow are design changes, change orders, and quantity estimation. Since the reinforcement bars are produced based on the customer's order, before ordering, the type of rebar, diameter, length, and quantity should be properly checked and verified. And it also needs to be checked whether the rebars are produced based on the order before being delivered to project sites. These factors should be controlled, and proper planning should be developed and implemented.

- **Production capacity**

The typical customer need and order for rebars at a construction site may vary due to the design, complexity, construction progress, or stage of the project. Since the reinforcement bars are fabricated at the rebar factories or at the central rebar production area, there should be enough capacity to fulfill the customer’s need or production demand.

Generally, if the above challenging factors are reduced or eliminated, implementing the JIT concept in rebar production would be more advantageous. Developing a proper plan and strategy is needed for effective implementation. Furthermore, the government should control the market in order to minimize price fluctuations and supply shortages.

5. CONCLUSIONS AND RECOMMENDATIONS

As mentioned earlier in the introduction section, the aim of the study was to explore the non-value-adding activities in the rebar production work flow and to improve the flow by changing the rebar production and delivery method based on the concept of JIT. The study focused on two case study contractors and their rebar production approach; the results of the research are based on the collected data from the referred case studies. Therefore, based on the findings and the result of the study, the following conclusions and recommendations are forwarded:

5.1. Conclusions

The first objective of the study was analyzing the rebar production flow and categorizing activities based on the production concept of value. After observing and understanding the overall rebar production process, activities were categorized as VA, NNVA, and NVA. Thus, the result of the study gives a clear indication that there are a lot of NVA and NNVA activities on the rebar production that require a lot of workers and take valuable time. Activities that don't generate value are stated as "non-value-adding activities" and should be removed from the production process. Activities that don't generate value but are necessary for the work are stated as "necessary non-value-adding activities" and should be minimized by simplifying the process.

Rebar production is a repetitive process with activities of transporting, straightening, cutting, and bending. Each activity takes time and resources, but not all activities add value. One of the causes of NVAAs in the onsite rebar production is a lack of storage and working space. Due to this problem, there is double handling of rebar and unnecessary transportation from one place to another. Similarly, improper rebar storage on the pathway disrupts the working environment. This unsatisfactory site condition affects the productivity.

The second objective of the study was evaluating the two rebar production systems using the concept of Ohno's seven wastes. According to the study's findings, more of the wastes occurred in the on-site rebar production system than off-site production. Inventory is one of the Ohno's seven wastes. Storing rebar on the site is one of the observed wastes that takes up valuable space and creates congestion that disrupts the working environment. It is also difficult to handle the rebar properly on site. The other waste observed in site rebar production is overproduction, which is producing more than the required quantity or before the needed time. In the off-site production, overproduction was avoided by the pull production system, and unnecessary transportation and movement wastes were reduced due to the site arrangement. Additionally, in the off-site case, the project sites were free from all wastes due to rebar production.

The third objective of the study was to identify the motivating and challenging factors for the implementation of JIT in rebar production and delivery. The first thing that motivates JIT implementations in Ethiopia, especially in urban areas like Addis Ababa, is the reduction of space or congestion on the construction sites. The other motivating factors are reduction of the labor requirement, reduction of reinforcement bar wastage, and improvement of the traditional labor-intensive site rebar production practices. The identified challenging factors for JIT implementation are the challenges of adopting a new system, the availability of production areas, production capacity, and uncertainty issues, including supply shortages, price fluctuations, change orders, etc.

The fourth objective of the study was to develop a discrete event simulation model and check the performance of the two production systems. To analyze the effectiveness of the on-site and off-site rebar production systems, four simulation models with different scenarios were developed. The four scenarios were created based on the rebar diameter, number of cuts, and bending point. According to the result of the model analysis, the off-site production system performs better than the on-site production system in all scenarios. The on-site rebar production system takes more time than the off-site production. The off-site rebar production system reduced production time in the first scenario by 23.62%, in the second scenario by 23.71%, in the third scenario by 23.85%, and in the fourth scenario by 26.92%. Correspondingly, the productivity of the off-site rebar production system is greater than the on-site production, and the idleness of the cutting and bending machines is also lower in the off-site case than on-site.

Improving the rebar production process is the main objective of the study. In order to achieve this, it is essential to eliminate or reduce NVAAs from the production process. One method of improving production is to eliminate or simplify processes. Thus, straightening is one of the rebar production activities that does not add value but takes time. This activity could be removed from the rebar production process in two ways: one, by producing the rebar off-site in reinforcement bar factories, and two, by transporting straight rebar using low-bed trucks. Transporting straight rebar to different project sites using low-bed trucks will be challenging, but if the production takes place off-site in central production, it will be easy.

Generally, the study showed that preparing reinforcement bars on site is NVA in terms of waste reduction and value improvement. Therefore, it is important to overcome the current practice and eliminate the challenging factors for JIT implementation. The construction industry should understand the system and develop a proper implementation strategy. In addition, the government should control the market in order to reduce uncertainty.

5.2. Recommendation

In order to advance the construction industry and minimize the non-value-adding activities from the site rebar production practice, it is important to eliminate the challenging factors and adopt new important concepts like JIT.

1. Currently, most of the construction projects in Addis Ababa are high-rise buildings, and they don't have enough storage and working space. If the reinforcement bar production is done off-site and only delivered to the site for assembly, it will reduce the need for working space on site for storing and producing reinforcement bar.
2. The current site rebar production practice is more labor-intensive, traditional, and inefficient. When the production will be off-site, the workmanship needed on site will decrease. This results in less congestion and a lower risk for worker safety and health on the site. Ensuring safe working conditions on the site provides greater motivation and increases productivity.
3. The rebar factories currently produce and supply standard rebar length (usually 12 m). However, the rebar factories start the reinforcement bar production, including cutting and bending according to the customer's needs, and deliver it in accordance with the agreed delivery schedule, the rebar production will be simplified, and the onsite rebar inventory will be reduced. Additionally, extra processing time due to straightening and unnecessary transport will be reduced. Defects and reworks related to straightening will also be removed.
4. However, if rebar production is delegated to rebar manufacturers, the project site will not be in control of rebar production and will only be responsible for fixing activities. The burden on construction site employees is thus reduced.
5. In order to increase resource utilization rates and minimize the total initial cost for purchasing cutting and bending machines for each project. It is recommended for real estate companies, public condominium projects, and other contractors with multiple project sites to centralize their rebar production instead of distributing and preparing

reinforcement bars at each site. This production approach reduced wastage of rebar by using wastes or leftovers from one project on another.

6. The construction personnel could reduce the cycle time by removing unnecessary steps from the production of rebar. In order to minimize the non-value-adding activities, they should first give attention to the value enhancement concept. To increase value, changing and improving the reinforcement bar production approach is essential. One of the approaches to rebar production is to prepare reinforcement bars off-site and deliver them when they are needed.
7. If there is a huge reinforcement bar inventory which are stored in the site for long time it increase holding costs thus it is better to purchase the rebar when it is needed without storing on the site for the long time.

5.3. Recommendation for Further Study

In order to implement the JIT philosophy in the reinforcement bar production and delivery system, a deep investigation is needed. This research focused mainly on increasing the value of and reducing non-value-adding activities. Thus, using this study as a preliminary investigation, it is recommended to conduct further research and investigation on the cost analysis of the two rebar productions.

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Appendix 1- Case study one (On-site rebar production)

