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Estimation of Optimal Productivity in Labor-Intensive Construction Operations

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ESTIMATION OF OPTIMAL PRODUCTIVITY IN LABOR-INTENSIVE CONSTRUCTION OPERATIONS

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ESTIMATION OF OPTIMAL PRODUCTIVITY IN LABOR-INTENSIVE CONSTRUCTION OPERATIONS

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In an attempt to evaluate the efficiency of labor-intensive construction operations, project managers typically compare actual with historical productivity for equivalent operations. However, this approach toward examining productivity only provides a relative benchmark for efficiency and may lead to the characterization of operations as objectively efficient when in reality such operations might simply be comparably efficient. Just because actual productivity equals average historical productivity does not necessarily mean that an operation is efficient; the case may be that the operation's efficiency is only in line with historical averages, which may be well below optimal productivity.

Optimal productivity is the highest sustainable productivity achievable under good management and typical field conditions. Optimal productivity is useful in the determination of the absolute efficiency of construction operations because an accurate estimate of optimal labor productivity allows for the comparison of actual vs. optimal (unbiased) rather than actual vs. historical (biased) productivity.

This research contributes to the body of knowledge by introducing a two-prong strategy for estimating optimal labor productivity in labor-intensive construction operations and applying it in an activity with a single worker and sequential tasks as well

as in an activity with multiple workers and sequential and parallel tasks. The first prong, or a top-down approach, estimates the upper limit of optimal productivity by introducing system inefficiencies into the productivity frontier – productivity achieved under perfect conditions. A qualitative factor model is used to achieve this objective. The second prong, or a bottom-up approach, estimates the lower limit of optimal productivity by taking away operational inefficiency from actual productivity – productivity recorded in the field. A discrete event simulation model is used to estimate this value. An average of the upper and lower limits is taken as the best estimate of optimal productivity.

In conjunction with a relevant literature review and a discussion of the two-prong approach's methodology, this research ultimately analyzes data from a pilot study with a single worker and sequential actions and an advanced study containing multiple workers and sequential and parallel tasks and actions, and evaluates the feasibility of this two-prong strategy for estimating optimal productivity in construction operations.

To:

My mother Tej Mati Kisi,

my brothers Punya Ram Kisi, Satya Ram Kisi, and Shiva Ram Kisi,

my sister Pramila Kisi,

Kisi family,

my relatives and friends

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CHAPTER 1

INTRODUCTION

This chapter explores the definitions, measurements, and interpretations that are relevant to this dissertation. It introduces major areas addressed within this dissertation including research background, research contents and perspectives, and research objectives and significances. Based on the exploration, the chapter outlines the problems and delineates the research objectives and significances. Finally, the chapter explains the structural organization of the dissertation and synopsis of the chapter.

1.1 Research Background

Ever since the beginning of industrialization, the topic of productivity has been of great interests among economists, professionals, and researchers. These interested parties want to produce more for every amount of money spent. The productivity trends in the construction industry that is considered one of the largest industries in the nation (Statistic Brain, 2013), have notable effects on national productivity and on the economy (Allmon, Borcherding, & Goodrum, 2000). Each individual at a job site can contribute to improved productivity. To improve productivity, we must be able to measure it. At all levels in the company, personnel must be able to measure the effects of changes adopted on methods, effort, and systems (Dozzi & AbouRizk, 1993). In order to measure it, we need to understand the meaning and parameters of productivity.

The goal of this dissertation is to conduct empirical research on how to estimate optimal labor productivity in labor-intensive construction operations. This dissertation considers analysis only at the activity level and thus the productivity analysis at project level is beyond the scope of this dissertation. However, the framework that this dissertation develops is scalable and can be applied at the project level.

This dissertation sheds light on the key factors affecting labor productivity, their uses in qualitative analysis, and their application in modeling the qualitative factor model that is developed in this research to estimate system inefficiencies. It elicits the meaning of optimal productivity and provides supporting evidence. The framework developed in this dissertation has potential to provide an objective benchmark for gauging performance. The dissertation advances practical suggestions to project managers to estimate efficiency of an activity in a more objective fashion.

1.2 Productivity and Construction

Productivity is perhaps one of the most important and influential basic variables governing economic production activities (Singh, Motwani, & Kumar, 2000; Tangen, 2006). Higher productivity levels allow constructors to simultaneously increase profitability, improve competitiveness, and pay higher wages to workers while completing activities sooner (Rojas, 2008). It is a commonly used but often poorly defined term that is often confused with profitability and performance (Pekuri, Haapasalo, & Herrala, 2011). Pekuri et al. (2011) also defined productivity as an ambiguous concept that seems to be dependent on the reviewer's point of view and the context in which it is used. Therefore the definition of productivity should be clear within the context described to provide proper meaning. In order to be able to understand how productivity is defined in a context, it is very necessary to explore the definitions of productivity and how they are being used in the construction industry.

1.2.1 Definitions of Productivity

In general, literature shows that there are two kinds of productivity definitions: verbal and mathematical. Verbal definitions of productivity aim to explain what the term means while mathematical definitions are used as a basis of measurement that is intended to improve productivity (Tangen, 2005).

1.2.1.1 Verbal Definitions of Productivity

The European Association of National Productivity Centres (EANPC, 2005) defines productivity as how efficiently and effectively products and services are being produced. In this context, efficiency refers to “doing things right” or utilizing resources to accomplish desired results (Grunberg, 2004) and effectiveness described as “doing the right things” or meeting the customer requirements (Neely, Gregory, & Platts, 1995). Bernolak (1997) defined productivity as “how much and how good we produce from the resources used.” Generally, productivity is often defined as the ratio of output to input (Rojas & Aramvareekul 2003). Output, in this context, can be seen as any outcome of the process, whether a product or service, while input factors consist of any human and physical resources used in a process (Pekuri et al., 2011). In contrast, it has also been defined traditionally as the ratio of input to output, where input refers as an associated resource (usually, but not necessarily, expressed in person hours) and output as real output in creating economic value (Dozzi & AbouRizk 1993). Because of these contradicting definitions of productivity there is lack of standard definition (Thomas & Mathews 1986). In 2006, Hee-Sung Park explained the two forms of productivity: the first form i.e., output/input has been widely used in the construction industry and the existing literature, and the second form i.e., input/output has been usually used for estimating (Park, 2006).

One can easily get confused with the terms productivity and profitability because, like productivity, profitability is also seen as a relationship between output and input. This relationship is monetary thus the influence of price factors is included (Tangen, 2005). According to Pekuri et al. (2011), the difference between these concepts is that profitability takes into account monetary effects, while productivity relates to a real process that takes place among purely physical phenomena. Similarly, productivity is often confused with performance; however, performance is a broader concept that covers both the economic and operational aspects of an industry (Pekuri et al., 2011). The graphical representation shown in Figure 1 explains how all of these concepts relate to one another. Construction Industry Institute (CII, 2006) reports productivity as “one of the most frequently used performance indicators to assess the success of a construction project because it is the most crucial and flexible resource used in such assessments.”

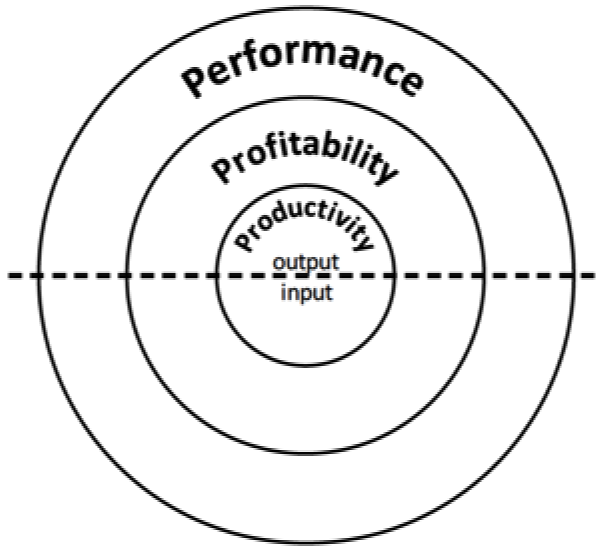


Figure 1.1: Relationships of Performance, Profitability and Productivity
(adapted from Pekuri et al., 2011)

1.2.1.2 Mathematical Definitions of Productivity

As discussed in previous sections, an association between an output and an input can simply illustrate productivity. While outputs are measured in terms of a specific result, the variables involved in inputs may vary from a single element to multiple elements. Depending upon the numbers of input variables involved in calculating productivity, total factor productivity (TFP) and partial factor productivity (PFP) are two types of productivity available in literature (Talhouni, 1990; Rakhra, 1991). Park (2006) described the two types as total factor productivity or multi-factor productivity and single factor productivity.

According to Thomas, Maloney, Horner, Smith Handa, & Sanders (1990), the Department of Commerce, Congress, and other governmental agencies use total factor productivity as shown in the following mathematical expression:

$$\text{TFP} = \frac{\text{Total Output}}{\text{Labor} + \text{Materials} + \text{Equipment} + \text{Energy} + \text{Capital}} \quad \ldots\ldots\ldots\ldots..\ (1)$$

In terms of the dollars unit, which is very common in economic analysis, Thomas et al. (1990) define Eq. (1) above in following expression:

$$\text{TFP} = \frac{\text{Dollars of Output}}{\text{Dollars of Input}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2)$$

However, the expressions in Eq. (1) and Eq. (2) are completely inverted in the definition described in Park (2006), i.e.

$$\text{TFP} = \frac{\text{Dollars of Input}}{\text{Dollars of Output}} = \frac{\text{Labor} + \text{Materials} + \text{Equipment} + \text{Capital}}{\text{Total Output}} \quad \ldots\ldots\ (3)$$

The expression of productivity, therefore, may be different depending upon its uses and measurement purposes. This statement aligns with Thomas et al. (1990) that the measurement of productivity has its own purpose: the meaning of the term productivity varies with its application to different areas of the construction industry, and a single industry measurement is insufficient (OECD, 2001). Thomas et al. (1990) state that Eq. (1) and Eq. (2) are useful for policy-making and evaluating the state of the economy but are not useful to constructors. Although Eq. (3) is expressed differently, the expression for total factor productivity is usually used in economics studies and not in construction (Park, 2006).

The partial factor productivity, by definition, is a part of total factor productivity in which only single or selected inputs are used. When a single input is used then the partial factor productivity is known as single factor productivity.

The mathematical expression of productivity may change as per requirement of a project. For example, a private sector may be interested in estimating its own projects by using

$$\text{Productivity} = \frac{\text{Output}}{\text{Labor} + \text{Materials} + \text{Equipment}} \quad \text{……………………. (4)}$$

or, for example,

$$\text{Productivity} = \frac{\text{Square feet}}{\text{Dollars}} \quad \text{……………..……………….………. (5)}$$

Depending upon requirements the input variables may differ. For example, the Federal Highway Administration may be interested in input factors such as design, inspection, construction, and right-of-way; and in terms of dollars, productivity may be ratio of lane mile to dollars (Thomas et al., 1990).

1.2.2 Construction Labor Productivity

According to Jarkas (2010) construction productivity is mainly dependent on human effort and performance. Yi and Chan (2014), therefore, state labor productivity as a crucial productivity index because of the concentration of human resources needed to complete a specific task. For example, a constructor may be interested in cubic yards of concrete used in concrete placement activity and the work-hours needed to place the concrete. Constructors are often interested in labor productivity at their project site. They may use different ways to define productivity as discussed in previous sections. Thomas and Mathews (1985) define labor productivity in following ways:

$$\text{Labor Productivity} = \frac{\text{Output}}{\text{Labor Cost}} \qquad \text{(6a)}$$

or

$$\text{Labor Productivity} = \frac{\text{Output}}{\text{Work-hour}} \qquad \text{(6b)}$$

Many definitions of construction labor productivity exist reflecting the different perspectives of the construction industry (Yi & Chan, 2014) and some constructors use productivity in the inverse of Eq. (6) as follows (Thomas et al., 1990, Thomas, Sanders, & Bilal, 1992):

$$\text{Labor Productivity} = \frac{\text{Labor costs or work-hours}}{\text{Output}} \qquad \text{(7)}$$

Dozzi and AbouRizk (1993) define labor productivity as the physical progress achieved per person-hour, for example, person-hours per linear meter of conduit laid or person-hours per cubic meter of concrete placed. In similar fashion, labor productivity that considers only labor as an input as the following expression (Woo, 1999; Hanna, Menches, Sullivan, & Sargent, 2005; Hanna, Taylor, & Sullivan, 2005; Park, 2006; Yi & Chan, 2014).

$$\text{Labor Productivity} = \frac{\text{Input}}{\text{Output}} = \frac{\text{Actual Work hours}}{\text{Installed Quantity}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

At activity level, Goodrum and Haas (2004) used the following expression, Eq. (9), to calculate labor productivity by using the expected physical output and crew formation data from the estimation manuals.

$$\text{Labor Productivity} = \frac{\text{Expected physical output (units)}}{\text{Workhour requirements (hours)}} \quad \ldots\ldots\ldots\ldots\ldots (9)$$

The expressions shown in Eq. (6) and Eq. (9) are aligned with the guidelines recommended by the Association for the Advancement of Cost Engineering (AACE International, 2004) and other literature (Horner & Talhouni, 1998; Rojas & Aramvareekul, 2003; Jarkas & Bitar, 2012).

1.3 Research Contents and Perspectives

The statistics show that the construction industry has the highest involvement of labor: over 7 million workers (Statistic Brain, 2015). It substantiates that construction is a labor-intensive industry. This raises the following questions: "*How sensitive and important is labor productivity*?" and "*Which definition of productivity, in our case labor productivity, should be used for measurement?"* Since labor productivity is considered one of the best indicators of production efficiency (Rojas, 2008) and higher productivity levels typically translate into superior profitability, competitiveness, and income (Rojas & Aramvareekul, 2003), labor productivity does matter. Therefore, this section will start with the measurement and interpretation of labor productivity specific to activity level of any construction operation in order to examine the efficiency of labor and estimate optimal productivity at activity level. It will focus on traditional methods of measuring labor productivity, identify the issues in traditional methods, and put forward an innovative framework to solve the issues in the dissertation and its research contents and perspectives.

1.3.1 Labor Productivity Measurement and Interpretations

Many studies have assessed the performance of the construction industry, primarily from a labor productivity perspective (Allen, 1985; Thomas et al., 1990, Allmon et al., 2000; Rojas & Aramvareekul 2003; Yi & Chan 2014). Since construction operations are highly diversified and unique, labor productivity is extremely difficult to measure due to heterogeneity of the industry's outputs as well as its inputs. Drucker (1993) articulates: "If you can't measure it, you can't manage it." Unfortunately, the lack of reliable means for evaluating the efficiency of labor-intensive construction operations makes it more difficult for the construction industry to improve productivity.

As discussed in definitions of productivity and construction labor productivity sections, it is clearly challenging which unit of measurement to use in measuring productivity. It is clear that the unit of measurement for one activity is different than another activity. For example, the unit of concrete placement may be measured in cubic meters of concrete placed per hour, whereas as a drywall may be measured in square feet of drywall finished per hour. Based on appropriateness, this dissertation will use the expression of output to input, as shown in Eq. (6), and Eq. (9) as labor productivity measurement which is consistent with the Bureau of Labor Statistics in the United States (2006) and the Organization for Economic Co-operation and Development (OECD, 2001) manual where they define labor productivity based on gross output and value added. Based on gross output, labor productivity is ratio of gross output to labor input whereas based on value added labor productivity is ratio of value added to labor input.

To maintain consistency and proper interpretation of labor productivity in this dissertation, output is interpreted as any installed quantity. For example, parts installed or items produced, and input is interpreted as work hours required by labor to finish producing such output. This interpretation is consistent with labor productivity research (Thomas & Yiakoumis 1987; Sonmez & Rowings 1998; Horner & Talhouni 1998; Rojas & Aramvareekul 2003; AACE International, 2004; Hanna, Chang, Sullivan, & Lackney, 2008; Jarkas & Bitar 2012) where labor hours are used as the input unit and the physical quantity of the completed work as output.

1.3.2 Traditional Labor Productivity Estimation

Traditionally, labor productivity has been benchmarked against historical data. While benchmarks serve to motivate employees by establishing realistic goals demonstrated to be achievable in other companies (Smith, 1997; Knuf, 2000; CII, 2002), it is an important continuous improvement tool that enables companies to enhance their performance by identifying, adapting, and implementing the best practice identified in a participating group of companies (Ramirez, Alarcon, & Knights, 2004). Based on labor productivity field data, Thomas et al. (1992) developed a factor model by modeling and analyzing labor productivity that can be used as a predictor of productivity. This factor model presented average daily productivity both on disrupted days and non-disrupted days that can be used for comparing labor productivity. Thomas and Zavrski (1999) also used database as a baseline productivity measurement. The United States Bureau of Labor Statistic expends considerable efforts in creating datasets with the aim of informing policy for productivity and economic growth. The concept of benchmarking has received widespread application in the construction industry as a technique for identifying ways to improve organizational and project performance (Thomas, Riley, & Sanvido, 1999; Jackson, Safford, & Swart, 1994; Thomas & Sanvido, 2000; Love & Smith, 2005; Liao, O'Brian, Thomas, Dai, & Mulva, 2011)

Many studies conduct questionnaire surveys, collect data, analyze collected data statistically, and present results by either comparing results with their study or drawing conclusions based on the survey. Hanna, Lotfallah, & Lee (2002) collected company specific and project specific data from electrical and mechanical constructors throughout the United States and presented benchmarking indicators for labor-intensive projects. Similarly, based on a questionnaire survey, Ramirez et al. (2004) developed a qualitative benchmarking system for the construction industry. To study productivity problems questionnaire surveys were common method to employ. For example, 1200 questionnaire surveys about craft workers' perceptions were studied on productivity problems and their causes in nuclear power plant projects (Garner, Borcherding, & Samelson, 1979). Nearly 2000 craft workers' perceptions nationwide were surveyed to quantify the relative impacts of several productivity factors (Dai, Goodrum, & Maloney, 2009). In a Chilean case study with the United States productivity, the study compares the findings with the results of previous studies in the United States in order to gain insight and a better understanding of factors affecting labor productivity (Rivas, Borcherding, Gonzalez, & Alarcon, 2011).

Several benchmarking indicators have been used for construction projects (Yeung, Chan,A., Chan,D., Chiang, & Yang, 2013), for example, manpower loading charts and related S-curves can be used as a basis for checking if the projects deviates from the planned benchmark (Hanna, Lotfallah, & Lee, 2002a). In 1999, Thomas and Zavrski developed a conceptual benchmarking model to compare labor productivity in one construction project to that of another. This model was also used to establish benchmarking construction labor productivity in Abdel-Hamid, Abd Elshakour, & Abdel-Razek (2004). In 2010, Lin and Huang criticized the model for lack of objectivity and proposed different methods to derive baseline construction labor productivity (Gulezian & Samelian 2003; Lin & Huan 2010).

Song and AbouRizk (2008) report that the current practice of estimating and scheduling relies on several sources to get productivity values, including an estimators personal judgments, published productivity data, and historical project data. RS Means Company publishes annual construction cost and productivity data collected from constructors and trade organizations (RS Means, 2007). These published productivity data only represent industry average rates (Song & AbouRizk, 2008). Moreover, a study conducted by Motwani, Kumar, & Novakoski (1995) showed that more than 20% of constructors rely on estimators' "gut feelings" and opinions for the majority of their estimates. Sonmez and Rowings define the term "productivity modeling" as an approach of analyzing and estimating the impact of productivity-influencing factors on construction productivity using historical project data (Sonmez & Rowings 1998).

The above literature and discussion show that the labor productivity is measured based on historical averages, questionnaire survey, and models developed on field data or expert judgments.

1.3.3 Main Problem in Traditional Labor Productivity Estimation

There is a general consensus that current construction data does not provide an adequate or accurate measure of productivity (BFC, 2006). In an attempt to evaluate the efficiency of labor-intensive construction operations, project managers typically compare actual with historical productivity for equivalent operations. However, this approach toward examining productivity only provides a relative benchmark for efficiency and may lead to the characterization of operations as objectively efficient when in reality such operations may be only comparably efficient. Just because actual productivity equals average historical productivity does not necessarily mean that an operation is efficient; the case may be that the operation's efficiency is only in line with historical averages, which may be well below optimal productivity (Kisi, Mani, & Rojas, 2014).

Song and AbouRizk (2008) assert that there is currently no systematic approach for measuring and estimating labor productivity, an assertion that implies that there are no benchmarks or standards to validate historical data as suitable for either estimating or evaluating productivity. Liberda, Ruwanpura, & Jergeas (2003) further complicate this idea when they presented several factors involved in the processes of construction change over time—productivity cannot be easily judged by the same data or information that was documented a decade or more ago. The AACE defines labor productivity as a "relative measure of labor efficiency, either good or bad, when compared to an established base or norm." Without a method for evaluating productivity against an objective standard, the practice of benchmarking against historical averages will continue to remain commonplace in the industry, regardless of how flawed the process is acknowledged.

Optimal productivity is defined as the highest sustainable productivity achievable in the field under good management and typical field conditions (Son & Rojas, 2010). It has the potential to provide an objective benchmark for gauging performance. An accurate estimation of optimal labor productivity would allow project managers to determine the efficiency of their labor-intensive construction operations by comparing actual vs. optimal rather than actual vs. historical productivity. However, to date, no substantive model for estimating optimal productivity has been proposed in the construction domain.

1.4 Research Objectives and Significance

This study proposes the development of a two-prong approach for estimating optimal productivity in labor-intensive construction operations. The first prong implements a top-down analysis in which the manager determines the theoretical maximum productivity conceivable under perfect conditions—the "productivity frontier"—and then proceeds to introduce estimated system inefficiencies derived from a novel Qualitative Factor Model (developed and described in Chapter 4). This top-down analysis tool would thereby estimate the upper threshold of optimal productivity by determining the physiological and systematic limits that affect the maximum productivity for labor-intensive operations.

Subsequently, the second prong of this approach would begin with the actual productivity observed in the field. Discrete event simulation is then used to remove the non-contributory work from the operation. The results of this prong would yield the lower threshold of optimal labor productivity since the findings would isolate value-added work by eliminating "operational inefficiencies." By averaging the upper and lower thresholds of optimal productivity, this two-prong approach would allow managers to evaluate operations against a quantifiable optimal productivity uniquely calculated for each operation.

Building upon the theory and results of a pilot study (discussed below), the current research specifically seeks to:

1. Evaluate the feasibility of the proposed two-prong approach for estimating optimal labor productivity for construction activities involving crews of multiple workers performing both sequential and parallel work.

Hypothesis: The proposed two-prong approach for estimating optimal labor productivity is applicable to complex construction operations with crews of multiple workers performing both sequential and parallel processes.

Significance of Success: If the proposed two-prong approach were found to be scalable, practical, and reliable for estimating optimal productivity in complex construction activities, then a novel and validated tool would be available for project managers to evaluate the efficiency of their construction operations.

2. Evaluate the feasibility of Qualitative Factor Model for estimating system inefficiencies in complex construction operations.

Hypothesis: The use of Qualitative Factor Model incorporating severity scores and probability technique is better for evaluating system inefficiencies that requires subjective evaluation in complex construction operations.

Significance of Success: If the inefficiencies are not all measurable in quantity, such as factors that are of subjective nature and require qualitative evaluation, then introducing Qualitative Factor Model for estimating system inefficiencies qualitatively would be justifiable.

1.5 The Structure of the Dissertation

Chapter 1 articulates an introduction to the research background of the dissertation, reviews its research contents and research perspectives, defines the research objectives and their significance, and finally delineates the structure of the dissertation.

Chapter 2 presents a review of literature on factors affecting labor productivity. It reviews existing literature from top five construction journals and other relevant articles. It also provides top factors that affect labor productivity by affinity grouping and how these are used in research.

Chapter 3 offers an explanation of existing measurement and frameworks used in labor productivity. It explains the existing methods for measuring productivity that are related to labor productivity in construction. It examines different approaches to estimate or forecast labor productivity. Since discrete-event simulation is a huge part of this dissertation, it will explain discrete-event simulation in detail.

Chapter 4 describes the research methods adopted in the dissertation. It puts forward a theoretical framework and definitions to understand the framework. Based on the framework, it will illustrate an empirical method to analyze the framework and describe the challenges. Based on challenges, it will illustrate a novel research method to address challenges with the help from literature. The quantitative and qualitative analysis will be described to address the challenges to estimate optimal productivity.

Chapter 5 discusses the feasibility test of the research method in an activity with a single worker and sequential tasks. The analysis from the pilot study will be presented. These include: data collection, results based on the research methods, conclusion drawn by the limitations in the study, and the lesson learned from the study.

Chapter 6 discusses the test of the research method in complex operations. The test includes an activity that has multiple workers and the tasks involved in the activity are both sequential and parallel. The results and discussion will be elaborated to make this complex operation as clear in as possible. Finally, the analysis, conclusion, limitations and recommendations will be presented.

Chapter 7 presents the research conclusions and recommendations of the dissertation. Since the research has some limitations during data collection and analysis, limitation and further recommendations will also be presented.

Chapter 8 explores the potential areas and advancement of this research. The improvement in current technology and its uses in advancing the framework developed in this dissertation will be explored. The potential areas will be discussed briefly.

The flowchart of the dissertation chapters, structural arrangements, its major content, and logic structure are summarized in a chapterwise flowchart as shown in the following Figure 1.2.

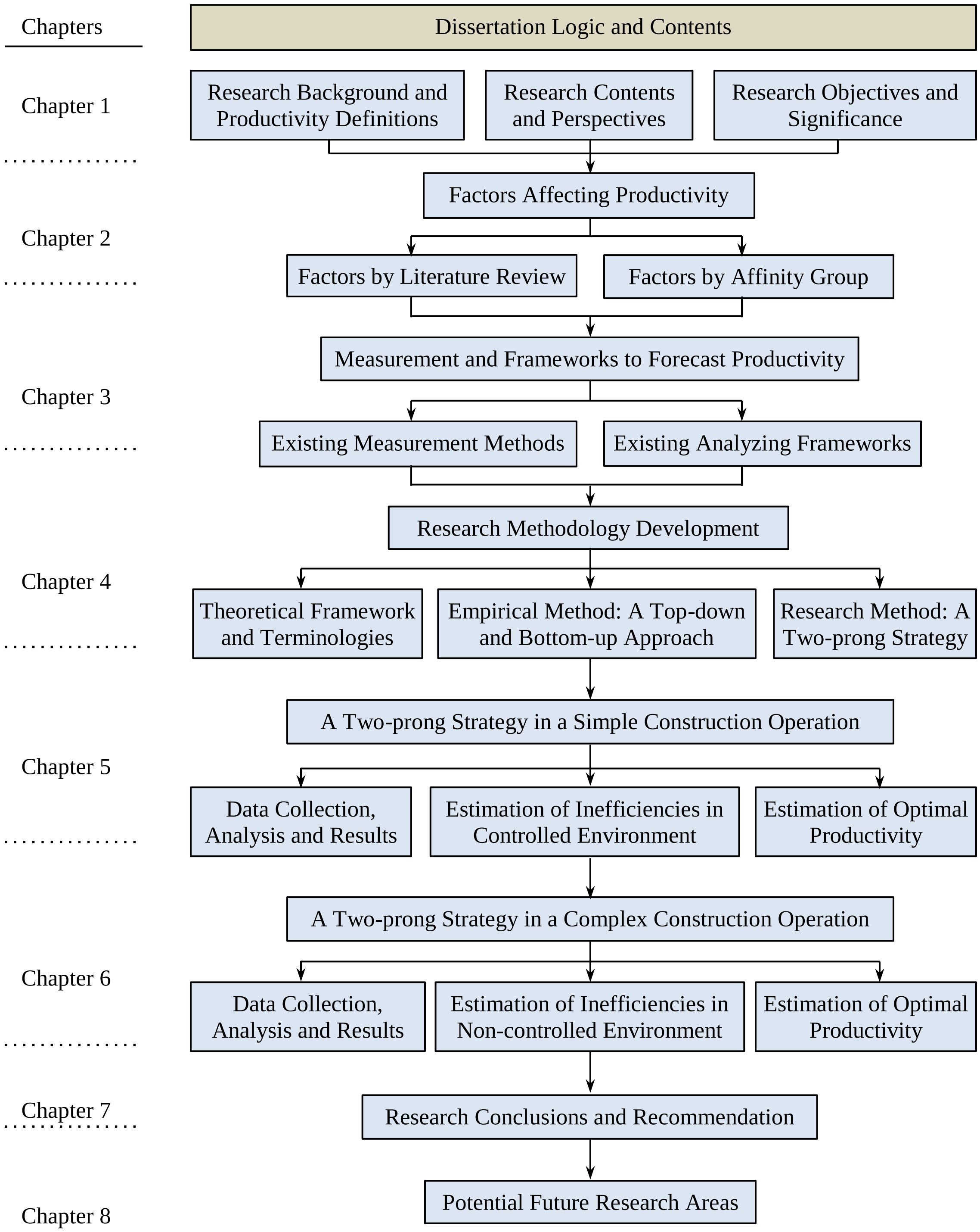


Figure 1.2: Structural Logic of the Dissertation

CHAPTER 2

FACTORS AFFECTING LABOR PRODUCTIVITY

In order to give insights into factors that affect labor productivity, this chapter provides a comprehensive literature review from top four construction journals as well as related articles analyzing labor productivity. It focuses on major factors that have some statistical significance and results. It also summarizes them by affinity grouping that will simplify the collection of data, and be further discussed in later chapters.

2.1 Background

The construction industry is considered one of the largest industries in the nation based on the number of workers involved and the revenue it generates (Statistic Brain, 2015). Hundreds of different activities are involved in the industry that creates a complex system. Civil, electrical, mechanical, plumbing, structure, acoustics, interior design, and heating, ventilation, and air conditioning are major areas in construction operations. In addition, there are dozens of sub-areas in the construction industry. Depending upon the nature of construction work, resources vary accordingly. Hundreds of workers performing multiple activities generate coordination issues among workers within trades or between different trades. Moreover, the vast network within the field itself adds a lot of complexity so that inefficiencies and losses in productivity are drawn to the forefront.

Inefficiencies associated with each activity develop a complex network so that determining productivity of an activity becomes a challenge. In terms of labor-intensive construction activities, the challenge of estimating labor productivity is more critical because of multiple, simultaneous factors affecting productivity. By nature, individuals are physically and emotionally unique. Even this creates challenges for measuring productivity because factors like high temperature, high noise level, and dense work environment affect individuals differently. In addition, factors influencing labor productivity are different in different countries, across sites, and possibly within the same site, depending on circumstances (Olomolaiye, Jayawardane, & Harris, 1998).