1-A. Collected data of rebar production activity duration

Rebar Diameter - 12

Time taken	Transport from storage to straightening	Return	Straightening	Select and transport to cutting area	Return	Cutting		Store	Transport to bending area	Return	Bending	Store/make it ready to transport
						3 times	4 times				1 point	
1	0.686	0.501	0.303	1.320	0.600	1.32	1.82	0.214	0.97	0.491	0.18	0.332
2	0.600	0.441	0.209	1.270	0.670	1.38	1.88	0.246	1.07	0.430	0.25	0.311
3	0.587	0.461	0.417	1.400	0.700	1.34	1.92	0.222	1.10	0.459	0.33	0.209
4	0.686	0.453	0.254	1.570	0.760	1.25	1.95	0.256	0.93	0.494	0.28	0.287
5	0.673	0.470	0.282	1.300	0.820	1.33	1.65	0.220	0.81	0.435	0.26	0.307
6	0.702	0.476	0.246	1.250	0.630	1.27	2.03	0.300	1.02	0.478	0.29	0.282
7	0.688	0.427	0.215	1.410	0.910	1.48	1.88	0.238	0.96	0.454	0.25	0.311
8	0.651	0.488	0.192	1.530	0.800	1.35	1.75	0.223	0.84	0.415	0.31	0.226
9	0.653	0.507	0.284	1.130	0.640	1.28	1.98	0.254	1.05	0.460	0.22	0.254
10	0.664	0.469	0.391	1.120	0.670	1.30	2.02	0.221	0.88	0.484	0.26	0.257
11	0.702	0.441	0.322	1.460	0.840	1.25	1.67	0.218	1.05	0.437	0.28	0.275
12	0.613	0.482	0.336	1.420	0.560	1.41	1.93	0.280	1.08	0.420	0.24	0.239
13	0.570	0.487	0.232	1.080	0.700	1.27	1.85	0.208	0.86	0.410	0.32	0.301
14	0.689	0.509	0.262	1.490	0.710	1.49	1.77	0.272	0.99	0.441	0.28	0.255
15	0.635	0.462	0.323	1.380	0.610	1.35	1.65	0.206	1.06	0.408	0.24	0.290
16	0.591	0.504	0.358	1.680	0.620	1.42	1.70	0.243	0.81	0.456	0.22	0.252
17	0.681	0.435	0.261	1.440	0.550	1.45	1.92	0.252	0.89	0.425	0.26	0.280
18	0.621	0.512	0.375	1.290	0.570	1.27	2.10	0.203	1.02	0.406	0.21	0.256
19	0.710	0.484	0.289	1.180	0.750	1.32	1.87	0.224	0.83	0.483	0.26	0.285
20	0.572	0.510	0.325	1.410	0.560	1.25	1.98	0.267	0.93	0.431	0.28	0.242
21	0.708	0.456	0.281	1.280	0.700	1.33	1.78	0.245	1.07	0.495	0.24	0.311
22	0.660	0.500	0.373	1.720	0.870	1.43	1.93	0.324	1.04	0.415	0.26	0.285
23	0.650	0.475	0.293	1.300	0.720	1.28	1.68	0.233	1.10	0.474	0.30	0.238
24	0.614	0.479	0.252	1.610	0.750	1.32	2.02	0.211	1.05	0.442	0.22	0.260
25	0.602	0.475	0.301	1.560	0.610	1.34	2.05	0.270	0.82	0.463	0.28	0.275
26	0.589	0.492	0.234	1.230	0.770	1.30	1.87	0.237	0.99	0.469	0.18	0.306
27	0.710	0.454	0.230	1.440	0.550	1.27	1.81	0.222	1.05	0.408	0.22	0.250
28	0.701	0.425	0.323	1.710	0.700	1.33	1.75	0.261	1.08	0.479	0.24	0.233
29	0.639	0.438	0.418	1.250	0.900	1.31	1.63	0.232	0.95	0.431	0.27	0.289
30	0.578	0.475	0.351	1.650	0.630	1.36	1.82	0.284	0.92	0.461	0.20	0.287
31	0.694	0.505	0.303	1.230	0.790	1.42	1.87	0.276	0.87	0.492	0.25	0.245
32	0.642	0.452	0.271	1.160	0.970	1.30	1.92	0.212	0.98	0.452	0.22	0.301
33	0.680	0.447	0.328	1.350	0.920	1.40	1.65	0.244	0.94	0.413	0.30	0.269
34	0.620	0.498	0.290	1.580	0.610	1.30	1.83	0.310	0.85	0.450	0.29	0.262
35	0.634	0.511	0.258	1.320	0.560	1.33	1.97	0.233	1.03	0.473	0.22	0.288
36	0.656	0.463	0.309	1.500	0.850	1.40	1.72	0.248	0.99	0.424	0.20	0.249
37	0.687	0.434	0.337	1.780	0.590	1.38	1.68	0.208	0.88	0.432	0.27	0.248
38	0.670	0.432	0.255	1.220	0.720	1.50	1.80	0.243	0.98	0.444	0.31	0.320
39	0.633	0.489	0.206	1.340	0.830	1.37	1.68	0.274	0.96	0.420	0.22	0.300
40	0.631	0.445	0.270	1.280	0.820	1.45	1.65	0.223	1.03	0.474	0.30	0.276
41	0.618	0.456	0.246	1.200	0.620	1.42	1.95	0.257	0.91	0.407	0.33	0.263
42	0.671	0.478	0.287	1.480	0.570	1.38	1.77	0.242	0.99	0.493	0.25	0.309
43	0.644	0.467	0.356	1.550	0.640	1.47	1.67	0.228	0.94	0.430	0.28	0.274
44	0.674	0.436	0.305	1.380	0.750	1.40	1.70	0.213	1.05	0.458	0.26	0.293
45	0.700	0.487	0.272	1.170	0.580	1.51	1.85	0.236	0.92	0.420	0.28	0.220
46	0.653	0.452	0.328	1.350	0.780	1.47	2.07	0.295	1.03	0.432	0.26	0.249
47	0.676	0.461	0.287	1.620	0.740	1.37	1.75	0.233	0.83	0.487	0.25	0.240
48	0.636	0.463	0.263	1.200	0.860	1.39	1.65	0.253	1.00	0.444	0.29	0.300
49	0.678	0.472	0.344	1.200	0.600	1.43	1.73	0.234	0.96	0.417	0.24	0.220
50	0.658	0.451	0.325	1.280	0.850	1.35	1.83	0.212	0.80	0.489	0.28	0.256

Rebar Diameter - 14												
Time taken	Transport from storage to straightening	Return	Straightening	Select and transport to cutting area	Return	Cutting		Store	Transport to bending area	Return	Bending	Store/make it ready to transport
						2 times	3 times				1 point	
1	0.670	0.469	0.255	1.91	1.06	1.120	1.46	0.258	1.28	0.541	0.251	0.254
2	0.627	0.433	0.229	1.82	1.14	1.090	1.58	0.283	1.11	0.499	0.287	0.296
3	0.669	0.459	0.344	2.07	1.17	0.990	1.53	0.323	1.13	0.521	0.243	0.220
4	0.588	0.433	0.298	2.09	1.08	0.956	1.49	0.296	1.22	0.460	0.283	0.310
5	0.654	0.434	0.248	1.86	1.11	1.057	1.56	0.260	1.09	0.528	0.303	0.283
6	0.679	0.419	0.343	2.02	1.13	0.959	1.44	0.259	1.04	0.470	0.226	0.210
7	0.649	0.438	0.314	2.09	1.20	1.007	1.49	0.303	1.24	0.543	0.175	0.332
8	0.677	0.472	0.346	1.78	1.17	1.250	1.61	0.241	1.00	0.519	0.334	0.201
9	0.672	0.451	0.330	2.16	1.15	0.973	1.48	0.284	1.13	0.535	0.279	0.254
10	0.685	0.427	0.278	1.50	1.18	1.040	1.56	0.320	1.15	0.530	0.199	0.290
11	0.585	0.420	0.263	1.37	1.11	1.241	1.43	0.280	1.22	0.499	0.264	0.215
12	0.590	0.469	0.277	2.01	1.21	0.923	1.46	0.237	0.99	0.540	0.292	0.273
13	0.646	0.442	0.324	1.86	1.16	0.890	1.53	0.302	1.32	0.510	0.236	0.254
14	0.635	0.425	0.239	2.11	0.91	1.007	1.49	0.324	1.21	0.548	0.214	0.326
15	0.587	0.439	0.282	2.07	1.23	1.107	1.58	0.271	1.28	0.487	0.179	0.284
16	0.618	0.429	0.210	1.94	1.08	1.240	1.51	0.302	1.04	0.490	0.271	0.243
17	0.600	0.452	0.336	1.62	0.87	0.957	1.44	0.252	1.15	0.513	0.270	0.252
18	0.652	0.489	0.300	2.11	1.12	0.990	1.56	0.292	1.22	0.506	0.309	0.230
19	0.620	0.440	0.337	2.16	1.20	1.040	1.43	0.239	1.02	0.471	0.253	0.303
20	0.608	0.431	0.316	1.87	0.98	1.107	1.48	0.270	1.24	0.500	0.303	0.294
21	0.637	0.480	0.344	1.96	1.13	1.157	1.54	0.318	1.28	0.530	0.325	0.238
22	0.632	0.492	0.287	2.07	1.03	0.923	1.49	0.315	1.09	0.506	0.221	0.318
23	0.680	0.454	0.326	1.84	1.23	0.973	1.46	0.267	1.11	0.470	0.199	0.219
24	0.570	0.434	0.217	2.04	1.22	1.247	1.59	0.301	1.16	0.524	0.236	0.259
25	0.628	0.484	0.289	1.86	1.15	1.007	1.48	0.277	1.09	0.534	0.306	0.308
26	0.686	0.417	0.341	1.59	1.05	1.057	1.44	0.252	1.12	0.480	0.225	0.208
27	0.671	0.496	0.270	1.81	1.18	0.907	1.56	0.286	1.15	0.467	0.183	0.300
28	0.610	0.448	0.311	1.76	1.03	0.940	1.53	0.317	1.03	0.516	0.241	0.268
29	0.579	0.425	0.246	2.02	1.20	1.023	1.58	0.275	1.06	0.508	0.247	0.250
30	0.655	0.482	0.340	1.61	1.21	1.160	1.46	0.318	1.17	0.520	0.267	0.321
31	0.602	0.453	0.331	1.92	1.13	1.207	1.51	0.238	1.25	0.535	0.312	0.240
32	0.630	0.428	0.265	2.16	0.85	1.180	1.54	0.281	1.08	0.484	0.310	0.276
33	0.594	0.469	0.320	2.07	1.12	0.957	1.51	0.302	1.08	0.518	0.245	0.303
34	0.667	0.421	0.236	1.47	1.18	0.882	1.43	0.252	1.16	0.461	0.275	0.234
35	0.600	0.429	0.329	2.11	1.05	0.873	1.48	0.258	1.22	0.460	0.255	0.254
36	0.635	0.468	0.280	1.70	0.94	1.190	1.54	0.322	1.17	0.477	0.335	0.300
37	0.621	0.442	0.309	1.64	1.14	1.242	1.44	0.271	1.01	0.468	0.294	0.305
38	0.658	0.462	0.233	1.57	0.97	0.923	1.53	0.256	1.10	0.514	0.243	0.251
39	0.650	0.428	0.217	1.71	1.12	1.022	1.49	0.310	1.15	0.480	0.317	0.318
40	0.605	0.464	0.260	1.97	1.08	0.890	1.43	0.257	1.03	0.479	0.210	0.274
41	0.642	0.417	0.304	1.77	0.91	1.223	1.51	0.305	1.27	0.542	0.237	0.260
42	0.619	0.443	0.278	1.87	1.19	1.160	1.46	0.278	1.14	0.518	0.290	0.230
43	0.580	0.471	0.254	1.94	1.15	1.117	1.61	0.248	1.05	0.454	0.231	0.226
44	0.665	0.431	0.319	2.04	0.97	0.908	1.58	0.291	1.21	0.500	0.193	0.280
45	0.677	0.460	0.339	1.43	0.85	1.190	1.48	0.246	1.17	0.485	0.288	0.323
46	0.640	0.447	0.277	1.38	1.12	1.090	1.43	0.283	1.09	0.504	0.324	0.243
47	0.601	0.458	0.230	1.99	0.79	0.873	1.56	0.268	1.22	0.522	0.280	0.271
48	0.610	0.450	0.315	2.16	1.16	0.940	1.53	0.309	1.17	0.499	0.183	0.251
49	0.656	0.444	0.297	2.06	1.08	1.073	1.58	0.262	1.31	0.526	0.320	0.287
50	0.612	0.422	0.325	1.76	0.96	1.250	1.48	0.292	1.07	0.549	0.220	0.319