2.2 Major Factors Affecting Construction Labor Productivity

Researchers have identified dozens of factors that affect labor productivity, the primary ones being management factors, project characteristics, technical factors, and external conditions. (Thomas & Yiakoumis, 1987; Borcherding & Alarcon, 1991; Alinaitwe, Mwakali, & Hanson, 2007; Rivas et al., 2011). The multitude of factors that affect labor productivity and the dynamic effect on their efficiency make estimation of labor productivity a challenging task. An understanding of the factors affecting labor productivity would help project managers to manage construction activities that could be completed more efficiently and would enable them to better estimate, plan, schedule, and manage projects. Therefore, the project managers must address those challenges to enhance labor productivity.

Based on articles from 1985 to the present, the following are the list of factors that affect labor productivity reviewed from four top engineering and management-focused journals. The journals selected are: *Journal of Construction Engineering and Management*, *Journal of Management in Engineering*, *Journal of Civil Engineering Management*, and *Construction Management and Economics*. The main lists are:

- workflow
- weather
- quality of supervision
- method of working
- site layout
- crew size and composition
- availability of power tools
- incentive scheme
- overtime
- over-staffing
- shift-work
- materials and tools availability in site
- site access
- interference
- poor lighting
- project size
- work type
- subcontract
- craft turnover
- fatigue
- wages
- skill of labor

- high/low temperature
- high humidity
- high noise
- change orders
- design errors
- methods and equipment
- management control
- site supervision
- skill of supervisor
- quality control and quality assurance
- rework
- commute time to the work site
- congestion
- confinement of working space
- shortage of experienced labor
- site accidents
- labor strikes
- payment delay
- communication problems between site management and labor
- inspection delay
- late arrival, early quits, and frequent unscheduled breaks
- lack of periodical meetings with crew leaders

- lack of suitable rest area offered to labor on site
- unsuitability of storage location
- design complexity level
- sequencing problem
- economic activity
- job availability
- project location
- poor material quality
- worker health issues
- riot
- lack of materials in the market
- lack of tools and equipment in the market
- disruption of power/water supplies
- lack of coordination among consultants
- coordination problem with suppliers
- inadequate site staffs, and
- absenteeism.

In addition to these, many related or similar factors are mentioned in the literature. For simplicity, factors with similar purposes have been merged in this list.

Out of factors listed above, some literature presented results based on analysis drawn from questionnaire surveys, whereas other literature discussed results based on quantitative data and statistical analysis. The following factors are discussed from four top engineering journals based on statistical analysis and significance. The following sections illustrate the factors that affect labor productivity and provide insight to project managers about the challenges that they need to overcome to enhance productivity.

1) **Workflow**: Efficiency of workflow has great impact on labor productivity on a construction site. Just as effective workflow management can improve construction labor performance (Ballard & Howell, 1998), likewise labor flow on a construction site can contribute to improved workflow (Thomas, Horman, Minchin Jr., & Chen, 2003). There is a codependence between labor flow and workflow, and each of them in turn impacts labor productivity. Thomas et al. (2003) concluded from a survey of three construction projects that ineffective workflow management led to a labor inefficiency of 51%, and that 58% of the total inefficient work hours were due to inefficient workflow management. However, in the manufacturing industry, Hadavi and Krizek (1994) state that working conditions at a manufacturing facility are very different from a construction site and the effect of workflow has not been well defined in manufacturing.

2) **Weather**: A general perception is that it is harder to work in conditions that are very hot, very cold, or very humid, or when it is raining, snowing, or extremely windy. In fact, adverse weather conditions are probably the most commonly cited cause for construction labor productivity losses in the literature (Halligan, Demsetz, & Brown, 1994; Christian & Hachey 1995; Thomas et al. 1999; Klanac & Nelson, 2004). High winds, snow, hot and cold temperatures, and

rain showers are common examples of adverse weather conditions that clearly affect the productivity of workers. Quantitative studies have demonstrated that weather can account for as much as a 30% decline in productivity (Thomas et al., 1999). Supporting this result, Halligan et al. (1994) discussed that precipitation, wind, and extremes of temperature and humidity may reduce performance due to both physiological and psychological factors. Similarly, in the case of the mining industry, adverse weather conditions, such as heavy rainfall can flood underground mines requiring extra labor to remove water (Topp, Soames, Parham, & Bloch, 2008), and cause reworking in agriculture (Schoellman & Herrendorf, 2011). Thus, weather is a great challenge over which project managers have no control with the potential for a large impact on productivity.

3) **Temperature and humidity**: Temperature and humidity has greater influence in labor productivity since it has direct impact on the physical body. In a several month study of productivity in the installation of structural steel, masonry, and formwork, it was found that the ideal temperature was 55^0F, with relative humidity having marginal effects below 80%, but reducing productivity above this level (Yiakoumis, 1986). The influence of temperature and humidity varies a great deal by individual and by the type of work being carried out (Oglesby, Parker, & Howell, 1989). Hanna (2004) conducted case studies on electrical projects showing that work performance decreases at temperatures above 80^0F and below 40^0F based on full day's work. The study

also found that: (1) Efficiency of 100% can be achieved only when the temperature is between 40^0F and 70^0F and the relative humidity is below 80%; (2) In extremely cold conditions, temperature is far more significant than humidity. Regardless of humidity, an effective temperature of -20^0F or lower may justify work stoppage. It was observed that prolonged work in hot and cold conditions accelerates the effects of fatigue (Hanna, 2004). While significant reactions were observed in both extremes, the degree to which they occurred was much greater at the higher temperatures that at lower temperatures. Therefore, the extent to which productivity is affected by temperature and humidity depends on several factors, including the severity of conditions, the nature of the task, the acclimatization of the individuals involved, and training.

4) **Overtime**: A number of publications report a loss of productivity when work is scheduled beyond 40 hours per week and/or beyond 8 hours per day. The scheduling of overtime, for example, may create an adverse effect on the motivation and physical strength of workers and may therefore decrease their productivity (Halligan et al., 1994; Cooper, Sparks, & Fried, 1997). Similarly, Klanac & Nelson (2004) also stated that as the workweek lengthens, productivity decreases due to worker fatigue and other effects. Furthermore, scheduling work out of sequence can also produce loss of momentum/rhythm, as crews need to stop working on their present assignments and plan and reorganize for the new work (Thomas & Napolitan, 1995).

Hanna (2004) mentioned that effects of overtime result in fatigue, reduced safety, increased absenteeism, and low morale. Hanna explained the causes of overtime as a response to an accelerated schedule; to exploit the benefits of good weather, maximize equipment use, avoid penalty clauses, achieve bonus clauses, or beat strike or rate-increase deadlines; in emergency rebuilding; or in outage work situations. On the other hand, overtime work is more difficult to manage than straight-time work because every worker experiences a loss of productivity caused by fatigue, low morale, and reduced supervisory effectiveness (Hanna et al., 2005). Additional problems include poor workmanship, increased illness, a higher accident rate, and voluntary absenteeism.

5) **Disruption/Interruption**: Interruptions to work in progress can reduce productivity. Halligan et al. (1994) categorized disruptions into short duration and long duration. They found that a long disruption or delay may interrupt productivity rates because of training. The most skilled workers may leave the job and become unavailable for rehire. Furthermore, work continued during a disrupted period happens at a less productive rate (Sanders & Thomas, 1991). In a study of short duration disruptions of piping insulation installation, productivity was reduced by 70 % when work was disturbed by two or more interruptions per section of pipe (Hester, 1987).

6) **Motivation**: Factors such as low morale, poor supervision, poor training, and unsafe working conditions are generally related to worker motivation. A survey of 703 construction workers showed that foremen have “a strong impact on worker motivation, performance, and satisfaction” (Maloney & McFillen, 1987). Rojas and Aramvareekul (2003) found that motivation was an important driver in workers productivity, as it cannot replace experience, activity training, or education. Similar results were found in mining and manufacturing industries. Hadavi and Krizek (1994) found that working conditions in a construction site are very different from those found at a manufacturing facility, and this can affect a worker’s morale and thus productivity. Besides these, especially in agriculture and mining, labor productivity may be affected by age, technological progress that influences motivation (Tilton & Landsberg, 1999; Polyzos & Arabatzis, 2005; Topp et al., 2008).

7) **Lack of material**: Lack of material refers to problems encountered due to inaccessibility of items or excessive time expended to acquire them (Kadir, Lee, Jaafar, Sapuan, & Ali, 2005). Lack of materials was found to be the most critical construction delay factor in Indonesia (Kaming, Holt, Kometa, & Olomolaiye, 1998), Iran (Zakari, Olomolaiye, Holt, & Harris, 1996), Nigeria (Olomolaiye, Wahab, 7 Price, 1987), and Gaza Strip (Enshassi, Mohamed, Mayer, & Abed, 2007). When there is lack of materials on site, workers are often idle waiting for materials. This would affect the workers’ motivation and productivity. Kadir et al. (2005) recommended that the procurement

department should always coordinate with site staff concerning the material shortage on site. It is equally important that storage has enough capacity. When materials are delivered too early to the site that does not have enough storage space then double handling occurs, increasing the number of man-hours.

8) **Non-payment to suppliers**: Another important factor resulting in low labor productivity is the stoppage of material delivery by the suppliers due to non-payment by the constructors. This makes the suppliers lose their confidence in the credibility of the constructors (Kadir et al. 2005). Delay in material delivery to site was also observed as significant impact in Singapore-based construction problems (Lim & Alum, 1995). This can be even worse if the activities are in the critical path, which not only impacts the current activity but also affects other subsequent activities and project performance as a whole.

9) **Change order**: Change order might occur due to design error during the planning stage or due to the need for additional design modification. This factor is a particularly annoying and costly problem if the work has already been done. For instance, hacking of hardened concrete is time consuming and affects the workers' motivation, causing disruption to work sequences due to rework (Kadir et al., 2005). Thomas and Napolitan (1995) observed an average of 30% loss in efficiency in three different case studies when changes were implemented. Change orders are very common in construction sites causing either rework or a change in plans. Change order by consultants was ranked

among the top five factors causing low labor productivity (Kaming et al., 1998; Hanna, Rusell, Nordheim, & Bruggink, 1999; Kadir et al., 2005; Alinaitwe et al., 2007). In addition, inadequate quality control/assurance programs can adversely affect labor productivity through the need for rework (Rojas & Aramvareekul, 2003).

10) **Economy**: The economy also plays an important role as a driver of labor productivity in the construction industry (Rojas & Aramvareekul, 2003, Klanac & Nelson, 2004, Dai et al., 2009). Rojas and Aramvareekul (2003) explained that strong economic expansion created some skilled labor shortfalls, which, in turn, forced constructors to hire suboptimal workers to fill in the gaps. This effect is also observed in manufacturing (Hadavi & Krizek 1994; Norsworthy, Harper, & Kunze, 1979), agriculture (Schoellman & Herrendorf, 2011), and mining (Norsworthy et al., 1979; Young, 1991; Tilton & Landsberg, 1999; Topp et al., 2008). Therefore, project managers should be very cautious in periods of economic expansion, because they might experience a drop in the productivity of the construction labor force. The economy has greater influence on agriculture labor productivity due to inter-industry shifts of labor and capital (Norsworthy et al., 1979).

11) **Late issuance of construction drawing**: Late issuance of the construction drawing by consultants was observed the most critical delay factor, which caused man-hours loss due to workers idling (Kadir et al., 2005;

Makulsawatudom, Emsley, & Sinthawanarong, 2004). For example, late issuance of the structural foundation construction drawing results in delay to progress of formwork and concrete placement because those tasks cannot be done without first completing the structural work.

12) **Site management**: An effective and efficient site management team is paramount to ensure that work sequence is accomplished according to work schedule. Poor knowledge and the inexperience of the site management team in planning, scheduling and procurement impedes the work progress (Kadir et al., 2005; Sugiharto, 2003; Enshassi et al., 2007). The project manager should check for discrepancies between structural, architectural, and electrical construction drawings to avoid rework. Researchers recommended appointing subconstructors even before site procession so that they can be familiar with the construction drawing and planning of labor.

13) **Lack of foreign and local workers**: Sometimes the construction industry faces an acute shortage of construction workers due to vacancies left by local workers who prefer to join lucrative and conducive working environments in the manufacturing and service sectors (Kadir et al., 2005). The situation may arise in many ways; may be the economy is down and there are no projects running, or the number of projects is so high that there is a high demand for a workforce but local workers are not sufficient. Klanac and Nelson (2004) say that labor market conditions that may affect productivity include the volume of

work in the labor market, size and base skills of the local labor pool, union versus non-union labor rules, local economy (wages and incentives), craft turnover and absenteeism, cultural issues (such as holidays and religious events), and abuse of drugs and alcohol. It is challenging for the constructors in this kind of situation when they may be forced to hire more workers that are marginal leading to reduced productivity.

14) **Coordination problem with subcontractor**: Coordination problems between main constructors and subconstructors pose a major hindrance to work progress (Kadir et al., 2005). Common coordination problems such as late issuance of revised construction drawings to subcontractor can cause rework due to construction errors (Makulsawatudom et al., 2004; Kadir et al., 2005). Therefore, in order to clarify any outstanding issues, site meetings should be held regularly between the main contractor and subcontractors.

15) **Equipment shortage**: Equipment shortage refers to frequent breakdown of major equipment, shortage of spare parts, improper service and maintenance, slack use of machinery or deliberate sabotage by operators (Kadir et al., 2005). This problem causes major idle time since employed workers are unable to progress in their work due to material transportation problems (Makulsawatudom et al., 2004; Kadir et al., 2005). If the right tools and equipment are not available, productivity is likely to suffer (Klanac & Nelson,

2004). The project manager is normally responsible for the availability and management of tools and equipment.

16) **Management systems and strategies**: Project managers can add or reallocate resources, modify schedules, and change working methods. Management skills are often cited in the literature as one of the major factors that influence labor productivity. Rojas and Aramvareekul (2003) found it one of the most relevant issues in determining construction labor productivity since the issue addresses management skills, scheduling, material and equipment management, and quality control. The drawback in management strategy creates increased workload, crowding of workers, stacking of trades, dilution of supervision, or rework (Halligan et al., 1994). The efficiency of production is determined by factors such as management and work practice in mining industry (Topp et al., 2008). Therefore, supervisors and managers who lack proper skills can negatively affect the performance of workers.

17) **Material management**: Extensive multiple-handling of materials, materials improperly sorted or marked, trash obstructing access and movement of materials, running out of materials, and inefficient distribution methods are just a few instances of adverse material management conditions (Thomas, Sanders, & Horner, 1989a; Thomas, Smith, Sanders, & Mannering, 1989b). A crew that has knowledge, skills, abilities, incentive to perform, and has been given appropriate direction should be highly productive. However, one factor that can

seriously constrain the productivity of a crew is the management of the production process, or organizationally imposed constraints (Thomas et al., 1990). This factor represents the failure of management to plan and maintain an orderly sequence of work, to provide sufficient resources, access to work area, to maintain uncongested work areas, and so forth that has direct impact on low labor productivity (Herbsman & Ellis 1990, Thomas et al., 1990, Sugiharto, 2003, Enshassi et al., 2007).

18) **Activity training**: Activity training has been reported as a major factor affecting labor productivity. Specific activity training refers to the education provided to workers before they begin working on a particular activity (Rojas & Aramvareekul, 2003). A survey conducted by Rojas and Aramvareekul indicated that if a worker does not possess experience in a particular operation, then the second best choice is to provide that training on-site before the operation commences. Training is equally observed essential to improve labor productivity in the mining industry, where large numbers of skilled workers are used (Topp et al., 2008).

19) **Site conditions**: Researchers have different definition about site conditions that influence labor productivity. These influences include access to the site, its distance from the labor pool (usually a major town or city), other work in congested areas (also known as density), crowding of labor or stacking of trades, work among hazardous materials or processes (which may necessitate

work interruptions or the use of appropriate protective clothing), the strictness of the owner's site safety requirements, and other safety/legal restrictions (Klanac & Nelson, 2004). Presence of those conditions, one way or the other, has great influence on labor productivity (Klanac & Nelson, 2004; Makulsawatudom et al., 2004).

20) **Supervision**: The quality and experience of supervision also affects labor productivity (Klanac & Nelson, 2004; Makulsawatudom et al., 2004). Typical supervision productivity influences are the ratio of supervisors to first-line supervision (foremen), to workers (also known as dilution of supervision), quality of first-line supervision (foremen), quality of supervision staff, and the experience of supervisors with the labor pool (Klanac & Nelson, 2004).

21) **Over-manning**: Over-manning can produce a higher rate of progress without the fatigue problems of overtime and the coordination problems of shift work (Hanna, 2004). However, the study shows that it also causes site congestion, stacking of trades, dilution of supervision, and a higher cost per unit hour, higher accident rate, and supply chain inefficiencies (Hanna, 2005).

22) **Shiftwork**: Labor productivity depends on shiftwork both positively and negatively depending upon the condition. Shiftwork can produce a higher rate of progress without the immediate fatigue problems of overtime and the congestion problems of over-manning. Conversely, poor coordination between

shifts, increased absenteeism and turnover, the unavailability of higher management, a higher cost per unit hour due to shift differentials, a higher accident rate, and interruptions of the workers' natural biorhythms result in fatigue (Hanna, 2004). In the case of the agriculture and mining industries, shiftwork has a different interpretation with agriculture workers than non-agriculture workers (who have a greater tendency of seeking a secondary job in the other sector and that causes variation in labor productivity) (Schoellman & Herrendorf, 2011).

23) **Absenteeism and turnover**: Two common problems that reduce labor productivity are absenteeism and turnover (Hanna, 2005). Major reasons that affect absenteeism and turnover were job satisfaction, worker's personal factors, organizational factors, management, and job performance. Hanna recommended that better management, incentive programs, and availability of overtime could reduce these problems.

24) **Congestion**: Congestion on a construction site can cause expensive inefficiencies in workflow and labor flow that negatively impact productivity (Thomas & Horman 2006). Guo (2001) has shown that resolution of workspace conflicts during construction by identifying interference between crew moving paths can reduce loss in productivity. This is specifically true for projects that involve considerable repetitive activities performed by the same crew(s). Thabet and Beliveau (1994) recommend that scheduling workspace constraints

and developing productivity-space capacities that plot variations in productivity as a function of activity space demand and current availability can address space conflicts between multiple trades and construction crews.

2.3 Top 14 Factors Affecting Labor Productivity by Affinity Grouping

Many of the factors mentioned in the literature have similar nomenclature. For example, shortage of materials and lack of material availability have a similar meaning. Since identification and classification of factors affecting labor productivity are part of the research methodology, systematic nomenclatures are important for analysis. From existing literatures, factors pertaining to the same meaning are represented by a single factor, and factors with the similar behavior/nature are grouped into the same category. Below is a list of factors based on affinity grouping that are used in collecting data from experts during research analysis.

1) Technical factors such as uncoordinated, incomplete, and illegible drawings, and complex designs of unusual shapes and heights (Arditi 1985; Herbsman & Ellis 1990; Thomas et al., 1992; Dai et al., 2009; Rivas et al., 2011).
2) Management factors such as inadequate supervision, management control/ project team, incompetent supervisors, inspection delays, overstaffing, and management practices (Arditi 1985; Herbsman & Ellis 1990; Sanders & Thomas 1991; Thomas et al., 1992; Rojas & Aramvareekul 2003; Alinaitwe et al., 2007; Enshassi et al., 2007; Dai et al., 2009).

3) Site conditions such as site access, site layout, congestion/inferences, and material handling (Thomas & Yiakoumis, 1987; AbouRizk, 2001; Makulsawatudom et al., 2004; Rivas et al., 2011).
4) Environmental conditions such as cold or hot temperatures, high or low humidity, and winter storms (Koehn & Brown 1985; Thomas & Yiakoumis 1987; Thomas et al., 1999).
5) Scheduling issues such as schedule acceleration, overcrowding and/or over-manning, scheduled overtime, shift work, and out of sequence work (Sanders and Thomas, 1991; Hanna et al., 2005; Chang et al., 2007; Hanna et al., 2008; Dai et al., 2009)
6) Coordination issues such as poor coordination and poor communication (Arditi, 1985; Koehn & Brown, 1986; Dai et al., 2009).
7) Changes and omissions such as rework and change orders (Sanders & Thomas, 1991; Borcherding, Palmer, & Jansma, 1986; Alinaitwe et al., 2007; Rivas et al., 2011).
8) Project characteristics such as ownership type, work type, and project goals (Thomas et al., 1992; Rojas & Aramvareekul, 2003).
9) Labor characteristics such as labor/manpower, quality of craftsmanship, absenteeism (factors such as workers unable to work due to fatigue and health issues (Koehn & Brown, 1986; Thomas et al., 1992; Rojas & Aramvareekul, 2003; Dai et al. 2009), craft turnover, skills, experience, motivation, and manpower shortages (Arditi, 1985; Koehn & Brown 1986; Rojas & Aramvareekul 2003; Dai et al., 2009; Enshassi et al., 2007; Rivas et al., 2011).

10) External conditions such as project location, government, economic activity, availability of skilled labor, and job availability (Koehn & Brown, 1986; Rojas & Aramvareekul, 2003; Dai et al., 2009).

11) Non-productive activities such as waiting idly, working slowly, doing ineffective work, frequent relaxation, and late starts and early quits (Borcherding et al., 1986; Dai et al., 2009).

12) Tools and equipment such as unavailability of suitable equipment, lack of tools, and maintenance of power tools (Arditi, 1985; Herbsman & Ellis 1990; Sanders & Thomas, 1991; Dai et al., 2009).

13) Material factors such as shortage of materials, difficulty in tracking materials, and poor material quality (Arditi, 1985; Sanders & Thomas, 1991; Thomas, Guevara, & Gustenhoven, 1984; Enshassi et al., 2007; Dai et al., 2009).

14) Safety factors such as lack of site safety resources, incidents, and accidents (Arditi, 1985, Sanders & Thomas, 1991; Thomas et al., 1992; Dai et al., 2009).

CHAPTER 3

MEASUREMENTS AND FRAMEWORKS TO FORECAST LABOR PRODUCTIVITY

Existing productivity measurement techniques that are more widely used to measure the effectiveness of construction workers and crews appear in this chapter. It explores existing research methodologies, methods for collecting data and measuring productivity, different frameworks developed to analyze and estimate productivity, and various techniques to forecast labor productivity. This chapter also provides a comprehensive literature review on the use of discrete-event simulation in construction since it is a major tool used in this dissertation.

3.1 Background

The objective of determining productivity can only be attained by understanding both concept and measurement techniques available. As articulated by Drucker (1993), anything that can't be measured is not manageable either, which implies that measurement has a direct relationship with the evaluation of management action. Since field data is the source of measurement, it is challenging to quantify all factors involved on site. Stathakis (1988) states that site productivity data is at the level where construction management can achieve timely, effective results in maintaining or improving productivity trends. Therefore, the easy way of measuring productivity is to create consistent units of measurement throughout the job site. Dozzi and AbouRizk (1993) state that the number of units produced per person-hour consumed (or its reciprocal, the number of person-hours consumed per unit produced) is the most accurate measure of productivity in construction.

3.2 Existing Research Methods in Productivity Analysis

Panas and Pantouvakis (2010) summarized the methodologies adopted within the published papers in major peer-reviewed journals into three broad classifications: qualitative, quantitative, and mixed-method research approaches.

3.2.1 Qualitative Research

The qualitative research methods are based on exploratory surveys and developing conceptual frameworks to analyze data that are subjective in nature. Crawford and Vogl (2006) developed conceptual frameworks for measuring productivity based on experts' experience and past data. Qualitative research is almost exclusively linked with questionnaire surveys in an attempt to explore the role and significance of specific factors, which are believed to affect productivity (Panas & Pantouvakis, 2010). Qualitative research uses survey and interviews to interpret the behavioral patterns adopted by construction operatives. For example, personnel management skills and manpower issues are two main improvement drivers in labor productivity (Rojas & Aramvareekul, 2003). Workers should be given enough attention prior to work based on craft workers' perceptions in the US regarding the relative impact of 83 productivity factors (Dai et al., 2009). Similar studies used questionnaire surveys to study productivity factors (Park, 2006; Thomas & Horman, 2006; Chan & Kaka, 2007).

3.2.2 Quantitative Research

Mathematics, probability, and statistics are major sources of quantitative research. Mathematical models are developed to represent abstractions of construction systems aiming at delineating the effect of a pre-selected set of variables of factors on productivity (Panas & Pantouvakis, 2010). The quantitative research may be based on historical data, questionnaire surveys, or simulation models. For example, a generic analytical framework was developed to study the impact of weather and material delivery methods on labor productivity (Thomas et al., 1999). In another instance, an equipment-oriented productivity estimation framework was developed based on operational parameters such as machine capacity, fleet size, and type of road surface (Schabowicz & Hola, 2007). Additionally, an empirical framework was developed utilizing historical data to quantitatively predict productivity (Song & AbouRizk, 2005), and a questionnaire-based framework was created to specify predominant demotivators influencing productivity by quantifying the negative effects in terms of the lost man-hours (Ng, Skitmore, Lam, 7 Poon, 2004). Lastly, there was the application of quantitative modeling methods using simulation such as probabilistic analysis (Huang & Hsieh, 2005) and stochastic data modeling (Rustom & Yahia, 2007).

3.2.3 Mixed-Method Research

The mixed method research approach is the combined approach using qualitative and quantitative techniques. Panas and Pantouvakis (2010) evaluated research methodology in construction productivity studies and defined mixed-method as such, which combines empirical work or archival study with quantitative modeling of productivity data for the formulation of mathematical models or simulation tools. A historical database of productivity data was studied to extract datasets that were given as input to develop artificial neural network and develop productivity models for steel drafting projects (Song & AbouRizk, 2008). In 2006, Cottrell associated qualitative and quantitative variables, such as project management vision, dedication, and experience with job site productivity using multiple regression analysis (Cottrell, 2006). Similarly, the mixed-method approach has been widely used in productivity analysis by using statistical regression, time studies and simulation. For example, Anson, Tang, & Ying (2002) developed simulation models based on time studies, Ok and Sinha (2006) developed both statistical regression model and artificial neural network model to associate operational and behavioral factors with productivity estimation.

3.3 Literature Review of Labor Productivity Measurement Methods

The following sections describe the existing techniques to measure labor productivity.

3.3.1 Work Sampling

It is very impractical to record all the minute details of every repetition on any construction operation. The usual practice is to collect data within acceptable limits. Taking samples from the real construction operation is simply a work sampling method. The American Institute of Industrial Engineers' official definition of work sampling is: "the application of statistical sampling theory and technique to the study of work systems in order to estimate universe parameters from sample data." Though the basic objective of work sampling is to observe an operation for a limited time and from the observations infer the productivity of the operation (Dozzi & AbouRizk, 1993). The study from Stathakis (1988) explains three objectives of work sampling: 1) to determine how time is employed by the work force; 2) to identify the problem areas that cause work delays and to allocate managerial attention to the areas where it is most needed; and 3) to set up a baseline measure for improvement and to serve as a challenge to management and the work force.

The work sampling involves periodic observations of workers, machines, or processes to analyze a task. Instead of dealing with the whole population, the procedure is to collect a sample, analyze it, and build a confidence limit around it (Dozzi & AbouRizk, 1993). Work sampling can be used to establish crew sizes or to determine the effectiveness of a specific crew size at the workplace (Adrian, 2004).

The detail method of work sampling is explained well in Dozzi and AbouRizk (1993) and is described based on statistical sampling theory. The advantages of work sampling listed in Oglesby et al. (1989) are: a) it is a simple procedure, b) no special equipment is required to conduct the study, c) results are available quickly, d) it is less exact but often useful preliminary results can be reported soon after the start of the study, e) the study is relatively inexpensive, and f) it is a useful technique for studying non-repetitive, noncyclical activities in which complete methods and frequency descriptions are not easy to quantify. Along with the detail lists of advantages listed by Oglesby et al. (1989), the disadvantages mentioned are: a) The technique in most cases is not economical for the study of a single worker or machine, b) It is not well-suited for sampling on short-cycle jobs, c) It is difficult, with this technique, to obtain data, which provide sufficient indicators about individual differences.

Though the work sampling method offers many advantages, the study from Dozzi and AbouRizk (1993) teaches us to be cautious while making decisions based on results since the results cannot be used to measure real labor efficiency; the results are only helpful to gain a better insight into motivation and explain the reasons behind drastic variations in production rates.

3.3.2 Foreman Delay Survey

There are often reworks and delays at a construction site. The delay may be a material delay, waiting on equipment, or waiting for other crews, while the reworks might be due to design errors, design changes, field errors or damage. The usual way of tracking this type of delay information is by filling out some type of questionnaire survey. Foreman delay survey relies on a questionnaire, which is to be filled out by the job foreman at the end of a working day according to a particular survey schedule, e.g., one week in each month (Dozzi & AbouRizk 1993). Once the survey is collected, information such as the delay of rework is extracted and presented in terms of percentages. This percentage will help management to identify the number of hours of a day lost due to delays and provide notable information.

The main advantage of a foreman delay survey is that it is a relatively low-cost method for analyzing the sources of delay during construction (Dozzi & AbouRizk 1993). This method is flexible and easy to implement (Tucker, Rogge, Hayes, & Hendrickson, 1982). The disadvantage is that it only measures losses due to delay and rework and does not facilitate other parameter measurements useful for determining efficiency of activities.

3.3.3 Time Studies

Time studies, developed Frederick W. Taylor in 1911, is defined as the process of determining the time required by a skilled, well-trained operator working at a normal pace doing a specific task. The purpose of time studies is to set time standards in the production area and record the incremental times of the various steps or tasks that make up an operation (Oglesby et al., 1989; Meyers, 1992).

The time study is a portion the methodology used for data collection in this dissertation. Therefore, it is important to briefly describe the steps. The detailed information about the steps is found in Taylor (1911) and Bernold and AbouRizk (2010). However, the steps can be summarized as: 1) dividing a laborer's cycle work into smaller tasks, or subtasks, that are executed repeatedly, 2) deciding the number of repetitions of the task, 3) recording all the pertinent information (e.g., date, temperature), 4) measuring the tasks' durations, either by observing the laborer directly while using a stopwatch or viewing video recordings, 5) computing averages of observed time from recorded data of repeated tasks duration, 6) assessing the person being observed in terms of how much his or her performance differed from an average work pace by assigning a performance rating factor, 7) computing the normal times of each element or subtask by taking the product of average observed time and performance rating factor, 8) summing up all the normal times of each element to develop normal time for the task, 9) accounting special conditions for factors that existed during the observed activity to calculate a standard time, and finally 10) computing the standard time by available information from steps 8 and 9.