Rebar Diameter - 16

Time taken	Transport from storage to straightening	Return	Straightening	Transport to cutting area	Return	Cutting			Store	Transport to bending area	Return	Bending	Store/make it ready to transport
						1 times	2 times	3 times				2 point	
1	0.585	0.442	0.372	1.49	1.020	0.291	1.120	1.45	0.348	1.12	0.554	0.635	0.28
2	0.650	0.496	0.304	1.93	0.929	0.336	1.090	1.58	0.391	1.22	0.506	0.684	0.22
3	0.646	0.432	0.340	1.70	0.911	0.179	0.990	1.53	0.346	1.14	0.535	0.737	0.33
4	0.635	0.479	0.299	1.76	0.838	0.258	0.956	1.49	0.383	1.22	0.570	0.673	0.22
5	0.587	0.509	0.405	1.67	0.980	0.209	1.060	1.56	0.368	1.25	0.511	0.609	0.26
6	0.618	0.439	0.363	2.06	0.888	0.269	0.959	1.44	0.309	0.95	0.567	0.686	0.29
7	0.600	0.430	0.298	1.75	0.933	0.312	1.010	1.49	0.362	1.24	0.530	0.738	0.21
8	0.652	0.485	0.306	1.62	0.950	0.249	1.250	1.61	0.384	1.27	0.491	0.624	0.27
9	0.620	0.454	0.403	1.54	0.904	0.325	0.973	1.48	0.314	1.25	0.536	0.633	0.25
10	0.608	0.502	0.348	2.04	0.929	0.231	1.040	1.56	0.383	1.15	0.560	0.685	0.33
11	0.637	0.469	0.294	1.61	0.915	0.199	1.240	1.43	0.323	1.03	0.513	0.780	0.31
12	0.632	0.433	0.361	1.67	0.819	0.237	0.923	1.46	0.396	1.15	0.576	0.649	0.24
13	0.654	0.459	0.304	1.53	0.950	0.287	0.890	1.53	0.361	1.23	0.486	0.702	0.23
14	0.636	0.427	0.389	1.57	0.797	0.356	1.070	1.49	0.359	0.95	0.517	0.770	0.21
15	0.628	0.434	0.346	1.89	0.870	0.182	1.170	1.58	0.290	1.25	0.484	0.688	0.30
16	0.686	0.419	0.386	1.81	0.883	0.208	1.240	1.51	0.341	1.22	0.532	0.719	0.29
17	0.671	0.438	0.372	2.09	0.814	0.193	0.957	1.44	0.323	1.05	0.501	0.702	0.24
18	0.598	0.472	0.321	1.59	0.832	0.238	0.990	1.56	0.380	1.19	0.582	0.670	0.32
19	0.679	0.451	0.298	2.09	0.860	0.204	1.040	1.43	0.237	1.12	0.559	0.805	0.22
20	0.655	0.427	0.344	1.52	0.821	0.191	1.110	1.48	0.302	1.10	0.499	0.635	0.26
21	0.602	0.419	0.250	1.61	0.926	0.271	1.160	1.54	0.324	1.24	0.571	0.677	0.31
22	0.641	0.469	0.330	1.73	0.870	0.169	0.923	1.49	0.271	1.21	0.491	0.646	0.22
23	0.694	0.442	0.257	2.05	0.821	0.227	0.973	1.46	0.294	1.27	0.550	0.669	0.30
24	0.667	0.422	0.228	1.95	0.906	0.252	1.250	1.59	0.252	1.22	0.518	0.713	0.24
25	0.600	0.439	0.380	1.91	0.870	0.177	1.010	1.48	0.387	1.10	0.539	0.650	0.25
26	0.635	0.429	0.416	1.60	0.884	0.170	1.060	1.44	0.339	1.25	0.545	0.759	0.32
27	0.621	0.452	0.314	1.73	0.803	0.205	0.907	1.56	0.370	1.16	0.484	0.756	0.22
28	0.658	0.489	0.286	1.49	1.010	0.196	0.940	1.53	0.264	1.22	0.555	0.786	0.28
29	0.668	0.440	0.225	2.13	0.838	0.303	1.030	1.58	0.315	1.25	0.507	0.737	0.30
30	0.605	0.431	0.352	1.51	1.040	0.206	1.160	1.46	0.367	1.11	0.537	0.667	0.23
31	0.642	0.480	0.382	1.99	0.848	0.177	1.210	1.51	0.301	1.08	0.568	0.702	0.25
32	0.689	0.492	0.246	1.86	1.020	0.271	1.180	1.54	0.377	1.03	0.528	0.684	0.27
33	0.594	0.454	0.274	1.67	0.795	0.237	0.957	1.51	0.352	1.18	0.489	0.656	0.30
34	0.665	0.427	0.385	1.85	0.990	0.288	0.882	1.43	0.386	1.22	0.526	0.687	0.25
35	0.677	0.469	0.377	1.67	0.818	0.191	0.873	1.48	0.317	1.15	0.549	0.736	0.32
36	0.640	0.417	0.299	1.52	0.964	0.189	1.190	1.54	0.360	1.23	0.500	0.767	0.27
37	0.601	0.496	0.313	1.80	0.850	0.178	1.240	1.44	0.318	1.15	0.500	0.695	0.22
38	0.599	0.448	0.238	1.69	0.850	0.206	0.923	1.53	0.338	1.23	0.520	0.728	0.26
39	0.656	0.425	0.321	1.65	0.935	0.242	1.020	1.49	0.381	1.12	0.584	0.653	0.23
40	0.612	0.489	0.347	1.57	0.911	0.335	0.890	1.43	0.282	1.12	0.550	0.779	0.28
41	0.623	0.453	0.281	1.97	0.884	0.181	1.220	1.51	0.352	1.20	0.483	0.808	0.32
42	0.670	0.428	0.353	2.03	0.830	0.319	1.160	1.46	0.358	1.07	0.569	0.664	0.24
43	0.634	0.469	0.356	1.73	0.896	0.218	1.120	1.61	0.322	1.15	0.506	0.648	0.23
44	0.603	0.421	0.363	1.58	0.875	0.271	0.908	1.58	0.371	1.21	0.534	0.612	0.21
45	0.654	0.446	0.290	1.65	0.848	0.173	1.190	1.48	0.356	1.22	0.536	0.691	0.29
46	0.618	0.468	0.393	2.02	0.919	0.261	1.090	1.43	0.312	1.27	0.508	0.806	0.32
47	0.594	0.442	0.267	1.77	0.837	0.172	0.873	1.56	0.357	1.20	0.520	0.621	0.22
48	0.667	0.462	0.339	1.49	0.972	0.192	0.940	1.53	0.296	0.99	0.563	0.678	0.29
49	0.652	0.428	0.342	1.64	0.858	0.320	1.070	1.58	0.378	1.17	0.493	0.630	0.23
50	0.649	0.464	0.302	1.92	0.840	0.174	1.250	1.48	0.321	1.12	0.565	0.659	0.31

Rebar Diameter - 20											
Time taken	Transport from storage to straightening	Return	Straightening	Transport after straightening to cutting area	Return	Cutting 2 times	Store	Transport to bending area	Return	Bending 1 point	Store/make it ready to transport
1	0.670	0.487	0.298	1.33	1.140	0.98	0.318	1.15	0.509	0.180	0.195
2	0.707	0.453	0.489	1.52	1.160	0.95	0.361	1.23	0.511	0.250	0.275
3	0.669	0.471	0.450	1.40	1.190	1.05	0.316	1.15	0.483	0.330	0.305
4	0.688	0.431	0.270	1.63	1.000	1.04	0.353	1.23	0.495	0.280	0.205
5	0.600	0.460	0.329	2.05	1.230	1.00	0.338	1.14	0.538	0.260	0.275
6	0.679	0.447	0.394	1.92	0.989	1.11	0.279	1.12	0.468	0.290	0.215
7	0.650	0.458	0.298	1.88	1.060	1.08	0.332	1.20	0.540	0.250	0.295
8	0.650	0.450	0.33	2.03	1.110	1.24	0.354	1.07	0.525	0.310	0.303
9	0.672	0.444	0.30	1.95	0.980	0.96	0.284	1.15	0.493	0.220	0.255
10	0.682	0.422	0.420	1.63	0.920	1.03	0.353	1.25	0.514	0.260	0.246
11	0.676	0.486	0.434	1.67	1.070	1.23	0.305	1.08	0.520	0.280	0.235
12	0.704	0.461	0.287	1.75	0.960	0.91	0.366	1.27	0.459	0.240	0.215
13	0.671	0.445	0.356	1.83	0.900	0.88	0.331	1.20	0.530	0.320	0.265
14	0.650	0.495	0.436	2.08	0.840	1.01	0.329	0.99	0.488	0.280	0.305
15	0.682	0.412	0.370	1.85	1.090	1.10	0.273	1.17	0.551	0.240	0.225
16	0.676	0.456	0.469	1.90	0.890	1.15	0.311	1.12	0.461	0.220	0.215
17	0.590	0.485	0.282	1.45	1.030	0.91	0.260	1.21	0.492	0.260	0.265
18	0.659	0.417	0.362	1.68	0.820	0.96	0.350	1.27	0.459	0.210	0.205
19	0.622	0.417	0.319	1.53	0.900	1.24	0.250	1.22	0.507	0.260	0.315
20	0.640	0.491	0.384	1.47	1.060	1.23	0.230	1.10	0.476	0.280	0.205
21	0.634	0.415	0.267	2.17	0.960	0.95	0.294	1.25	0.476	0.240	0.235
22	0.714	0.478	0.419	1.97	0.910	1.00	0.241	1.16	0.510	0.260	0.278
23	0.58	0.421	0.320	1.92	1.090	0.98	0.282	1.22	0.545	0.300	0.195
24	0.63	0.467	0.284	1.82	0.890	1.03	0.222	1.25	0.486	0.220	0.255
25	0.661	0.482	0.450	1.58	0.900	1.10	0.357	1.11	0.542	0.280	0.285
26	0.640	0.451	0.420	1.93	0.860	1.05	0.309	1.08	0.505	0.180	0.215
27	0.630	0.489	0.321	2.02	0.930	0.90	0.340	1.03	0.466	0.220	0.235
28	0.570	0.456	0.372	1.98	0.980	0.97	0.288	1.14	0.557	0.240	0.255
29	0.664	0.438	0.390	1.95	0.870	1.01	0.285	1.22	0.534	0.270	0.285
30	0.572	0.477	0.300	1.85	0.884	1.15	0.337	1.15	0.482	0.200	0.235
31	0.608	0.442	0.403	1.78	0.990	1.20	0.271	1.23	0.546	0.250	0.308
32	0.600	0.496	0.339	1.63	1.020	0.91	0.347	1.20	0.466	0.220	0.245
33	0.663	0.432	0.285	1.89	0.860	1.01	0.322	1.25	0.511	0.300	0.265
34	0.660	0.479	0.271	1.88	0.960	0.88	0.356	1.26	0.535	0.290	0.235
35	0.59	0.455	0.361	1.87	0.988	1.21	0.287	0.99	0.475	0.220	0.315
36	0.65	0.439	0.435	1.78	0.990	1.15	0.330	1.19	0.495	0.200	0.265
37	0.541	0.430	0.317	1.65	1.170	1.11	0.300	1.12	0.559	0.270	0.225
38	0.612	0.485	0.269	1.70	0.890	1.17	0.308	1.14	0.482	0.310	0.215
39	0.585	0.454	0.367	1.91	0.930	0.95	0.351	1.24	0.512	0.220	0.195
40	0.694	0.423	0.339	1.80	0.890	0.87	0.260	1.21	0.543	0.300	0.292
41	0.624	0.434	0.390	1.70	0.840	0.86	0.322	1.05	0.503	0.330	0.279
42	0.607	0.465	0.402	1.58	0.920	1.18	0.328	1.05	0.464	0.250	0.225
43	0.554	0.470	0.349	1.38	1.220	1.23	0.292	1.18	0.501	0.280	0.235
44	0.637	0.486	0.310	1.92	0.980	1.04	0.341	1.26	0.524	0.260	0.305
45	0.689	0.460	0.433	1.78	1.091	1.18	0.326	1.05	0.483	0.280	0.205
46	0.708	0.473	0.340	2.08	1.200	1.08	0.254	1.24	0.529	0.260	0.285
47	0.626	0.449	0.385	1.63	1.080	0.86	0.327	1.27	0.525	0.250	0.255
48	0.640	0.426	0.450	1.83	1.130	0.93	0.285	1.25	0.458	0.290	0.205
49	0.701	0.481	0.353	1.42	0.996	1.06	0.348	1.16	0.544	0.240	0.245
50	0.620	0.464	0.357	2.02	1.050	1.24	0.260	1.03	0.481	0.280	0.295

Time taken	Select and put to cutting/bending machine			Time taken	Transport from production to fixing area			Time taken	Return to production area		
1	0.117	31	0.095	1	4.200	31	4.717	1	3.083	31	2.817
2	0.100	32	0.094	2	4.083	32	4.650	2	2.750	32	2.850
3	0.107	33	0.118	3	4.317	33	4.967	3	2.833	33	2.700
4	0.098	34	0.098	4	4.367	34	4.267	4	2.767	34	3.117
5	0.135	35	0.104	5	4.833	35	4.583	5	2.800	35	3.033
6	0.101	36	0.096	6	5.100	36	4.183	6	3.033	36	2.917
7	0.121	37	0.137	7	4.250	37	4.500	7	3.233	37	2.967
8	0.103	38	0.093	8	4.100	38	4.650	8	2.917	38	2.817
9	0.105	39	0.101	9	4.333	39	4.367	9	2.800	39	2.900
10	0.124	40	0.103	10	4.350	40	4.633	10	2.867	40	3.083
11	0.109	41	0.088	11	4.300	41	4.267	11	3.017	41	3.133
12	0.146	42	0.128	12	4.633	42	4.567	12	2.850	42	2.767
13	0.116	43	0.091	13	4.500	43	4.417	13	2.917	43	2.817
14	0.094	44	0.086	14	4.267	44	4.467	14	3.183	44	2.867
15	0.105	45	0.105	15	4.833	45	4.500	15	3.050	45	3.117
16	0.138	46	0.138	16	4.733	46	4.250	16	3.150	46	3.167
17	0.119	47	0.106	17	4.967	47	4.333	17	2.867	47	2.817
18	0.131	48	0.100	18	5.083	48	4.033	18	2.650	48	2.950
19	0.091	49	0.101	19	4.333	49	4.267	19	2.883	49	2.767
20	0.108	50	0.119	20	4.267	50	4.417	20	2.950	50	3.030
21	0.135	51	0.103	21	4.167	51	4.183	21	2.983	51	2.983
22	0.094	52	0.090	22	4.783	52	4.617	22	3.083	52	3.183
23	0.097	53	0.099	23	4.117	53	4.500	23	3.200	53	3.100
24	0.099	54	0.104	24	4.250	54	4.600	24	2.933	54	2.967
25	0.118	55	0.090	25	4.667	55	4.333	25	2.900	55	2.817
26	0.120	56	0.102	26	4.333	56	4.800	26	2.967	56	2.783
27	0.109	57	0.094	27	4.633	57	4.500	27	3.017	57	3.083
28	0.100	58	0.118	28	4.500	58	4.583	28	3.150	58	2.817
29	0.136	59	0.134	29	4.917	59	4.650	29	2.800	59	2.950
30	0.107	60	0.102	30	4.367	60	4.950	30	2.717	60	2.767

1-B. Overall the rebar production diameter, length and bending point

Diameter	Optimized cutting length					Total length	No of berga	No of cut	Bending point		Straight bar	Total pcs	Total bent pcs	Straight pcs	Minimize/waste pcs
									1	2					
	3.55	3.55	3.55	1.35		12	16	3	3			64	48	0	16
	3.6	3.6	3.6	1.2		12	6	3	3			24	18	0	6
	3.91	3.91	3.91	0.27		12	14	3			3	56	0	42	14
	4.05	4.05	3.5	0.4		12	10	3	2		1	40	20	10	10
	3.55	3.5	1.65	3.3		12	1	3	2		2	4	2	2	
	3.55	3.5	3.5	1.45		12	1	3	1		3	4	1	3	
	3.6	3.2	2.5	2.5	0.2	12	1	4	2		2	5	2	2	1
	3.2	3.2	2.9	2.5	0.2	12	22	4	1		3	110	22	66	22
	3.2	3.2	2.9	2.6	0.1	12	2	4	1		3	10	2	6	2
	3.2	3.2	3.2	2.25	0.15	12	26	4	1		3	130	26	78	26
	3.5	3.2	2.6	2.6	0.1	12	29	4			4	145	0	116	29
	3.5	3.5	2.5	2.5		12	16	3	2		2	64	32	32	
	3.5	3.5	3.2	1.65	0.15	12	35	4	2		2	175	70	70	35
	3.55	3.55	3.2	1.65	0.05	12	5	4	2		2	25	10	10	5
	4.2	2.45	2.45	2.45	0.45	12	9	4	3		1	45	27	9	9
12	4.2	2.55	2.55	2.55	0.15	12	10	4	3		1	50	30	10	10
	4.2	4.2	2.45	1.15		12	105	3	1		2	420	105	210	105
	4.2	4.2	2.65	0.95		12	87	3	1		2	348	87	174	87
	4.27	4.27	2.65	0.81		12	15	3	3			60	45	0	15
	4.2	4	2.65	1.15		12	1	3	1		2	4	1	2	1
	4.27	2.45	2.45	2.45	0.38	12	1	4	4			5	4	0	1
	3.95	3.95	3.95	0.15		12	11	3			3	44	0	33	11
	4.2	4.2	2.2	1.4		12	38	3	1		2	152	38	76	38
	4.2	4.2	2.35	1.25		12	24	3	1		2	96	24	48	24
	4.2	4.2	2.7	0.9		12	24	3	1		2	96	24	48	24
	4.2	4.2	3.47	0.13		12	12	3	1		2	48	12	24	12
	4.28	4.28	2.35	1.09		12	24	3	3			96	72	0	24
	5.75	3.95	2.2	0.1		12	15	3	1		2	60	15	30	15
	4.2	3.95	2.65	1.2		12	10	3	1		2	40	10	20	10
	4.28	2.35	2.2	3.17		12	1	3	3			4	3		1
	4.2	4.2	2.55	1.05		12	2	3	1		2	8	2	4	2

Diameter	Optimized cutting length					Total length	No of berga	No of cut	Bending point		Straight bar	Total pcs	Total bent pcs	Straight pcs	Minimize/waste pcs
									1	2					
	4.2	4.2	2.4	1.2		12	120	3			3	480	0	360	120
	4.2	4.2	1.6	1.6	0.4	12	80	4	2		2	400	160	160	80
	4.2	4.2	3.6			12	112	2			2	336	0	224	112
	5.06	5.06	1.88			12	90	2			2	270	0	180	90
	5.06	5.02	1.92			12	1	2	1		1	3	1	1	1
	5.02	5.02	1.96			12	44	2	2			132	88	0	44
	5.02	4.8	2.18			12	30	2	1		1	90	30	30	30
	4.8	4.8	2.4			12	36	2			2	108	0	72	36
	5.52	5.52	0.96			12	45	2	2			135	90	0	45
	5.39	5.39	1.22			12	270	2	2			810	540	0	270
	5.38	5.38	1.24			12	206	2	2			618	412	0	206
	5.23	5.23	1.54			12	112	2	2			336	224	0	112
	3.88	3.88	3.88	0.36		12	2	3	3			8	6	0	2
	5.02	3.88	2.35	0.75		12	37	3	3			148	111	0	37
14	5.13	5.13	1.74			12	15	2			2	45	0	30	15
	5.3	5.3	1.4			12	15	2			2	45	0	30	15
	5.4	3.25	3.25	0.1		12	6	3	3			24	18	0	6
	5.6	5.6	0.8			12	3	2			2	9	0	6	3
	5.84	5.84	0.32			12	52	2	2			156	104	0	52
	5.98	5.98	0.04			12	37	2			2	111	0	74	37
	6.33	5.52	0.15			12	30	2	2			90	60	0	30
	6.33	5.6	0.07			12	75	2	1		1	225	75	75	75
	7	4.8	0.2			12	30	2			2	90	0	60	30
	5.38	5.23	1.39			12	1	2	2			3	2	0	1
	5.4	4.8	1.8			12	1	2	1		1	3	1	1	1
	5.4	5.02	1.58			12	1	2	2			3	2	0	1
	5.6	3.25	2.35	0.8		12	1	3	2		1	4	2	1	1
	5.84	3.88	2.28			12	1	2	2			3	2	0	1
	5.98	3.88	2.14			12	1	2	1		1	3	1	1	1