The main advantage of time studies is that they are very cost effective and easy to use. It requires a stopwatch and an interval timer that can record a specified sequence of events. However, the major drawback is that it can be useful only if the activity involves a few workers or machines. Oglesby et al. (1989) mentioned that it is inherently difficult for a single observer to cover activities accurately when it involves a substantial period of observation over different cycles. A maximum of five workers in a crew per observer is recommended by Geary (1962).

3.3.4 Continuous Time Study

This method is an advancement of the time study method that used a stopwatch, but modern digital recording and tracking devices in continuous time study have replaced it. The objective is still the same: to develop time records for the various tasks comprising a process (Bernold & AbouRizk, 2010). However, unlike time studies where a stopwatch, pencil, and paper are used, this method can collect information from the data just by sitting at an office. The common technologies used for collecting data include digital cameras; camcorders; and remotely accessible, controllable and programmable Internet cameras.

The main advantage of this method is that data can be captured remotely in a real-time processing mode, or recorded automatically for processing later, which minimizes the unnecessary presence for the observer on-site (Bernold & AbouRizk, 2010). The other advantages are that playbacks of video camera allow analysis of multiple processes by the same person, data recording directly into spreadsheets allows quick processing, travel time to install a video camera on-site is minimized, and the recording can be used for other managerial purposes such as safety inspection. The major disadvantages are that the method is costly and the Internet may not be available at every construction site.

3.3.5 Audio-Visual

For many years, the audio-visual methods like time-lapse film with 1- to 5-second intervals and time-lapse video with various time intervals have been used to record construction field operations for productivity analysis, improvement of construction operations, training of workers, and as evidence in construction claims and contract disputes (Everett, Halkali, & Schlaff, 1998; Noor, 1998). It is a recording technique that can be used effectively to document a lengthy building construction process by using special cameras/video camcorders. In addition, the recording can be viewed in a much shorter period of time with the appearance of actions being rather fast and jerky. This technique can also provide a permanent record of the activities on pictures or film which can be reviewed at any stages of a construction process to recognize problems (such as flow of workers and materials, equipment utilization and balance, and safety and working conditions) (Christian & Hachey, 1995; Noor, 1998).

As described above from an owner's point of view, Everett et al. (1998) further discussed the usage of time-lapse film and video that has the equivalent value to the constructors, designers, and even the craft workers for faulty claims and legitimate contractor claims against the owner. Overall, its benefits accrue to all parties and possibly prevent problems from occurring. The technique has been proven to resolve claims and disputes and has been used for education, public relations, fund raising, media applications, and construction project management.

However, there are some difficulties with the applications of this technique. First, it has high initial costs and requires technical competence for picture quality – as there is a possibility of a loss of data due to equipment failure, technical incompetence, weak illumination, and human error (Noor, 1998). Second, the use of a camera/video camcorder is restrictive in the coverage area – as the movement in the entire construction process being captured in time-lapse film. It is impractical to use the data to recognize the performance of individual craft workers or a piece of equipment (Kim, 2008). Finally, some construction sites may not have access to the Internet for transmissions of high-resolution, full motion live pictures to distant office locations because the intent is to send up-to-date data to the project owner, project manager, architect, and engineer for properly visualizing the actual status of the project (Everett et al., 1998).

3.3.6 The Five-Minute Rating

Oglesby et al. (1989) defined the five-minute rating technique as a quick and less-exact appraisal of activity that is based on the summation of the observations made in a short study period, with the number of observations usually too small to offer the statistical reliability of work sampling. The observer that does a five-minute rating should have a watch and a form for recording observations during work. The detail steps are explained in Dozzi and AbouRizk (1993). The advantage of this technique is that since the workers will not know whether they are being watched, the workers will not react to the observer's presence. Oglesby et al. (1989) expanded the definition that if the delay noted for an individual in any block of time exceeds 50 percent of the period of observation, then the rating for that individual is classified under delay; if not, then the appropriate block is classed as effective, whereas the method explained in Dozzi and AbouRizk (1993) would leave the cell empty if the crew member has been inactive for over half the interval. Finally, the effectiveness percentage for the whole crew is found by multiplying 100 to the ratio of the sum of effective times for each individual and for the crew divided by the total time of observation, which is also called the effectiveness ratio. The disadvantage of this method is that this technique is not based on statistical sampling theory and relies on simply observing an operation for a short time (Dozzi & AbouRizk 1993). Also the result does not apply to drawing conclusions from the large samples and may not be taken as a decision-making tool.

3.3.7 Field Rating

The fundamental concept of field rating, also known as the productivity rating, is used to estimate a construction operation at activity level; however, the rating provides only a crude estimation (Dozzi & AbouRizk, 1993). The field rating method categorizes the observed worker into different stages: either working or non-working ((Dozzi & AbouRizk, 1993); and effective, contributory, and not-useful work, or idle (Oglesby et al., 1989). The activities are effective or working only if they add value to complete the job. Since the terms are similar to what is later used in the analysis part of this dissertation, the following definitions are useful to understand and are abstracted from Oglesby et al. (1989). They are:

- “Effective work, or activities directly involved in the actual process of putting together or adding to a unit being constructed, such as necessary disassembly of a unit that must be modified and movements essential to the process that are carried out in the immediate area where the work is being done.”
- “Essential contributory work, or work not directly adding to but essential to finishing the unit, such as handling material plans, waiting while some other member of a balanced crew is doing productive work, and necessary movement outside the work station but within (say) a radius of 35 feet of it.”
- “Not useful or idle, or all other activities.”

Oglesby et al. (1989) also described ineffective work which, when incorporated into non-contributory category in this dissertation, are: work being idle or doing something that is in no way necessary to complete the job, activities as walking empty-handed, and rework of a job done incorrectly in the first place.

Explanation of the method is found in Dozzi and AbouRizk (1993); but, simply put, the calculation is done by dividing total observation of “working” category by the total number of observations plus 10% to account for foreman and supervisory activity. The advantage of a field rating system is a random selection of sample and estimating efficiency based on total number of observation. Thus, it is very simple and quick rating system. However, it has a huge disadvantage in that there is no correct way to categorize the multitude of activities for productivity rating purposes (Oglesby et al., 1989). Also there is no clear explanation of accounting 10% for foreman and supervisory activity into the field rating method. Thus, Dozzi and AbouRizk (1993) conclude that the method does not tell the analyst anything about the courses of inefficiencies and merely suggests something is wrong in the activity.

3.3.8 Time-Lapse Photography

The British Standards Institution describes time-lapse photography as a method that records activity by a cine-camera adapted to take pictures with longer intervals between frames than normal. Since pictures are taken at unusually low speeds, Stathakis (1988) stated the following advantages: a) the technique is well suited for long cycle and irregular cycle studies, b) groups of workers and machines can be recorded simultaneously, c) the technique eliminates most of the errors found in studies because of multiple observer recordings, d) films can be used for training purposes, e) a permanent record of interrelated activities is obtained for later analysis, f) reduction of analysis time, g) foremen can study the film and improve the performance of their crews without analyzing detailed work study reports. The disadvantages are: a) method expenses because of equipment and film costs, b) time lag between reading and development of film, and c) possibility of partial or complete data loss due to technical inadequacy.

3.3.9 Group Timing Technique

Group timing technique is mainly useful to study highly repetitive group operations as well as when the operation has a very short cycle. The technique involves the observation of artisans at a fixed time interval, which is much less than the time needed for a work sampling study where the time interval is also random. The main advantage of this technique is that it can be very beneficial when there are limited observers available for the study and when the operation is highly repetitive with a short cycle. However, since the activities in the construction operations are highly dynamic, this technique may not be quite as applicable to analyze productivity studies.

3.3.10 Method Productivity Delay Model

The method productivity delay model was proposed as a way to combine both time study and productivity measurement (Adrian & Boyer, 1976). The method mainly deals with the sources of delay and provides useful statistics for measuring productivity. The detailed explanation of this method with implementation examples can be found in Dozzi and AbouRizk (1993). The main advantages of this method are that it provides more information than other work sampling techniques and it can identify sources of delay and their relative contribution to the lack of productivity (Dozzi & AbouRizk 1993).

3.4 Literature Review of Frameworks to Analyze and Forecast Labor Productivity

Researchers have presented models to forecast construction labor productivity (Thomas et al. 1984; Lu, AbouRizk, & Hermann, 2000; Srinavin & Mohamed 2003; Fayek & Oduba 2005; Dissanayake et al., 2005). These models take advantage of a variety of techniques, including simulation, artificial intelligence, expert systems, factor models, and statistical and regression approaches. Each technique has its own merit and demerit. For example, Srinavin and Mohamed (2003) developed a model using regression analysis for qualitative evaluation of the impact of different factors on construction labor productivity. However, since a regression equation is limited to certain variables, the limitation did not allow for the subjective evaluation of qualitative factors. In response to this limitation, expert systems have been widely used to quantify this kind of subjective evaluation. Yi and Chan (2014) performed a critical review of labor productivity research published in construction journals and claimed that expert systems are superior to statistical models because of their flexibility in adapting to different project contexts.

Many construction studies have focused on the identification of factors that affect productivity, and the quantification of the impact of such factors on productivity. Thus, productivity prediction models are centered on various qualitative and quantitative factors that have been discussed in literature (Hanna et al., 2005; Sanders & Thomas, 1991, Sonmez & Rowings, 1998).

The following sections provide frameworks developed in existing literature to measure and improve productivity.

3.4.1 Statistical Framework

Multiple regression analysis was performed to quantify the impact of the various factors on labor productivity. Thomas and Sudhakumar (2013) used the regression model to analyze daily productivity and variability in productivity among subcontracted labor and direct labor. A similar case was used by Talhouni (1990) to study the productivity of the two groups of a workforce. A regression analysis was performed between the latent factor scores, and a project productivity rating was assigned by the craft workers to see which areas possessed the greatest possibility for project productivity improvement from the craft worker’s perspective (Dai et al., 2009).

Lost labor productivity is one of the key factors associated with construction claims, therefore, many studies used techniques that are based on data collected from a large number of projects and derive regression curves that show the impact that change has on labor productivity (Hanna, Russell, Gotzion, & Nordheim, 1999a; Hanna, Russell, Nordheim, & Bruggink, 1999b; Ibbs & Allen 1995; Ibbs 1997; Ibbs, Lee, & Li, 1998; Ibbs, Kwak, Ng, & Odabasi, 2003; Leonard, 1988).

By using analysis of variance and regression, Goodrum and Haas (2004) found that activities experiencing significant changes in equipment technology have witnessed substantially greater long-term improvements in labor productivity than those that have not experienced a change in equipment technology. Considering the characteristics of productivity of ongoing operations and the required conditions of predictive methods, a few potential statistical methodologies were selected and demonstrated in a previous study that used smoothing techniques and time series analysis (Hwang and Liu, 2010).

3.4.1.1 Time Series Analysis

Time series analysis has been used in many domains for forecasting processes; however, its uses in the construction domain are very few. Time series analysis follows a standard procedure in sequence: examine the main features of a data series, check dependency in data, choose a model to fit the series, diagnose the constructed model, and forecast and update (Brockwell & Davis 2002). Time series analysis is meaningful only when the series is autocorrelated or cross-correlated. Abdelhamid and Everett (1999) used time series analysis in managing construction productivity. Hwang (2010) used autoregressive moving average and multivariate autoregressive analysis for the purpose of forecasting short-term productivity. Some studies used weekly productivity rates along with overtime and apparent temperature data due to the significance of their influence on productivity, for instance, over time (Thomas, 1992; Hanna et al., 2005) and weather conditions (Benjamin & Greenwald, 1973). Mohamed and Srinavin (2005) developed mathematical models reflecting the relationship between the thermal environment and construction labor productivity. The main disadvantage of statistical models based on time series analysis is limited to precision of data.

3.4.1.2 Smoothing Techniques

According to Nau (2007), "the basic assumption behind smoothing models is that the time series is locally stationary with slowly varying mean." Therefore, smoothing methods can be appropriate for analyzing time series productivity data so as to predict productivity in the future where construction productivity series are locally stationary with a slowly varying mean (Hwang, 2010; Hwang & Liu, 2010). Cumulative average, simple moving average, and simple exponential smoothing are three smoothing techniques explained well in Hwang (2010) for the purpose of forecasting short-term productivity.

3.4.2 Expert Systems Framework

An expert system is a computer program designed to simulate the problem-solving behavior of a human who is an expert in a narrow domain (Nada, 2013). It is also called a knowledge-based system, which is part of artificial intelligence. While it is well understood that expert system implementation should not be applied across all disciplines, the domain of construction estimating satisfies the six classic requirements that are used to gauge a domain's suitability to application of an expert system (Herbsman & Wall 1987). The six necessary criteria mentioned by Herbsman and Wall (1987) are: 1) genuine experts must exist, 2) the experts must generally agree about the choice of an acceptable solution, 3) the experts must be able to articulate and explain their problem solving methodology, 4) the problems of the domain must require cognitive, not physical skills, 5) the task cannot be too difficult, and 6) the problem should not require common sense or general world knowledge.

From the critical analysis of existing papers, Yi and Chan (2014) mentioned that an expert system is superior to the flexibility in adapting models to suit different project contexts. Nada (2013) introduced an expert system, which demonstrated a new method for an accurate estimate of building house cost. Christian and Hachey (1995) introduced an expert system to estimate the production rates for concrete placement in the construction industry. Some expert systems are based on fuzzy numbers and fuzzy set theory, which are called fuzzy expert systems and are used in a great deal of construction literature. For example, sources have described predicting labor productivity using fuzzy expert systems (Oduba, 2002), estimating labor productivity using fuzzy set theory (Mao, 1999), fuzzy logic to estimate productivity by including both qualitative and quantitative factors (Zayed & Halpin, 2004), fuzzy expert systems to predict labor productivity of pipe rigging and welding (Fayek & Oduba (2005), and fuzzy experts systems for construction labor productivity estimation (Muqeem, Bin Idrus, Khamidi, Siah, & Saqib, 2012).

3.4.3 Simulation Framework

Simulation frameworks are often used to model construction data using probability approaches on productivity analysis. Simulation is defined as building a mathematical model or logical model of a system and experimenting with it on a computer (Prisker, 1986). Discrete event simulation (DES), agent based simulation (ABS), and many construction simulation tools such as CYCLONE and STROBOSCOPE are used in construction domain to analyze productivity. Smith (1998) used discrete event simulation to model construction operations utilizing the probability distribution of each event involved in a construction activity. Zhang (2013) presented an alternative DES method for estimating construction emissions by addressing uncertainties and randomness as well as complex interactions.

There have been a lot of developments and modifications to simulation applications in the construction industry. Due to an increase in the effectiveness and accuracy of available tools, the modeling and simulation applications for planning and decision-making in construction operations have gained acceptance over the decades. Current DES tools provide intuitive environments and functional elements that adequately model and simulate most construction operations, including those that include state-dependent stochastic components and strategies (e.g. CYCLONE (Halpin, 1974); INSIGHT (Paulson, Douglas, Kalk, Touran, & Victor, 1983); RESQUE (Chang, 1986); COOPS (Liu, 1991); CIPROS (Odeh, 1992); STEPS (McCahill & Bernold, 1993); STROBOSCOPE (Martinez, 1996); EZStrobe (Martinez, 1998); SIMPHONY (Hajjar & AbouRizk, 1999); and RISIM (Chua & Li, 2002)).

Several studies have utilized simulation models to study various construction operations (Martinez & Ioannou, 1994; Shi & AbouRizk, 1998; Martinez, 1998). These include road construction operations (Lu, 2003; Hassan & Gruber, 2007; Polat & Buyuksaracoglu, 2009; Mawlana, Hammad, Doriani, & Setayeshgar, 2012), earthmoving operations (Smith, Osborne, & Forde1995; Pena-Mora, Han, Lee, & Park, 2008), concrete placing (Smith, 1998; Lu & Chan, 2004), and tunnel boring (Shaneen, Fayek, & AbouRizk, 2009).

Simulation studies have been conducted to understand the relationship between the effects of various factors on productivity. Simulation can be a very effective tool to plan for productivity and can also be used to support claims that may arise due to loss of productivity from bad weather, unexpected delays, changed conditions, and changes in the contract (Dozzi & AbouRizk 1993).

3.4.4 Hybrid Framework

Various hybrid frameworks have been developed to model construction operations. DES is often used in collaboration with system dynamics (SD) when there is a need to model a cause-effect relationship between the simulation variables that cannot be done by DES alone. DES and SD are the two main simulation methodologies employed to support the automated systems used to analyze complex models. DES is quantitative in nature, discreet in change, and narrow in details. Conversely, SD is more suitable for handling problems that have a context/strategic focus, and that are more holistic, qualitative, continuous in behavior, and broader in details (Brailsford & Hilton, 2001). The hybrid simulation approach has been applied successfully in other management fields such as in the software industry (Martin & Raffo, 2001). It has also been used with success in manufacturing and supply chain management applications (Lee, Cho, Kim,s., & Kim,Y., 2002; Venkateswaran & Son, 2005; Rabelo, Helal, Jones, & Min, 2005), as well as in the construction industry. Hamm, Szczesny, Nguyen, & Konig (2011) presented an optimization framework to determine efficient construction schedules by linking discrete-event simulation with optimization concepts.

Pena-Mora et al. (2008) combined DES with SD to model an earth-moving operation by addressing both strategic and operational issues. The results demonstrate that a systematic integration of the strategic perspective (using SD) and operational details (using DES) can enhance the process performance, thereby enabling construction managers to identify areas for potential process improvements that traditional approaches may lack. Based on the results of the simulation (but with some limitations), the study authors conclude that the proposed hybrid simulation model has the potential to support not only the strategic and operational aspects of construction project management but also to ultimately help improve the overall project performance outcomes. Alzraiee, Moselhi, & Zayed (2012) also developed a methodology that integrates DES and SD in a construction operation simulation that highlights the two methods' respective advantages.

Other researchers have also shown interest in combining DES with other techniques and methodologies. Lu, Chen, Shen, Xuesong, Hoi-Ching, & Liu (2007) and Lu, Chen, & Shen (2007) combined discrete-event and continuous simulation to model a mining operation. AbouRizk and Wales (1997) combined a discrete critical-path method (CPM) with DES to simulate weather effect as a continuous stochastic process. Shi and AbouRizk (1998) simulated a pipeline project in which a continuous process was used to represent the aggregation of discrete and repetitive pipe-laying components. Shaheen et al. (2009), proposed a methodology for integrating fuzzy expert systems and DES in the construction-engineering field. Hamm et al. (2011) presented an optimization framework to determine efficient construction schedules by linking DES with optimization concepts. Finally, Zhang (2013) presented an alternative discrete event simulation method for estimating construction emissions by addressing concerns related to uncertainties, randomness, and complex interactions. Therefore, DES now has a rich set of theories and practices in various domains. It has been widely used in construction modeling and simulation. Researchers have been integrating other simulation techniques such as ABS, SD, and fuzzy logic to make it more meaningful and useful in construction research. Therefore, DES can be used together with other approaches to better understand construction productivity.

3.4.5 Percent Complete Approach

The simplest and most widely used method of forecasting labor productivity is to divide the current work-hour total by the completed percentage of an activity. This is called percent-complete (PC) approach. Instead of assuming how labor productivity may vary over time, the PC approach assumes that cumulative productivity will not change from the time the forecast is made until the activity is completed (Thomas & Sakarcan, 1994). Hence, the forecast using the PC approach can be misleading, especially if the labor productivity varies appreciably (Thomas & Kramer, 1987). This approach is particularly prone to erroneous forecasts when made in the early phases of the activity (Thomas & Sakarcan, 1994).

3.4.6 Factor Model

Thomas and Yiakoumis (1987) stated, “The theory underlying the factor model is that the work of a crew is affected by a number of factors and, if the cumulative effect of these disturbances can be mathematically represented, then the expected actual productivity can be estimated.” The factor model is so named because it is based on the factors that affect labor productivity (Thomas & Sakarcan, 1994). The model considers different amounts of labor resources to complete different activities. For example, slab formwork and wall formwork both require different work-hours resources on a per-unit basis. Thomas and Sakarcan (1994) use the factor model to develop a predicted labor-productivity curve. The factor model has been proposed as a reliable method of forecasting labor productivity (Thomas & Yiakoumis 1987; Thomas et al., 1989a, b). The mathematical model and the process of using this model to forecast labor productivity can be found in Thomas and Sakarcan (1994) where the forecast calculated was found to be more accurate than the percent complete approach. Most studies of construction productivity have focused on the identification of factors and the evaluation of their impact on productivity. Studies of such factors resulted in factor-based models, such as regression (Hanna et al., 2005, Mohamed and Srinavin, 2005). However, Hwang (2010) provided some limitations of the factor-based model; for example, it is not always feasible to quantify the impact of various factors and to represent the relationships mathematically.

3.4.7 Neural Network Techniques

Neural network techniques have been used to develop methods for productivity prediction (Sonmez & Rowings, 1998, Portas & AbouRizk, 1997). This method fails to incorporate sufficiently the time factor in predicting productivity of ongoing operations by analyzing the dynamic and stochastic behavior of productivity. Artificial neural network models are more suitable for modeling construction labor productivity problems requiring analogy-based solutions than either traditional decision analysis techniques or conventional expert systems (Moselhi et al., 1991). Neural networks have shown potential for quantitative evaluation of the effects of multiple factors on productivity, especially when interactions and nonlinear relations were present (Sonmez & Rowings 1998). Sonmez and Rowings (1998) also mentioned that many of the neural network approaches to model fitting are closely related to their statistical counterparts.

3.4.8 Learning Curve

A learning mechanism is associated with repetition of performing any activities: the higher the repetitions the better the performance. The basic principle of a learning curve is that time, cost and person-hours for accomplishing repetitive and subsequent tasks decrease in each repetition, according to a predictable learning rate (Thomas, Mathews, & Ward, 1986). According to the Economic Committee of Europe, the improvement is significant when the worker gets more and more comfortable with the task and identifies small changes in the work method and organization that can streamline the activity (UNCHBP, 1965). Rojas (2008) noted that the reasons for gaining efficiency is due to greater familiarity with the task, standardization of the procedure, more effective and efficient use of the tools and equipment, and better coordination and teamwork within the crew.

There are learning curve models developed to quantify the losses in the manufacturing industry (Carlson, 1973) such as the Straight-line Model, the Stanford “B” Models, the Piecewise Model, the Exponential Model, Boeing Curves, and the Cubic Model (Thomas et al., 1986, Couto & Teixeira 2005). However, Rojas (2008) succinctly articulated that the learning curve effect in and of itself is not a cause of productivity losses (or gains) because it is an inherent characteristic of repetitive work, not something that happens that causes losses or gains. Similarly, Emir (1999) stated that the learning curve can be used to predict the expected productivity over the lifetime of the project but cannot be used as a proof of loss of productivity entitlement as there is no link of causation to the damage.

Learning curves are used to forecast manpower requirements and productivity (Wideman, 1994). The use of these curves has been limited to comparing the performance against case studies in construction industry. For example, the linear model has proven reliable in predicting the performance of a crew (Cuoto & Teixeira, 2005). Also, when applying the learning curve to estimate the anticipated duration, it is important to keep in mind the type of task being performed and limit on the minimum time the task can take because the tasks can be limited if they: are complex and intricate, require special inspections, rely on a piece of specific equipment, and already are performed at the maximum rate (Rojas, 2008).

3.5 Discrete Event Simulation in Construction

DES is one simulation technique widely used when evaluating potential financial investments, operations research, and modeling procedures and processes in various industries. This kind of modeling is frequently employed, for example, in the manufacturing, construction, and healthcare industries. DES can be defined as the process of codifying the behavior of a complex system as an ordered sequence of well-defined events. Here, an event should be understood as a specific change in the system's state at a specific point in time. DES has various world-views (e.g., event-scheduling, process interaction, activity scanning, state machines, and other formalisms) that vary greatly in modeling flexibility and analytical power (Kiviat, 1969).

Brito, Silva, Botter, Pereira, & Medina (2010) define the main functions of DES:

- to analyze a new system before its implementation;
- to improve the operation of an already existing system;
- to better understand how an already existing system functions; and
- to enable a comparison with results from hypothetical situations ("what if" analysis).

Modeling construction operations is one of the ways in which DES is very useful in the construction industry. DES has been recognized as a very useful technique for quantitative analysis of operations and processes that take place during the life cycle of a constructed facility (Martinez, 2010). Several studies have used simulation models to study various construction operations (Martinez & Ioannou, 1994; Shi & AbouRizk, 1998; Martinez, 1998). These include road construction operations (Lu, 2003; Hassan & Gruber, 2007; Polat & Buyuksaracoglu, 2009; Mawlana et al., 2012), earthmoving operations (Smith et al., 1995; Pena-Mora et al., 2008), concrete placing (Smith, 1998; Lu & Chan, 2004), and tunnel boring (Shaneen et al., 2009). The DES method is also used extensively in the manufacturing and production engineering industries (Law, 1986; Law & McComas, 1989; Law & Kelton, 1991).

DES is used to find solutions to vital logistical issues in the CEM business. For example, it can be used to answer questions such as "What is the best possible layout for the system? How many repair stations are required to meet the throughput? What are the requirements for driver and operator staffing?" in manufacturing process design and operations (Harrell & Tumay, 1995). Overall, DES is a highly effective tool for the design of a manufacturing system relative to its ability to meet throughput goals within the constraints of operational complexity. It has been successfully employed in the design and implementation of a variety of automotive manufacturing systems (Ulgen, Gunal, Grajo, & Shore, 1994; Upendram & Ulgen, 1995; Jayaraman, Nepogodiev, & Stoddart, 1997).

DES is useful for problems related to queuing simulations or complex networks of queues, in which the processes can be well defined and the emphasis is on representing uncertainty through stochastic distributions (Siebers, Macal, Garnett, Buxton, & Pidd, 2010). They also emphasize that DES models are process-oriented. The primary focus is on modeling the whole system, not the separate entities in detail. Lu (2003) argues that the methodology of a DES is a promising alternative solution to designing and analyzing dynamic, complicated, and interactive construction systems.

Despite the ways in which the use of DES has been beneficial to the construction industry (AbouRizk & Hajjar, 1998; Marzouk & Moselhi, 2003), the simulation lacks detailed analysis techniques of the operational aspects of a project (Lee et al., 2002; Alvanchi, Lee, & AbouRizk, 2011). First, it cannot model all aspects of the operations including the cause-effect relationship between the simulation variables (Alzraiee et al., 2012). A similar drawback of DES is echoed by Pena-Mora et al. (2008) when they claim that DES mainly deals with operational issues without aggressively considering the project feedback structure. DES focuses on the efficiency of process logistics (time, cost, and resource usage), yet fails to address the strategic issues that can be resolved by analyzing the project feedback structures. DES also does not analyze the effectiveness of control policies against the continuously changing project environment. Brito et al. (2012) emphasize that the DES model is not a substitute for logical/intelligent thought. The simulation is not able to replace natural human reasoning and decision-making processes. They also argue that DES cannot be considered an optimization tool. Rather, the simulation should be considered a tool best used for analyzing scenarios in combination with other optimization tools. Given the stated weaknesses of DES, researchers have started integrating DES with other simulation techniques, such as system dynamics, agent-based simulation, and game theory.

In a DES model, entities are simple, reactive, and have limited capabilities. Entities in most DES rely on some central mechanism (e.g., the event scheduling function) to invoke actions that can change the state of an entity. Entities also have no learning or cognitive reasoning abilities (Chan, Son, & Macal, 2010). For example, consider a truck in a queue waiting for earth loading. In the real world, entities in a queue determine whether to stay or leave by sharing and gathering waiting time information from nearby entities. This kind of situation is hard to model using discrete-event simulation as demonstrated in Chan et al. (2010). Chan therefore employed the agent based simulation (ABS) technique. Though ABS has its own drawbacks, researchers used the discrete-event simulation algorithm based only on the events, updating continuous variables in every time step (Page, Knaak, & Kruse, 2007).

CHAPTER 4

RESEARCH METHODOLOGY

This chapter presents a theoretical framework upon which the research method is built. More specifically, it describes terminologies developed, illustrates the approaches taken, and presents flow diagrams of the methodology developed in this research project. This chapter mainly focuses on research method developed to estimate optimal productivity in labor-intensive construction operations by explaining the techniques to estimate system and operational inefficiencies.

4.1 Theoretical Framework

Since the proposed two-prong approach builds upon a novel theoretical framework for determining optimal productivity, certain foundational concepts must first be discussed. Son and Rojas (2011) defined optimal productivity as “the highest productivity achievable in the field on a sustainable basis under good management and typical field conditions.” This concept relies on two terms: “good management” and “typical field conditions.” To standardize these principles, the common law concept of the “reasonable person” (Sweet, 1989) is used to define these terms. “Good management” is understood as the level of proficiency that a project manager would exhibit while conducting business according to generally acceptable practices. In other words, the expectation is for a manager to behave according to what the community of construction managers would judge to be a typical member of their professional community. In analogous fashion, “typical field conditions” is understood as the collection of field circumstances that a project manager would encounter in a project run according to industry standards. “Typical field conditions” excludes unforeseeable events, such as earthquakes and labor strikes.

Both “good management” and “typical field conditions” can experience temporal and spatial differences. Management techniques may evolve over time and practices considered acceptable a few years ago might not be acceptable today (e.g. emphasis on quality assurance vs. quality control). Typical field conditions may be dependent on geography and season (e.g. a winter storm in Buffalo, New York vs. summertime in San Diego, California). Therefore, when optimal productivity is proposed as an objective benchmark to gauge performance, this objectivity must be understood not as one value for a construction activity across time and space, but as one value for a particular activity characterized by specific temporal and spatial considerations.

This research is an extension of the study performed by Son and Rojas (2011), where they identified some basic productivity concepts as shown in Figure 4.1. The figure, which is plotted as productivity on the vertical axis and duration along the horizontal axis graphically, depicts the dynamic relationships among productivity levels.

Since there is a learning phase in every construction installation, it is important to note that productivity can best be measured during the steady state condition; the point at which workers have learned how to approach their tasks and have leveled out their productivity. Figure 4.2 depicts different productivity levels once the steady state condition is reached for a construction operation (i.e. once the learning phase is over and productivity has leveled out).