Diameter	Optimized cutting length					Total length	No of berga	No of cut	Bending point		Straight bar	Total pcs	Total bent pcs	Straight pcs	Minimize/waste pcs
									1	2					
16	11.13	0.87				12	4	1		1		8	4	0	4
	10.44	1.56				12	4	1			1	8	0	4	4
	7.25	4.75				12	4	1			2	8	0	8	
	7	4.95	0.05			12	4	2		1	1	12	4	4	4
	7	4.05	0.95			12	2	2			2	6	0	4	2
	7	4	1			12	1	2			2	3	0	2	1
	4.05	4.05	3.85	0.05		12	4	3		1	2	16	4	8	4
	3.15	3.15	2.85	2.85		12	4	3			4	16	0	16	
	5.67	3.6	2.73			12	4	2			2	12	0	8	4
	6.2	3.85	1.95			12	4	2		1	1	12	4	4	4
	6.45	3.6	1.95			12	4	2		1	1	12	4	4	4
	9.74	2.26				12	4	1		1		8	4	0	4
	7.3	4.67	0.03			12	2	2			2	6	0	4	2
	4.75	3.6	3.6	0.05		12	4	3			3	16	0	12	4
	6	6				12	1	1			2	2	0	2	
	6.1	2.7	2.7	0.5		12	8	3			3	32		24	8
	6.1	5.9				12	4	1		1	1	8	4	4	
	6.9	5.1				12	4	1		1	1	8	4	4	
	5	3.6	3.3	0.1		12	2	3		2	1	8	4	2	2
	3.6	3.3	2.5	2.5	0.1	12	4	4		1	3	20	4	12	4
	6.3	5.5	0.2			12	4	2		1	1	12	4	4	4
	4.1	4.1	3.6	0.2		12	2	3			3	8	0	6	2
	4.9	3.3	3.3	0.5		12	1	3		3		4	3	0	1
	6	4.9	1.1			12	4	2		1	1	12	4	4	4
	4.9	4.9	2.2			12	6	2		2		18	12	0	6
	4	4	4			12	136	2			3	408	0	408	
20	10.8	1.2				12	3	1	1			6	3	0	3
	10.63	1.37				12	4	1	1			8	4	0	4
	10	2				12	4	1			1	8	0	4	4
	9.7	2.3				12	7	1	1			14	7	0	7
	9.5	2.5				12	23	1	1			46	23	0	23
	9.35	2.65				12	13	1	1			26	13	0	13
	9	3				12	12	1		1		24	12	0	12
	9	3				12	3	1	1			6	3	0	3
	8.88	3.04	0.08			12	4	2	1		1	12	4	4	4
	8.6	3.4				12	4	1	1		1	8	4	4	
	8.15	3.15	0.7			12	4	2	1		1	12	4	4	4
	8	3.6	0.4			12	3	2	1		1	9	3	3	3
	6.57	5.1	0.33			12	4	2			2	12	0	8	4
	6.4	3.6	2			12	4	2	1		1	12	4	4	4
	6.3	3.6	2.1			12	4	2	1		1	12	4	4	4
	6.3	5.7				12	30	1	1			60	30	0	30
	6.3	5.7				12	32	1			1	64		32	32
	6	6				12	9	1			2	18		18	
	6	5.85	0.15			12	1	2			2	3		2	1
	5.85	5.85	0.3			12	1	2			2	3		2	1
	5.57	5.57	0.86			12	2	2			2	6		4	2
	4.9	4.9	2.2			12	2	2			2	6		4	2
	4	4	4			12	128	2			3	384	0	384	

Appendix 2- Case study two (Off-site rebar production)

2-A. Collected data of rebar production activity duration

Rebar Diameter - 12													
Time taken	Transport from storage to straightening	Return	Straightening	Select, transport and put to cutting machine	Cutting		Move to bending place	Return to storage	Select and put to bending machine	Bending			Store/make it ready to transport
					3 times	4 times				1 point	2 point	4 point	
1	0.587	0.278	0.217	0.534	1.50	1.85	0.215	0.360	0.094	0.204	0.588	1.633	0.241
2	0.540	0.246	0.338	0.592	1.55	1.92	0.179	0.412	0.117	0.215	0.690	1.400	0.139
3	0.670	0.341	0.264	0.489	1.25	1.74	0.217	0.340	0.092	0.259	0.660	1.333	0.121
4	0.581	0.351	0.311	0.531	1.37	1.63	0.189	0.291	0.095	0.223	0.704	1.350	0.170
5	0.661	0.251	0.222	0.575	1.37	2.01	0.172	0.329	0.104	0.215	0.609	1.300	0.131
6	0.653	0.259	0.315	0.589	1.25	1.56	0.220	0.347	0.127	0.234	0.700	1.167	0.156
7	0.551	0.324	0.268	0.700	1.47	1.58	0.211	0.370	0.115	0.297	0.670	1.700	0.136
8	0.635	0.258	0.233	0.536	1.50	1.89	0.246	0.390	0.112	0.327	0.624	1.500	0.252
9	0.533	0.291	0.317	0.568	1.67	1.95	0.235	0.452	0.102	0.233	0.662	1.300	0.126
10	0.491	0.320	0.321	0.533	1.43	1.78	0.175	0.358	0.086	0.243	0.689	1.167	0.198
11	0.571	0.275	0.304	0.495	1.53	1.82	0.201	0.312	0.118	0.287	0.580	1.467	0.178
12	0.593	0.282	0.267	0.520	1.65	1.62	0.238	0.320	0.094	0.239	0.638	1.533	0.131
13	0.449	0.341	0.242	0.690	1.62	1.70	0.226	0.318	0.095	0.270	0.630	1.433	0.153
14	0.519	0.272	0.167	0.670	1.55	1.75	0.196	0.349	0.124	0.327	0.592	1.217	0.172
15	0.621	0.305	0.193	0.538	1.52	1.67	0.171	0.400	0.100	0.214	0.711	1.450	0.180
16	0.649	0.298	0.229	0.535	1.30	1.65	0.180	0.390	0.105	0.234	0.679	1.683	0.155
17	0.593	0.299	0.354	0.529	1.48	1.58	0.221	0.353	0.092	0.220	0.721	1.367	0.223
18	0.511	0.263	0.224	0.491	1.53	1.62	0.189	0.426	0.110	0.263	0.688	1.500	0.216
19	0.622	0.269	0.341	0.558	1.50	1.68	0.229	0.457	0.106	0.315	0.751	1.767	0.261
20	0.587	0.324	0.335	0.502	1.58	1.60	0.201	0.335	0.086	0.279	0.590	1.733	0.154
21	0.649	0.304	0.305	0.486	1.45	1.72	0.240	0.443	0.102	0.319	0.678	1.783	0.192
22	0.674	0.257	0.216	0.607	1.50	1.73	0.226	0.370	0.125	0.288	0.657	1.650	0.145
23	0.638	0.279	0.186	0.583	1.63	1.76	0.187	0.360	0.088	0.236	0.743	1.750	0.163
24	0.610	0.326	0.324	0.692	1.67	1.97	0.207	0.390	0.099	0.306	0.688	1.583	0.138
25	0.660	0.247	0.371	0.630	1.30	1.85	0.232	0.430	0.104	0.256	0.673	1.533	0.151
26	0.630	0.353	0.313	0.492	1.53	1.77	0.171	0.337	0.100	0.320	0.655	1.800	0.141
27	0.665	0.327	0.293	0.513	1.47	1.82	0.185	0.310	0.121	0.276	0.753	1.700	0.171
28	0.618	0.252	0.239	0.557	1.42	1.88	0.197	0.288	0.090	0.221	0.688	1.500	0.157
29	0.567	0.264	0.316	0.641	1.52	1.92	0.242	0.400	0.124	0.302	0.648	1.650	0.159
30	0.459	0.321	0.328	0.544	1.48	1.83	0.213	0.390	0.108	0.275	0.613	1.717	0.168
31	0.671	0.324	0.214	0.492	1.34	1.78	0.177	0.340	0.120	0.255	0.669	1.783	0.219
32	0.604	0.356	0.303	0.518	1.40	1.70	0.234	0.411	0.107	0.290	0.706	1.467	0.137
33	0.616	0.304	0.298	0.650	1.45	1.65	0.227	0.370	0.099	0.247	0.666	1.550	0.186
34	0.529	0.280	0.270	0.602	1.60	1.68	0.238	0.410	0.112	0.312	0.695	1.417	0.177
35	0.516	0.249	0.301	0.571	1.39	1.80	0.216	0.400	0.113	0.323	0.622	1.500	0.166
36	0.486	0.248	0.284	0.510	1.58	1.83	0.221	0.343	0.104	0.241	0.648	1.633	0.226
37	0.552	0.336	0.287	0.720	1.62	1.87	0.200	0.390	0.090	0.319	0.630	1.683	0.134
38	0.652	0.299	0.202	0.680	1.53	1.82	0.217	0.290	0.105	0.267	0.677	1.250	0.173
39	0.660	0.329	0.184	0.620	1.32	1.75	0.187	0.405	0.102	0.219	0.658	1.483	0.143
40	0.620	0.319	0.332	0.598	1.48	1.63	0.245	0.335	0.120	0.305	0.607	1.583	0.153
41	0.670	0.293	0.267	0.640	1.57	1.67	0.201	0.380	0.090	0.239	0.720	1.517	0.234
42	0.600	0.280	0.300	0.499	1.27	1.70	0.181	0.295	0.094	0.290	0.635	1.650	0.218
43	0.580	0.267	0.269	0.529	1.52	1.77	0.191	0.457	0.110	0.216	0.618	1.667	0.135
44	0.674	0.281	0.339	0.550	1.45	1.84	0.197	0.329	0.106	0.210	0.710	1.600	0.195
45	0.540	0.248	0.236	0.602	1.29	1.65	0.223	0.423	0.097	0.213	0.630	1.550	0.190
46	0.664	0.269	0.179	0.670	1.58	1.68	0.208	0.337	0.117	0.291	0.670	1.700	0.230
47	0.640	0.351	0.283	0.640	1.55	1.73	0.237	0.333	0.096	0.222	0.589	1.567	0.128
48	0.667	0.306	0.262	0.660	1.42	1.60	0.210	0.460	0.086	0.326	0.608	1.617	0.190
49	0.610	0.271	0.322	0.620	1.35	1.72	0.172	0.390	0.126	0.255	0.600	1.500	0.200
50	0.550	0.261	0.261	0.584	1.38	1.67	0.194	0.310	0.102	0.310	0.702	1.533	0.150