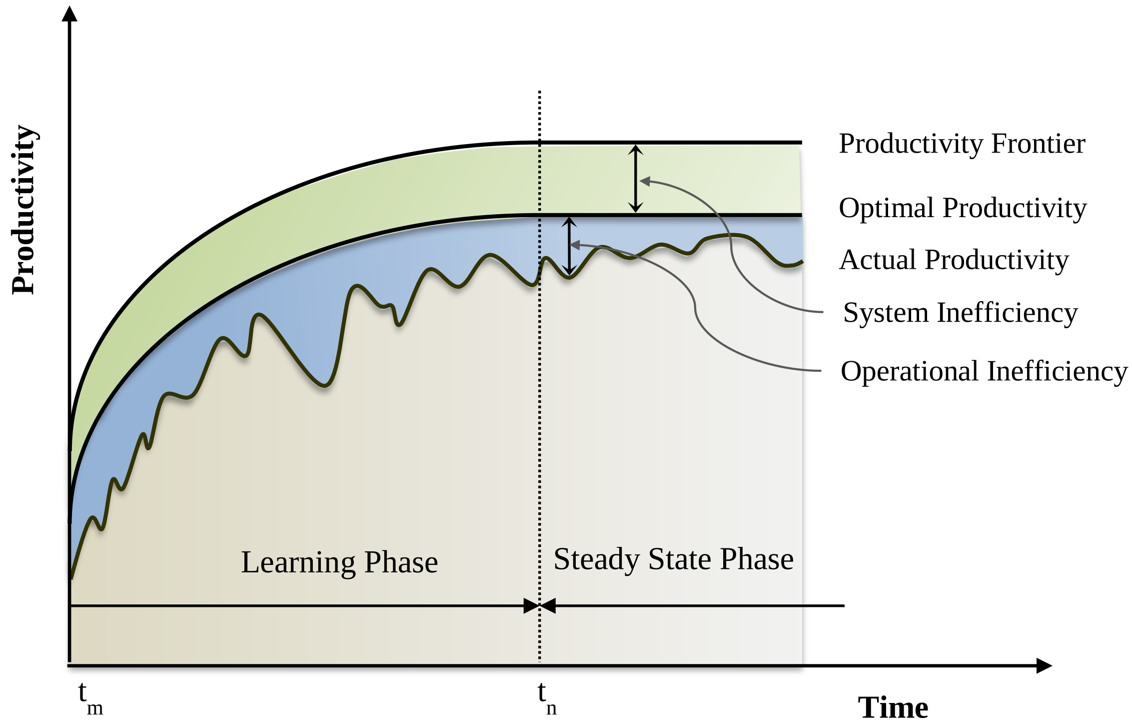


Figure 4.1: Productivity Dynamics

(edited from Son & Rojas, 2011)

A section of the steady state condition as shown in Figure 4.2 illustrates that optimal productivity (OP) lies between the productivity frontier (PF) and actual productivity (AP) (definitions of these terminologies are provided in following sub-sections). The difference between the PF and the OP reveals the system inefficiencies (Δ_{si}) caused by factors outside the control/influence of project managers. The difference between the OP and the AP represents the operational inefficiencies (Δ_{oi}), which are the result of suboptimal managerial strategies such as poor scheduling and inadequate resource planning. The difference between PF and AP is the total inefficiency (Δ_{i}).

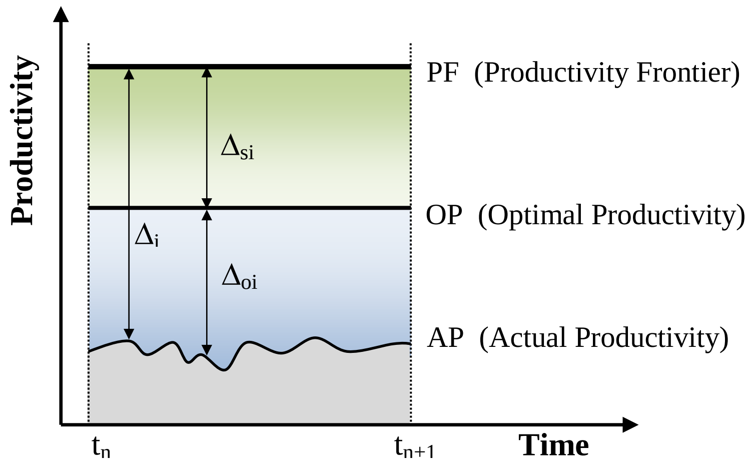


Figure 4.2: Basic Productivity Concepts

4.1.1 Productivity Frontier

The productivity frontier is the theoretical maximum productivity level conceivable under perfect conditions. If everything is perfect: idle conditions, skilled worker with no internal of external impacts, and no rework then the productivity achieved in the field is the productivity frontier.

4.1.2 Optimal Productivity

Optimal productivity is the highest productivity achievable in the field under good management and typical field conditions, and it has to be sustainable. There may be instances of highest productivity in the field; however, if the instances cannot be maintained over a sustained period of time then it is not optimal productivity.

4.1.3 Actual Productivity

The actual productivity is the productivity measured in the field. The ratio of quantity installed to the labor hours to complete the installation is termed as actual productivity in our case. Though scheduled breaks are part of daily activities, the actual productivity calculation excludes these breaks.

4.1.4 System Inefficiency

System inefficiencies (Δ_{si}) emerge due to factors outside the control or influence of project managers such as high temperatures, high humidity, poor workers' health, absenteeism caused by health or family issues, and interferences from other trades. These factors have direct or indirect impact on labor productivity; however, project managers have no control over these factors. For example, a project manager has no control or influence on high temperatures that directly affect a worker's physical health that lowers productivity. As an indirect impact, high temperature increases workers absenteeism. An option for minimizing the effects of high temperature would be to offer shift work during the night when temperature is relatively low compared to a hot summer day. However, the challenge is shift work at night may not guarantee the presence of workers. The reason could be personal factors or family issues. Studies show that many factors affect absenteeism and discuss the impact of shiftwork (Hanna, 2004; Hanna et al., 2005). Therefore, system inefficiency, in this dissertation, assumes that inefficiency is caused by factors that are not under the control of project managers.

4.1.5 Operational Inefficiency

Operational inefficiencies (Δ_{oi}) are under the control of project managers. Examples of such inefficiencies include inappropriate construction methods, crew size and composition issues, poor quality control, disorganized scheduling, inaccurate material management, and inadequate supervision. Project managers can control these inefficiencies by practicing good management techniques. For example, forming cast-in-place concrete structure for any repetitive construction project at heavily congested traffic sites can increase operational inefficiency. Instead of cast-in-place, project managers can use precast concrete, which are produced off-site in a factory and erected on-site to form robust structures, ideal for repetitive construction projects. Therefore, operational inefficiency in this research must be understood as any inefficiencies caused by factors that are under the control of project managers.

The system and operational inefficiencies are the breakdown of total inefficiencies. The total inefficiency can be mathematically equated as follows.

$$\Delta_i = \Delta_{si} + \Delta_{oi} \qquad \text{(10)}$$

Where:

Δ_{si} = total inefficiencies

Δ_{si} = system inefficiencies

Δ_{oi} = operational inefficiencies.

4.3 Empirical Methods: A Top-down and a Bottom-up Approach

The theoretical framework provides information and insight of how estimating the magnitude of system and operational inefficiencies will help project managers determine optimal productivity. The effort of this research is to focus on optimal productivity because it can provide a benchmark for gauging performance.

This research proposes to estimate optimal productivity from two directions: a top-down approach and a bottom-up approach. The top-down approach estimates optimal productivity by introducing system inefficiencies into productivity frontier. The bottom-up approach estimates optimal productivity by filtering out operational inefficiencies from actual productivity.

System inefficiencies can only be estimated rather than directly measured. Introducing this estimate (Δ'_{si}) to the productivity frontier does not yield the optimal productivity, rather what this research refers to as the "upper limit of optimal productivity (OP_{UL})." Analogously, by eliminating estimated non-contributory actions (Δ'_{oi}) from the model, the "lower limit of optimal productivity (OP_{LL})" determines productivity levels unhampered by operational inefficiencies. These limits are illustrated in Figure 4.3.

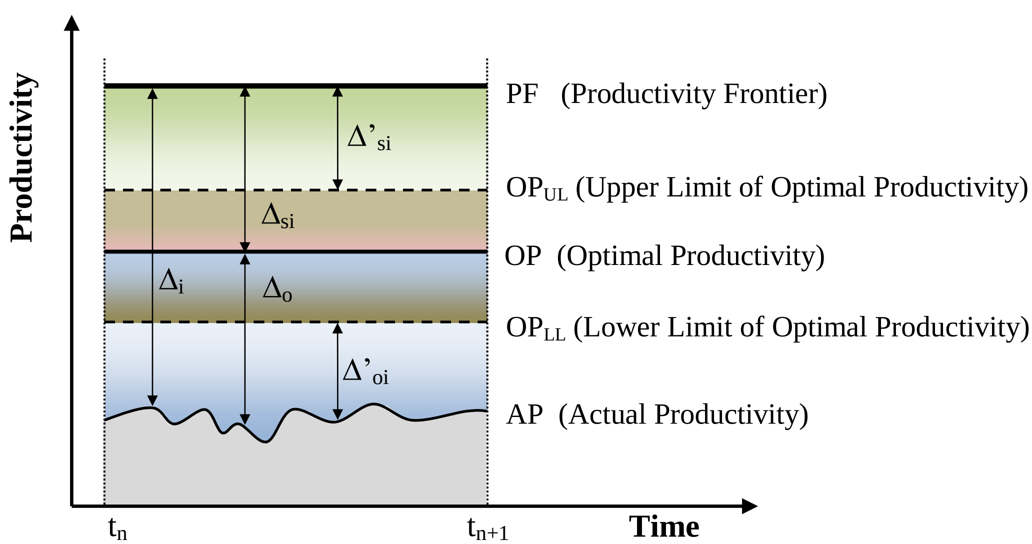


Figure 4.3: Upper and Lower Limits of Optimal Productivity

The top-down approach estimates the losses due to system inefficiencies minus the losses from the productivity frontier level and adjusts it to a level yielding the upper limit of optimal productivity. The bottom-up approach determines optimal productivity by removing non-contributory work from actual productivity. The bottom-up approach estimates losses due to operational inefficiencies. It adds the losses to actual productivity by compensating for losses that increase productivity level, and ascend to the lower limit of optimal productivity. Finally, the estimate of optimal productive is determined by averaging the upper and the lower limits of these respective productivity values.

In summary, the upper and lower limits of optimal productivity are calculated as follows:

$OP_{UL} = PF - \Delta'_{si}$ ………………………………..……………………… (11)

$OP_{LL} = AP + \Delta'_{oi}$ ………………………………..…………………… (12)

Where:

Δ'_{si} = estimate of productivity loss due to system inefficiencies Δ_{si}.

Δ'_{oi} = estimate of productivity loss due to operational inefficiencies Δ_{oi}.

In order to estimate inefficiencies and solve the Eq. (11) and Eq. (12) above, the conceptual framework is developed, as shown in Figure 4.4, which portrays the basic steps of top-down and bottom-up approaches. The framework presents the contextual relation between literature review, research objectives, and innovative models proposed. The development of this framework aligns with the structural logic of the dissertation shown in Figure 1.2 of Chapter 1.

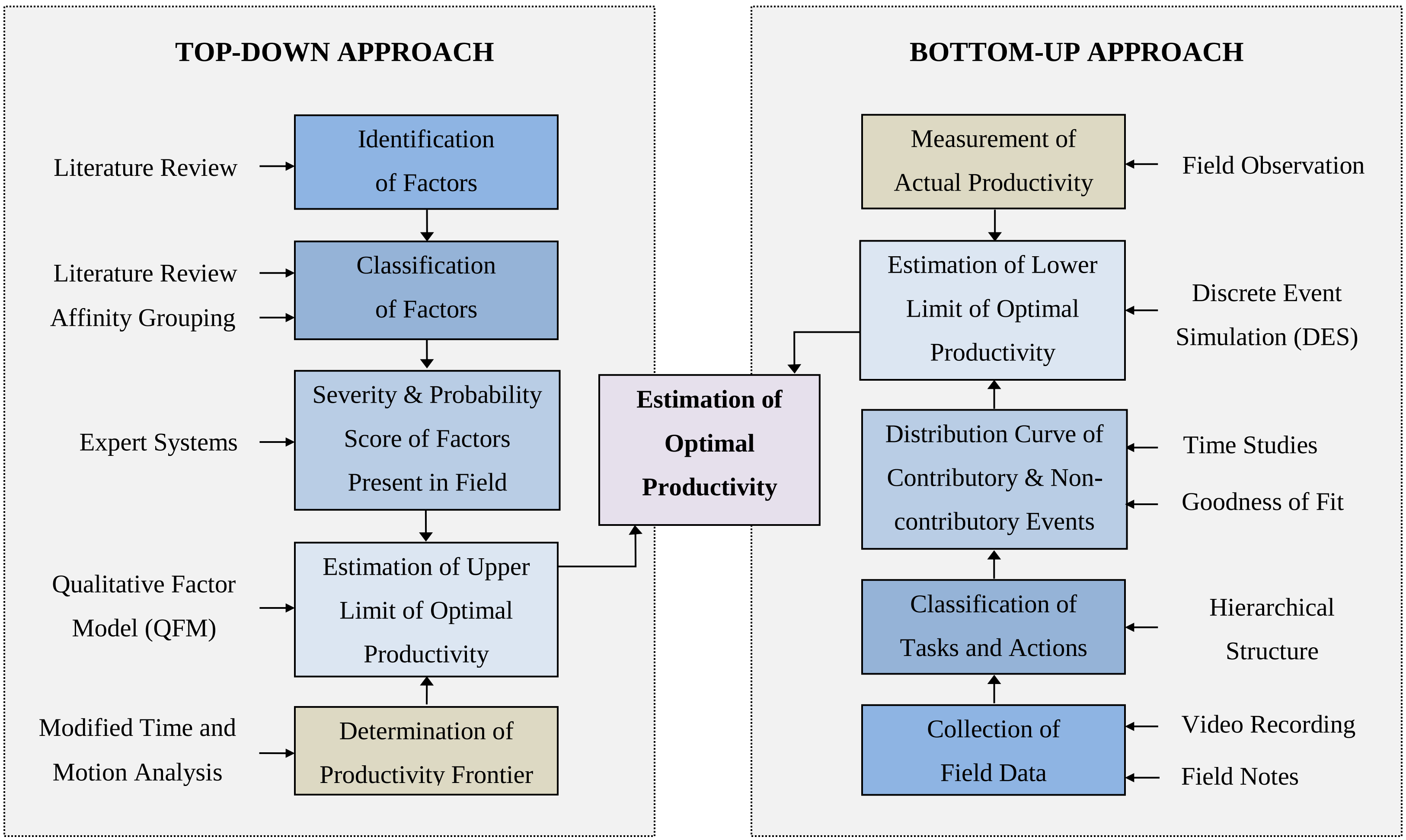


Figure 4.4: Conceptual Framework of a Top-down and a Bottom-up Approach

As shown in Figure 4.4, the top-down approach deals with system inefficiencies and focuses on estimating upper limit of optimal productivity as equated in Eq. (11). Since system inefficiencies cannot be directly measured in the field and these are caused by factors that are not under the control of project managers, they must be evaluated qualitatively. For example, the impact of temperature on productivity is subjective and the measurement can only be done by qualitative analysis. The research uses different methods and techniques available in existing literature, modifies as required, and develops a new method such as the Qualitative Factor Model (QFM) to appropriately address the problem. As an illustration, identification of factors affecting labor productivity is presented from the top four engineering and management journals since 1985. The factors are classified based on literature and affinity grouping techniques, and severity and probability scores of factors collected from experts that are present at job sites. Based on the experts' severity and probability scores, the inputs are used in a QFM (described in following section) to estimate losses due to system inefficiencies. The determination of the productivity frontier is beyond the scope of this research; therefore, the dataset values adopted are from the research presented by Mani et al. (2014).