Rebar Diameter - 14												
Time taken	Transport from storage to straightening	Return	Straightening	Select, transport and put to cutting machine	Cutting		Move to bending place	Return to storage	Select and put to bending machine	Bending		Store/make it ready to transport
					2 times	3 times				1 point	2 point	
1	0.627	0.299	0.282	0.505	1.040	1.50	0.215	0.336	0.094	0.204	0.588	0.126
2	0.514	0.340	0.304	0.552	0.817	1.55	0.179	0.321	0.117	0.215	0.690	0.198
3	0.618	0.328	0.323	0.680	0.742	1.25	0.217	0.310	0.092	0.259	0.660	0.178
4	0.569	0.274	0.293	0.539	0.733	1.37	0.189	0.287	0.095	0.223	0.704	0.131
5	0.450	0.313	0.265	0.588	1.050	1.37	0.172	0.359	0.104	0.215	0.609	0.131
6	0.520	0.310	0.219	0.602	1.102	1.25	0.22	0.320	0.127	0.234	0.700	0.156
7	0.602	0.244	0.270	0.537	0.783	1.47	0.211	0.341	0.115	0.297	0.670	0.136
8	0.372	0.301	0.355	0.652	0.882	1.50	0.246	0.302	0.112	0.327	0.624	0.252
9	0.540	0.335	0.299	0.556	0.750	1.67	0.235	0.292	0.102	0.233	0.662	0.241
10	0.462	0.279	0.351	0.605	1.083	1.43	0.175	0.286	0.086	0.243	0.689	0.139
11	0.570	0.289	0.368	0.573	1.020	1.53	0.201	0.242	0.118	0.287	0.580	0.121
12	0.630	0.280	0.204	0.607	0.977	1.65	0.238	0.320	0.094	0.239	0.638	0.170
13	0.530	0.315	0.249	0.485	0.768	1.62	0.226	0.298	0.095	0.270	0.630	0.153
14	0.582	0.287	0.345	0.519	1.050	1.55	0.196	0.273	0.124	0.327	0.592	0.172
15	0.361	0.319	0.228	0.553	0.950	1.52	0.171	0.340	0.100	0.214	0.711	0.180
16	0.620	0.292	0.174	0.632	0.733	1.30	0.18	0.254	0.105	0.234	0.679	0.155
17	0.560	0.276	0.312	0.505	0.800	1.48	0.221	0.353	0.092	0.220	0.721	0.223
18	0.640	0.330	0.256	0.604	0.933	1.53	0.189	0.308	0.110	0.263	0.688	0.216
19	0.490	0.297	0.234	0.635	1.110	1.50	0.23	0.261	0.106	0.315	0.751	0.261
20	0.623	0.308	0.332	0.584	0.980	1.58	0.201	0.287	0.086	0.279	0.590	0.154
21	0.590	0.245	0.251	0.711	0.950	1.45	0.24	0.347	0.110	0.319	0.678	0.192
22	0.556	0.238	0.270	0.503	0.850	1.50	0.226	0.259	0.125	0.288	0.657	0.145
23	0.562	0.290	0.323	0.621	0.816	1.63	0.187	0.324	0.088	0.236	0.743	0.163
24	0.390	0.219	0.233	0.535	0.917	1.67	0.23	0.281	0.099	0.306	0.688	0.138
25	0.620	0.227	0.296	0.652	0.819	1.30	0.232	0.370	0.104	0.256	0.673	0.186
26	0.446	0.256	0.344	0.520	0.867	1.53	0.171	0.293	0.100	0.320	0.655	0.177
27	0.600	0.238	0.264	0.554	1.110	1.47	0.185	0.340	0.121	0.276	0.753	0.166
28	0.490	0.241	0.290	0.570	0.833	1.42	0.197	0.263	0.090	0.221	0.730	0.226
29	0.420	0.218	0.329	0.613	0.900	1.52	0.242	0.330	0.124	0.302	0.648	0.134
30	0.630	0.268	0.268	0.585	1.101	1.48	0.213	0.314	0.108	0.275	0.613	0.168
31	0.589	0.235	0.310	0.485	0.783	1.34	0.177	0.318	0.120	0.255	0.669	0.219
32	0.660	0.260	0.335	0.525	0.750	1.40	0.234	0.285	0.107	0.290	0.706	0.137
33	0.590	0.254	0.336	0.648	0.867	1.45	0.227	0.293	0.099	0.247	0.666	0.141
34	0.640	0.249	0.382	0.576	0.967	1.60	0.238	0.273	0.112	0.312	0.695	0.182
35	0.337	0.231	0.283	0.531	1.100	1.39	0.216	0.347	0.113	0.323	0.622	0.157
36	0.630	0.275	0.294	0.662	0.817	1.58	0.221	0.304	0.104	0.241	0.648	0.159
37	0.359	0.234	0.272	0.517	0.850	1.62	0.240	0.257	0.090	0.319	0.630	0.151
38	0.480	0.244	0.322	0.550	0.900	1.53	0.217	0.293	0.105	0.267	0.677	0.173
39	0.452	0.251	0.314	0.609	0.967	1.32	0.187	0.275	0.102	0.219	0.658	0.143
40	0.342	0.222	0.228	0.563	1.017	1.48	0.245	0.325	0.120	0.305	0.607	0.153
41	0.367	0.237	0.189	0.614	0.783	1.57	0.201	0.324	0.090	0.239	0.720	0.234
42	0.381	0.271	0.260	0.681	0.833	1.27	0.181	0.254	0.094	0.290	0.635	0.218
43	0.411	0.270	0.287	0.648	1.107	1.52	0.191	0.339	0.110	0.216	0.618	0.135
44	0.436	0.230	0.298	0.536	0.867	1.45	0.197	0.288	0.106	0.210	0.710	0.195
45	0.490	0.260	0.335	0.596	0.917	1.29	0.223	0.269	0.097	0.213	0.630	0.190
46	0.467	0.219	0.346	0.640	0.767	1.58	0.208	0.312	0.117	0.291	0.670	0.230
47	0.431	0.255	0.320	0.526	0.800	1.55	0.237	0.267	0.096	0.222	0.589	0.128
48	0.407	0.239	0.316	0.614	0.883	1.42	0.210	0.322	0.086	0.326	0.608	0.190
49	0.440	0.219	0.342	0.529	1.020	1.35	0.172	0.285	0.126	0.255	0.600	0.200
50	0.505	0.221	0.206	0.655	1.067	1.38	0.194	0.236	0.102	0.310	0.702	0.150

Rebar Diameter -16												
Time taken	Transport from storage to straightening	Return	Straightening	Select, transport and put to cutting machine	Cutting			Move to bending place	Return to storage	Select and put to bending machine	Bending	Store/make it ready to transport
					1 times	2 times	3 times				2 point	
1	0.510	0.354	0.284	0.485	0.160	1.040	1.47	0.235	0.341	0.094	0.588	0.211
2	0.570	0.299	0.326	0.534	0.171	0.817	1.58	0.199	0.296	0.117	0.690	0.221
3	0.664	0.347	0.300	0.468	0.269	0.742	1.65	0.181	0.326	0.092	0.660	0.265
4	0.510	0.349	0.316	0.520	0.208	0.733	1.31	0.191	0.357	0.095	0.704	0.274
5	0.369	0.313	0.392	0.434	0.237	1.050	1.33	0.197	0.321	0.104	0.609	0.285
6	0.619	0.328	0.325	0.667	0.207	1.102	1.60	0.223	0.274	0.127	0.700	0.308
7	0.575	0.299	0.384	0.759	0.257	0.783	1.49	0.208	0.286	0.115	0.670	0.221
8	0.661	0.352	0.263	0.473	0.210	0.882	1.57	0.237	0.265	0.112	0.624	0.311
9	0.620	0.321	0.277	0.685	0.302	0.750	1.35	0.210	0.322	0.102	0.662	0.239
10	0.560	0.334	0.324	0.512	0.251	1.083	1.45	0.196	0.254	0.086	0.689	0.295
11	0.647	0.334	0.239	0.804	0.161	1.020	1.40	0.175	0.279	0.118	0.580	0.250
12	0.562	0.260	0.282	0.852	0.289	0.977	1.57	0.180	0.311	0.094	0.638	0.316
13	0.530	0.232	0.210	0.510	0.195	0.768	1.38	0.221	0.259	0.095	0.630	0.228
14	0.630	0.241	0.336	0.732	0.341	1.050	1.35	0.189	0.346	0.124	0.592	0.289
15	0.520	0.237	0.258	0.465	0.162	0.950	1.62	0.236	0.271	0.100	0.711	0.251
16	0.550	0.280	0.337	0.735	0.197	0.733	1.64	0.250	0.406	0.105	0.679	0.273
17	0.434	0.218	0.216	0.630	0.331	0.800	1.37	0.240	0.324	0.092	0.721	0.303
18	0.580	0.274	0.327	0.618	0.174	0.933	1.47	0.197	0.356	0.110	0.688	0.260
19	0.502	0.227	0.245	0.490	0.162	1.110	1.39	0.242	0.370	0.106	0.751	0.283
20	0.526	0.290	0.408	0.704	0.336	0.980	1.43	0.213	0.421	0.086	0.590	0.208
21	0.436	0.320	0.283	0.467	0.318	0.950	1.68	0.177	0.340	0.110	0.678	0.253
22	0.378	0.256	0.308	0.815	0.237	0.850	1.62	0.234	0.242	0.125	0.657	0.234
23	0.415	0.267	0.351	0.784	0.303	0.816	1.40	0.227	0.359	0.088	0.743	0.300
24	0.480	0.260	0.405	0.817	0.173	0.917	1.53	0.238	0.411	0.115	0.688	0.276
25	0.337	0.221	0.339	0.820	0.284	0.819	1.55	0.216	0.330	0.104	0.673	0.240
26	0.365	0.300	0.285	0.721	0.329	0.867	1.43	0.221	0.422	0.100	0.655	0.295
27	0.434	0.269	0.377	0.655	0.365	1.110	1.40	0.210	0.325	0.121	0.753	0.279
28	0.459	0.260	0.313	0.754	0.176	0.833	1.53	0.217	0.269	0.090	0.688	0.252
29	0.389	0.240	0.294	0.767	0.308	0.900	1.63	0.271	0.300	0.124	0.648	0.286
30	0.500	0.258	0.334	0.818	0.179	1.101	1.55	0.197	0.259	0.108	0.613	0.268
31	0.467	0.220	0.302	0.469	0.306	0.783	1.58	0.220	0.246	0.120	0.669	0.302
32	0.423	0.252	0.317	0.546	0.260	0.750	1.53	0.211	0.287	0.107	0.706	0.320
33	0.452	0.280	0.352	0.600	0.235	0.867	1.43	0.246	0.342	0.099	0.666	0.277
34	0.600	0.243	0.272	0.581	0.161	0.967	1.62	0.235	0.232	0.112	0.695	0.304
35	0.399	0.260	0.401	0.735	0.232	1.100	1.50	0.189	0.288	0.113	0.622	0.238
36	0.428	0.230	0.389	0.673	0.189	0.817	1.48	0.201	0.342	0.104	0.648	0.268
37	0.407	0.223	0.373	0.800	0.224	0.850	1.60	0.230	0.289	0.090	0.630	0.302
38	0.413	0.251	0.361	0.653	0.187	0.900	1.51	0.226	0.267	0.105	0.677	0.222
39	0.342	0.310	0.345	0.670	0.157	0.967	1.37	0.217	0.401	0.102	0.658	0.235
40	0.435	0.277	0.354	0.736	0.223	1.017	1.41	0.187	0.371	0.120	0.607	0.270
41	0.366	0.250	0.322	0.668	0.184	0.783	1.56	0.245	0.253	0.090	0.720	0.261
42	0.341	0.244	0.291	0.593	0.168	0.833	1.43	0.261	0.285	0.094	0.635	0.233
43	0.372	0.270	0.410	0.661	0.202	1.107	1.31	0.172	0.401	0.110	0.618	0.250
44	0.410	0.224	0.326	0.564	0.250	0.867	1.55	0.194	0.312	0.106	0.710	0.207
45	0.471	0.280	0.311	0.536	0.317	0.917	1.34	0.211	0.354	0.097	0.630	0.317
46	0.503	0.272	0.255	0.487	0.164	0.767	1.67	0.273	0.412	0.117	0.670	0.287
47	0.550	0.243	0.343	0.501	0.186	0.800	1.52	0.227	0.332	0.096	0.589	0.230
48	0.427	0.235	0.312	0.542	0.170	0.883	1.40	0.188	0.302	0.086	0.608	0.271
49	0.352	0.220	0.283	0.616	0.289	1.020	1.48	0.204	0.381	0.126	0.600	0.240
50	0.336	0.275	0.272	0.640	0.154	1.067	1.33	0.215	0.290	0.102	0.702	0.216

Rebar Diameter - 20							
Time taken	Select, transport and put to cutting machine	Cutting	Move to bending place	Return to storage	Select and put to bending machine	Bending	Store/make it ready to transport
		2 times				1 point	
1	0.602	1.040	0.220	0.354	0.094	0.204	0.290
2	0.633	0.817	0.183	0.299	0.117	0.215	0.268
3	0.670	0.742	0.197	0.347	0.092	0.259	0.264
4	0.594	0.733	0.208	0.360	0.095	0.223	0.303
5	0.634	1.050	0.237	0.313	0.104	0.215	0.272
6	0.615	1.102	0.210	0.328	0.127	0.234	0.336
7	0.554	0.783	0.196	0.299	0.115	0.297	0.250
8	0.602	0.882	0.175	0.360	0.112	0.327	0.312
9	0.485	0.750	0.180	0.321	0.102	0.233	0.318
10	0.479	1.083	0.221	0.334	0.086	0.243	0.260
11	0.584	1.020	0.175	0.334	0.118	0.287	0.290
12	0.670	0.977	0.180	0.260	0.094	0.239	0.310
13	0.622	0.768	0.221	0.232	0.095	0.270	0.260
14	0.548	1.050	0.189	0.241	0.124	0.327	0.320
15	0.583	0.950	0.236	0.237	0.100	0.214	0.280
16	0.486	0.733	0.180	0.350	0.105	0.234	0.256
17	0.518	0.830	0.240	0.218	0.092	0.220	0.324
18	0.571	0.933	0.236	0.274	0.110	0.263	0.282
19	0.550	1.110	0.201	0.227	0.106	0.315	0.240
20	0.626	0.980	0.240	0.256	0.086	0.279	0.330
21	0.754	0.950	0.197	0.221	0.110	0.319	0.314
22	0.711	0.850	0.242	0.256	0.125	0.288	0.320
23	0.726	0.816	0.213	0.267	0.088	0.236	0.297
24	0.700	0.917	0.177	0.260	0.115	0.306	0.254
25	0.534	0.819	0.234	0.421	0.104	0.256	0.270
26	0.735	0.867	0.227	0.410	0.100	0.320	0.240
27	0.765	1.110	0.238	0.269	0.121	0.276	0.300
28	0.743	0.833	0.216	0.380	0.090	0.221	0.245
29	0.774	0.920	0.221	0.240	0.124	0.302	0.286
30	0.495	1.101	0.171	0.270	0.108	0.275	0.275
31	0.655	0.783	0.227	0.220	0.120	0.255	0.334
32	0.504	0.750	0.188	0.252	0.107	0.290	0.316
33	0.647	0.867	0.204	0.280	0.099	0.247	0.250
34	0.690	0.967	0.215	0.243	0.112	0.312	0.240
35	0.537	1.100	0.171	0.357	0.113	0.323	0.290
36	0.629	0.817	0.187	0.230	0.104	0.241	0.270
37	0.584	0.850	0.245	0.223	0.090	0.319	0.310
38	0.506	0.910	0.201	0.451	0.105	0.267	0.275
39	0.548	0.967	0.172	0.250	0.102	0.219	0.328
40	0.520	1.017	0.194	0.370	0.120	0.305	0.295
41	0.660	0.783	0.211	0.289	0.090	0.239	0.274
42	0.563	0.833	0.189	0.280	0.094	0.290	0.245
43	0.614	1.107	0.236	0.315	0.110	0.216	0.307
44	0.652	0.867	0.180	0.287	0.106	0.210	0.330
45	0.680	0.917	0.240	0.319	0.097	0.213	0.266
46	0.536	0.767	0.213	0.392	0.117	0.291	0.248
47	0.596	0.800	0.177	0.276	0.096	0.222	0.278
48	0.640	0.883	0.234	0.344	0.086	0.326	0.242
49	0.526	1.020	0.227	0.297	0.126	0.255	0.274
50	0.614	1.067	0.238	0.308	0.102	0.310	0.281

2-B. Overall the rebar production diameter, length and bending point

Diameter	Optimized cutting length						Total length	No of berga	No of cut	Bending point			Straight bar	Total pcs	Total bent pcs	Straight pcs	Minimize/ waste pcs
										1	2	4					
	9	3					12	20	1				2	40	0	40	
	3.67	3.67	3.67	0.96	0.03		12	37	4	1		3		185	148	0	37
	3.87	2.8	2.8	1.42	1.11		12	12	4	1	1	3		60	60	0	
	7.77	3	1.21	0.02			12	6	3		2		1	24	12	6	6
	7.77	1.93	1.15	1.15			12	53	3	1	2		1	212	159	53	
	3.87	3.87	1.42	1.42	1.42		12	1	4			2	3	5	2	3	
	3.57	3.57	1.41	1.15	1.15	1.15	12	48	5		3	2	1	288	240	48	
	3.67	3.57	3.57	1.15	0.04		12	77	4		1	3		385	308	0	77
	3.87	3.57	2.8	1.42	0.34		12	47	4			3	1	235	141	47	47
	3.87	3.87	2.8	1.15	0.31		12	24	4		1	3		120	96	0	24
	5.93	2.8	1.15	1.15	0.97		12	8	4		2	1	2	40	24	16	
	3.57	3.33	2.8	1.15	1.15		12	47	4		2	2	1	235	188	47	
12	3.87	2.8	2.8	1.42	1.11		12	10	4		1	3	1	50	40	10	
	3.87	2.8	1.92	1.15	1.15	1.11	12	11	5	1	3	2		66	66	0	
	7.77	3.06	1.15	0.02			12	21	3		2		1	84	42	21	21
	3.87	3	2.8	1.15	1.15	0.03	12	9	5		2	2	1	54	36	9	9
	3.57	3.57	2.8	1.15	0.9	0.01	12	6	5		1	3	1	36	24	6	6
	3.87	3.87	2.8	1.42	0.04		12	10	4			3	1	50	30	10	10
	3.87	3.87	1.96	1.15	1.15		12	1	4	1	2	2		5	5	0	
	3.87	3.67	1.15	1.15	1.15	1.01	12	1	5		3	2	1	6	5	1	
	3.87	3.87	2.8	1.42	0.04		12	2	4			3	1	10	6	2	2
	3.87	3.87	3.06	1.15	0.05		12	1	4		1	2	1	5	3	1	1
	3.87	3.57	3.57	0.96	0.03		12	1	4	1		3		5	4	0	1
	7.77	2.8	1.41	0.02			12	1	3		1	1	1	4	2	1	1
	7.77	2.8	1.15	0.28			12	1	3		2	1		4	3	0	1

Diameter	Optimized cutting length						Total length	No of berga	No of cut	Bending point(pcs)		Straight bar	Total pcs	Total Bent pcs	Straight pcs	Minimize /minimize pcs
										1 pt.	2pt.					
	4.84	4.84	1.08	1.08	0.16		12	1	4	2		2	5	2	2	1
	4.83	4.83	1.08	1.08	0.18		12	1	4	2		2	5	2	2	1
	4.82	4.82	1.08	1.08	0.2		12	2	4	2		2	10	4	4	2
	4.73	4.73	1.08	1.08	0.38		12	1	4	2		2	5	2	2	1
	4.72	4.72	1.08	1.08	0.4		12	1	4	2		2	5	2	2	1
	4.43	4.43	1.08	1.08	0.98		12	2	4	3		2	10	6	4	
	4.24	4.24	3.52				12	1	2			3	3	0	3	
	4.98	4.98	0.98	0.98	0.08		12	3	4	2		2	15	6	6	3
	4.49	4.49	0.98	0.98	0.98	0.08	12	2	5	3		2	12	6	4	2
	4.5	4.5	0.98	0.98	0.98	0.06	12	2	5	3		2	12	6	4	2
	4.44	3.77	3.77	0.02			12	1	3			3	4	0	3	1
	4.45	3.76	3.76	0.03			12	1	3			3	4	0	3	1
	4.46	3.75	3.75	0.04			12	1	3			3	4	0	3	1
	4.47	3.74	3.74	0.05			12	1	3			3	4	0	3	1
	4.51	4.51	0.98	0.98	0.98	0.04	12	3	5	3		2	18	9	6	3
	4.26	4.26	3.38	0.1			12	2	3			3	8	0	6	2
	5.23	3.37	3.37	0.03			12	3	3	1		2	12	3	6	3
	5.22	3.37	3.37	0.04			12	3	3	2		1	12	6	3	3
	5.21	3.37	3.37	0.05			12	3	3	2		1	12	6	3	3
	5.2	3.37	3.37	0.06			12	4	3	2		1	16	8	4	4
12	5.19	3.37	3.37	0.07			12	5	3	2		1	20	10	5	5
	5.18	3.37	3.37	0.08			12	6	3	2		1	24	12	6	6
	5.17	3.37	3.37	0.09			12	5	3	2		1	20	10	5	5
	5.26	3.37	3.37				12	3	2	2		1	9	6	3	
	5.03	4.81	1.08	1.08			12	1	3	2		2	4	2	2	
	4.39	4.23	3.37	0.01			12	2	3	1		2	8	2	4	2
	5.24	3.37	3.37	0.02			12	3	3	2		1	12	6	3	3
	5.04	4.8	1.08	1.08			12	3	3	2		2	12	6	6	
	5.05	4.79	1.08	1.08			12	4	3	2		2	16	8	8	
	5.06	4.78	1.08	1.08			12	3	3	2		2	12	6	6	
	5.07	4.77	1.08	1.08			12	2	3	2		2	8	4	4	
	5.08	4.76	1.08	1.08			12	6	3	2		2	24	12	12	
	4.52	4.52	0.98	0.98	0.98	0.02	12	1	5	3		2	6	3	2	1
	5.27	4.57	1.08	1.08			12	1	3	2		2	4	2	2	
	5.28	4.56	1.08	1.08			12	2	3	2		2	8	4	4	
	5.29	4.55	1.08	1.08			12	3	3	2		2	12	6	6	
	5.27	4.52	1.08	1.08	0.05		12	2	4	2		2	10	4	4	2
	4.61	4.25	1.08	1.08	0.98		12	2	4	3		2	10	6	4	
	4.46	4.3	1.08	1.08	1.08		12	2	4	3		2	10	6	4	
	5.09	4.75	1.08	1.08			12	2	3	2		2	8	4	4	
	4.4	4.23	3.37				12	1	2	1		2	3	1	2	
	4.41	4.22	3.37				12	2	2	1		2	6	2	4	

Diameter	Optimized cutting length						Total length	No of berga	No of cut	Bending point(pcs)		Straight bar	Total pcs	Total Bent pcs	Straight pcs	Minimize /minimize pcs
										1 pt.	2pt.					
	4.08	4.08	3.76	0.08			12	61	3	2		1	244	122	61	61
	4.08	4.08	3.72	0.12			12	30	3	2		1	120	60	30	30
	4.08	4.07	3.72	0.13			12	1	3	2		1	4	2	1	1
	4.07	4.07	3.72	0.14			12	30	3	2		1	120	60	30	30
	4.06	4.06	3.72	0.16			12	30	3	2		1	120	60	30	30
	4.06	4.05	3.72	0.17			12	1	3	2		1	4	2	1	1
	4.05	4.05	3.72	0.18			12	45	3	2		1	180	90	45	45
14	4.05	4.05	3.6	0.3			12	1	3	2		1	4	2	1	1
	4.05	4.05	3.56	0.34			12	14	3	2		1	56	28	14	14
	4.05	4.04	3.56	0.35			12	1	3	2		1	4	2	1	1
	4.04	4.04	3.56	0.36			12	30	3	2		1	120	60	30	30
	4.04	4.04	3.92				12	30	2	2		1	90	60	30	
	4.04	4.03	3.93				12	1	2	2		1	3	2	1	
	4.03	4.03	3.94				12	121	2	2		1	363	242	121	

Diameter	Optimized cutting length				Total length	No of berga	No of cut	Bending point (pcs)		Total pcs	Bent pcs	Straight pcs	Minimize/ waste pcs
								1point	2 point				
	4.95	4.95	2.1		12	75	2		2	225	150	-	75
	3.85	3.85	3.85	0.45	12	25	3		3	100	75	-	25
	4.95	3.85	2.9	0.3	12	44	3		3	176	132	-	44
	4.95	3.85	3	0.2	12	37	3		3	148	111	-	37
	4.6	3.85	3.35	0.2	12	94	3		3	376	282	-	94
	5.2	5.2	1.6		12	24	2		2	72	48	-	24
14	4.5	4.5	3		12	15	2		3	45	45	-	
	5.2	3.35	3.35	0.10	12	5	3		3	20	15	-	5
	4.95	3.85	3.2		12	1	2		2	3	2	-	1
	5.2	3.85	2.95		12	1	2		2	3	2	-	1
	3.8	3.8	3.8	0.6	12	30	3	3		120	90	-	30
	3.7	3.7	3.7	0.9	12	16	3	3		64	48	-	16
	4	4	4		12	46	2	3		138	138	-	
	3.8	3.8	3.8	0.6	12	22	3	3		88	66	-	22
20	3.7	3.7	3.7	0.9	12	10	3	3		40	30	-	10
	3.7	3.7	4.6		12	1	2	2		3	2	-	1

Diameter	Optimized cutting length						Total length	No of berga	No of cut	Bending point(pcs)		Straight bar	Total pcs	Total Bent pcs	Straight pcs	Minimize /minimize pcs
										1 pt.	2pt.					
16	3.67	3.67	3.67	0.99			12	101	3		3		404	303	0	101
20	4.48	4.48	2.23	0.81			12	39	3	1	2		156	117	0	39
	4.48	4.48	2.23	0.81			12	1	3	1		2	4	1	2	1
	4.48	4.48	2.23	0.81			12	2	3	1	1	1	8	4	2	2
	4.47	4.47	2.23	0.83			12	30	3	1	2		120	90	0	30
	4.47	4.47	2.23	0.83			12	2	3	1		2	8	2	4	2
	4.46	4.46	2.23	0.85			12	30	3	1	2		120	90	0	30
	4.44	4.44	3.1	0.02			12	57	3		2	1	228	114	57	57
	4.44	4.44	3.1	0.02			12	1	3		1	2	4	1	2	1
	4.43	4.43	3.1	0.04			12	38	3		2	1	152	76	38	38
	4.29	4.29	3.42				12	1	2			3	3	0	3	
	4.28	4.28	3.44				12	1	2			3	3	0	3	
	4.27	4.27	3.46				12	2	2			3	6	0	6	
	4.26	4.26	3.48				12	2	2			3	6	0	6	
	4.24	4.24	3.52				12	1	2			3	3	0	3	
	4	4	4				12	185	2			3	555	0	555	
	4.25	4.25	3.43	0.07			12	1	3			3	4	0	3	1
	4.22	4.22	3.45	0.11			12	1	3			3	4	0	3	1
	4.43	4.43	2.23	0.91			12	74	3	1	2		296	222	0	74
	4.43	4.43	2.23	0.91			12	4	3	1	1	1	16	8	4	4
	4.43	4.43	2.23	0.91			12	1	3	1		2	4	1	2	1
	5.29	4.45	2.23	0.03			12	2	3	1	1	1	8	4	2	2
	5.29	4.45	2.23	0.03			12	1	3	1		2	4	1	2	1
	5.28	4.45	2.23	0.04			12	4	3	1	1	1	16	8	4	4
	5.27	4.45	2.23	0.05			12	2	3	1	1	1	8	4	2	2
	5.27	4.45	2.23	0.05			12	1	3	1		2	4	1	2	1
	5.26	4.45	2.23	0.06			12	4	3	1	1	1	16	8	4	4
	5.25	4.45	2.23	0.07			12	4	3	1	1	1	16	8	4	4
	5.24	4.45	2.23	0.08			12	3	3	1	1	1	12	6	3	3
	5.23	4.45	2.23	0.09			12	4	3	1	1	1	16	8	4	4
	5.22	4.45	2.23	0.1			12	4	3	1	1	1	16	8	4	4
	5.21	4.45	2.23	0.11			12	6	3	1	1	1	24	12	6	6
	5.2	4.45	2.23	0.12			12	8	3	1	1	1	32	16	8	8
	5.19	4.45	2.23	0.13			12	3	3	1	1	1	12	6	3	3
	5.19	4.45	2.23	0.13			12	1	3	1		2	4	1	2	1
	5.18	4.45	2.23	0.14			12	3	3	1	1	1	12	6	3	3
	5.17	4.45	2.23	0.15			12	1	3	1	1	1	4	2	1	1
	4.25	4.22	3.53				12	1	2			3	3	0	3	

Diameter	Optimized cutting length						Total length	No of berga	No of cut	Bending point			Straight bar	Total pcs	Total bent pcs	Straight pcs	Minimize/ waste pcs
										1	2	4					
16	9	2.82	0.18				12	9	2				2	27	0	18	9
	9	2.82	0.18				12	5	2				2	15	0	10	5
	9	2.83	0.17				12	17	2				2	51	0	34	17
	9	2.83	0.17				12	11	2				2	33	0	22	11
	9	1.55	1.42	0.03			12	10	3	1			2	40	10	20	10
	9	1.42	1.42	0.16			12	1	3				3	4	0	3	1
	9	1.41	1.41	0.18			12	6	3	2			1	24	12	6	6
	9	2.85	0.15				12	32	2				2	96	0	64	32
	9	2.89	0.11				12	1	2				2	3	0	2	1
	9	3					12	136	1				2	272	0	272	
	9	3					12	202	1				2	404	0	404	
	7.8	3.65	0.55				12	6	2			1	1	18	6	6	6
	7.72	3.63	0.65				12	6	2		1	1		18	12	0	6
	7.72	3.61	0.67				12	9	2		1	1		27	18	0	9
	7.72	3.59	0.69				12	6	2		1	1		18	12	0	6
	7.72	3.55	0.73				12	6	2		1	1		18	12	0	6
	7.72	3.53	0.75				12	6	2		1	1		18	12	0	6
	7.72	3.51	0.77				12	6	2		1	1		18	12	0	6
	7.72	3.49	0.79				12	9	2		1	1		27	18	0	9
	7.72	3.45	0.83				12	6	2		1	1		18	12	0	6
	7.72	3.43	0.85				12	6	2		1	1		18	12	0	6
	7.72	3.41	0.87				12	6	2		1	1		18	12	0	6
	7.72	3.39	0.89				12	6	2		1	1		18	12	0	6
	7.72	3.37	0.91				12	3	2		1	1		9	6	0	3
	7.72	3.34	0.94				12	2	2		1		1	6	2	2	2
	7.72	3.33	0.95				12	22	2		1		1	66	22	22	22
	7.71	3.33	0.96				12	6	2				2	18	0	12	6
	7.59	3.33	1.08				12	4	2				2	12	0	8	4
	7.59	3.28	1.13				12	2	2				2	6	0	4	2
	7.46	3.28	1.26				12	6	2				2	18	0	12	6
	7.34	3.28	1.38				12	6	2				2	18	0	12	6
	7.22	3.28	1.5				12	6	2				2	18	0	12	6
	6.07	3.28	2.65				12	10	2				2	30	0	20	10
	3.28	3.28	3.28	2.16			12	6	3				3	24	0	18	6
32	5.82	5.82	0.36				12	22	2				2	66	0	44	22
	7.31	1.55	1.55	1.55	0.04		12	2	4	3			1	10	6	2	2
	9.56	1.55	0.89				12	2	2	2				6	4	0	2
	7.31	4.69					12	14	1				1	28	0	14	14
	9.56	2.44					12	70	1	1				140	70	0	70

Appendix 3- Observation of construction sites in Addis Ababa


Rebar stored on the roadside

Rebar stored on the roadside

Poor working environment and safety

Rebar stored on the roadside

Rebar stored for long period of time