The bottom-up approach uses on Eq. (12), which focuses on operational inefficiencies and the estimate of the lower limit of optimal productivity. Recall that the operational inefficiencies are under the control of project managers, which means they can be analyzed quantitatively and minimized during field operation. The block diagram in Figure 4.4 shows:

- Field notes and videotape are used to collect field data

- A hierarchical structure is used to classify activity into identifiable tasks and measurable actions
- Time studies method classifies contributory and non-contributory events
- Goodness of fit method obtains the distribution curve for the events. All the events are modeled into DES: one with contributory events and the other with non-contributory events.

4.2 Research Challenges

Out of all the variables shown in Figure 4.2 and brief introduction of empirical method from Figure 4.3, only actual productivity (AP) can be directly measured in the field. Given this limitation and the theoretical and empirical framework explained herein, the main challenges involved in the estimation of optimal labor productivity in labor-intensive construction operations include:

- Accurately measuring actual productivity (AP).
- Estimating system inefficiencies (Δ_{si}).
- Estimating operational inefficiencies (Δ_{oi}).
- Estimating optimal productivity (OP).

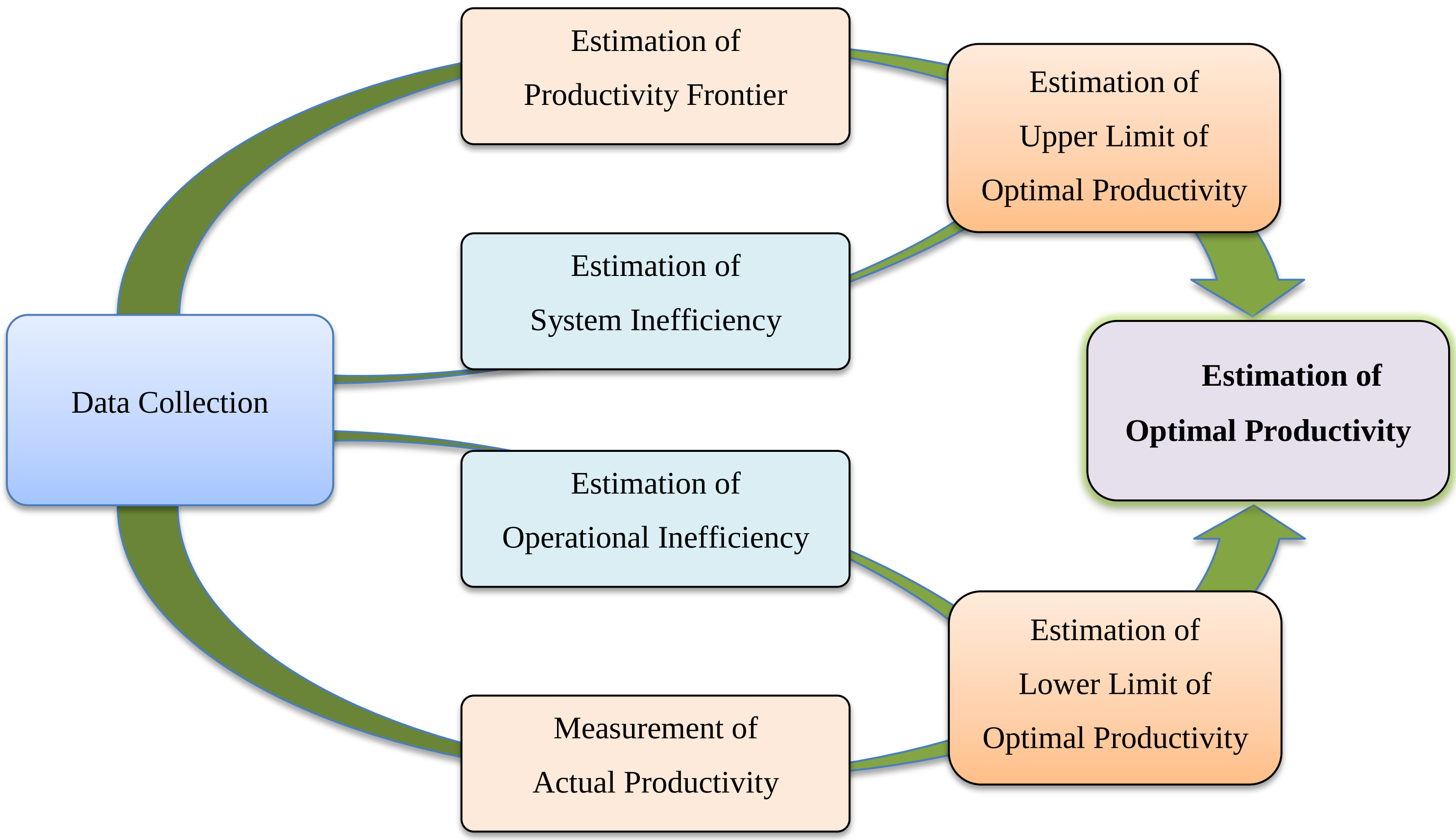


Figure 4.5: A Two-Prong Strategy Methodology

4.4 Research Methodology: A Two-prong Strategy

Based on the theme of the top-down and bottom-up approaches, this research develops a two-prong strategy for estimating optimal labor productivity. Figure 4.5 shows a pictorial representation of the two-prong strategy. The first prong represents a top-down approach that estimates upper limit of optimal productivity by introducing system inefficiencies into the productivity frontier. A QFM is used to determine the impact of system inefficiencies. The second prong is a bottom-up approach that estimates lower limit of optimal productivity by removing operational inefficiencies from actual productivity. DES is used to analyze operational inefficiencies. An average of these two limits provides the best estimate of optimal productivity because these two limits consider both qualitative and quantitative aspects of inefficiencies.

The following sections explain how the two-prong methodology can be implemented in the field to address the research challenges previously stated. It is important to note that the following material outlines the essential methodology upon which analysis of field study will build.

4.4.1 Accurately Measuring Actual Productivity

This research uses three Canon XF professional camcorders to collect video data from three different locations, which capture the movements of workers. The camcorders provide the benefit of reviewing the video whenever required as well as to break down tasks and actions. One thing to note here is: whether the analysis is done at activity level or task level the events must be repetitive in nature.

4.4.1 Estimating System Inefficiencies

The identification of system inefficiencies necessitates a qualitative analysis. Different methods and models for assessing qualitative factors and their implementation can be found in papers such as Thomas and Sakarcan (1994), Christian and Hachey (1995), Kindinger and Darby (2000), Srinavin and Mohamad (2003), and Dai et al. (2009). Inspired by these papers, this research developed a Qualitative Factor Model (QFM) to evaluate the productivity lost due to system inefficiencies—those factors that affect productivity but are outside the control/influence of project managers. The QFM uses a severity score technique following a probabilistic approach. In this context, Δ'_{si} is the estimated productivity loss due to system inefficiencies rather than the actual productivity loss Δ_{si}. Based on this QFM, system inefficiencies for the research is calculated as follows:

$$\Delta'_{\mathrm{si}} = \Delta'_{(\mathrm{PF-OP_{LL}})} * \sum_{z=1}^{n}[\sum_{i=1}^{m}\left(\frac{S_i P_i}{TS_i}\right)]\, W_z \qquad \text{……………………………(13)}$$

Where:

Δ'_{si} = estimate of productivity loss due to system inefficiencies.

$\Delta'_{(\mathrm{PF-OP_{LL}})}$ = estimate of the difference between productivity frontier and the lower limit of optimal productivity.

n = number of work zones.

m = number of productivity factors.

z = work zone (classrooms, lockers, and corridor/hallways).

i = system inefficiency factors in each work zone z.

S_i = severity score of individual productivity factor i.

P_i = probability of individual productivity factor i.

TS_i = total severity score (sum of severity scores for all productivity factors).

W_z = relative weights of each work zone.

Experts provide qualitative definitions of severity for each of the factors according to a severity ranking score (“0”=no impact; “1”=very low impact; “2”=low impact; “3”=medium impact; “4”=high impact; and “5”=very high impact). Probabilities are used to establish the likelihood of factors being present during the work. For example, a severity score of 4 with a 0.5 probability means that the factor has a probability of occurrence of 50 percent, and when it occurs, it has a high impact on labor productivity.

Depending on the nature of the work environment, the severity score may vary across work zones. In addition, the number of tasks (e.g., number of bulbs installed) at one zone may be different than other zones. A relative weight of each zone is calculated based on how many tasks are completed in a particular zone. This is important because severity score and probability are assumed uncorrelated. For example, a zone having ten tasks might have the same severity product as another zone having thirty tasks. But logically, the zone having more tasks completed has more weights than the other having less tasks completed. Therefore, the model considers relative weights for each zone.

As shown in Eq. (13), the estimate of difference between productivity frontier and lower limit of optimal productivity is used to determine Δ'_{si}. The input of lower limit is considered for QFM analysis because it models every case including the worst-case scenario. The worst-case scenario could happen if all system inefficiencies were present and they each have a significant impact. If this condition exists in the field then the highest productivity that could be achieved in the field is by minimizing loss due to operational inefficiencies. For example, Eq. (13) assumes that all the system inefficiencies are present and each of the factors that affect labor productivity have a probability of "1" and severity score of "5". Consequently, the highest productivity in the field would be the productivity after eliminating noncontributory parts from actual productivity. This, by definition, is the lower limit of optimal productivity that is shown in Fig. 4.3. The analysis and discussion of estimating lower limit of productivity is discussed in the following section.

4.4.2 Estimating Operational Inefficiencies

The process of estimating operational inefficiencies involved developing a DES to model the construction process. The purpose of this simulation was to emulate the processes observed in the video recordings as close as possible so as to later be able to differentiate contributory from non-contributory actions. Contributory actions include those actions that are necessary to accomplish the task. For example, if one considers the bulb replacement task, then basic actions and movements required to replace bulb are contributory actions. Non-contributory actions include those that are non-productive in nature, such as unscheduled breaks, late starts, early quits, idle time, and engagement of personal discussions during work (Heizer & Render 1996).

In order to build the simulation model, the primary work involves breaking down the activity into tasks, splitting each task into measurable actions, and modeling the duration of each action with probability distribution curves representing the observed field durations. The secondary work involves modeling the sequence of workflow to simulate the construction operation. Ultimately, it is necessary to compare the simulation's output with the actual field results to establish validity. After validation, the simulation is repeated; however, the non-contributory actions from the tasks are eliminated, thereby, decreasing the simulated duration and creating a synthetic scenario. The difference between the productivity of the synthetic and the actual scenarios forms the estimate of operational inefficiencies (Δ'_{oi}).

4.4.3 Estimating Optimal Productivity

The estimate of upper boundary and lower boundary determines the range over which optimal productivity can fluctuate. Once the upper and lower limits are estimated the average of these limits provides the best estimate for optimal productivity. The project managers can then use the result to determine the efficiency of their labor-intensive construction operations by comparing actual vs. optimal rather than actual vs. historical productivity.

CHAPTER 5

ESTIMATING OPTIMAL PRODUCTIVITY IN AN ACTIVITY WITH A SINGLE WORKER AND SEQUENTIAL TASKS USING A TWO-PRONG STRATEGY

An accurate estimation of optimal productivity would allow project managers to determine the efficiency of their labor-intensive construction operations by comparing actual vs. optimal rather than actual vs. historical productivity. This research reports on a pilot study performed to evaluate the feasibility of using a two-prong strategy within a simple electrical installation to estimate optimal labor productivity.

5.1 Replacement of Electrical Lighting Fixtures: A Pilot Study

Commonwealth Electric Company completed an electrical lighting fixture installation project at Omaha South Magnet High School. This project involved a repetitive process of replacing lighting fixtures in a controlled environment (i.e. inside the school building). Data was recorded from five different zones: classrooms, locker room, corridors/hallways, weight/training room, and family consumer science room. This project included multiple sequential tasks such as removal of the existing frame for the lighting fixtures, removal of the old T-12 fluorescent bulbs, removal of the ballast, installation of new Type-2 ballasts, installation of T-8 fluorescent bulbs, and closure of the main outer cover (frame).

5.1.1 Data Collection

Two electrical workers from Commonwealth Electric Company, a veteran and a novice, participated in the pilot study. The study focused exclusively on analyzing the activities performed by the veteran worker given their level of experience performing similar operations. The data collection method was similar to time studies, and three Canon XF 100 camcorders were used to record the repetition of the veteran worker performing the tasks. The calibration of the cameras was performed similar to "Camera Calibration Toolbox" in Matlab (Bai, Huan, & Peddi, 2008; Sigal, Balan, & Black, 2010). One or more camcorders were used as dictated by space availability to capture movements from different angles. One of the benefits of video recording is that data can be reviewed from the video whenever required. Field notes were also recorded for more information such as workers start time, break time, finishing time etc.

Different types of ballasts and fluorescent bulbs were used in the project. For consistency, activities involved with Type-2 ballast and T8 fluorescent bulbs were considered in this study. Type-2 ballasts can supply power up to two fluorescent bulbs. Similarly, the working height of scaffold used for the project was also taken into consideration by analyzing data having equal scaffold height.

The veteran worker completed 62 stations at five different zones. Each station included replacing one Type-2 ballast and two T8 bulbs. Video data from 62 stations, which is 62 Type-2 ballasts and 124 T8 bulbs, were captured for time and motion study at different zones.

Data were collected at activity and action levels as shown in Table 5.1. Factors contributing to system inefficiency were collected at the "Replacement of Electrical

Lighting Fixtures" activity level since system inefficiencies tend to affect all tasks and actions within an activity equally. Factors contributing to operational inefficiency were analyzed at the action level for the "Fluorescent Bulb Replacement" task since actions produced enough data for a preliminary analysis without creating an unnecessary burden for data processing. Table 5.1 provides a summary of information collected at activity and action levels, inefficiencies studied, models approached to analyze inefficiencies and the result of the models.

Table 5.1 Levels of Study and Estimation Scope

Level	**Inefficiency**	**Analysis**	**Input**	**Output**
Activity	System	Qualitative Factor Model	Severity Scores and Probabilities	Estimation of System Inefficiency
Action	Operational	Discrete Event Simulation	Events	Estimation of Operational Inefficiency

The data were collected in video files, which document all of the tasks, actions, and movements necessary to replace the old lighting fixtures with new ones. The experts' input on severity and probability of factors that affect labor productivity at the project site were also collected via questionnaire survey.

5.1.2 Data Analysis

As previously shown in Table 5.1, the analysis is carried out in two levels. The QFM is used to analyze system inefficiencies whereas DES is used to analyze operational inefficiencies. Severity scores and probabilities are inputs for QFM while events and their distribution parameters are required for the DES model. A hierarchical structure was defined to break down activities into tasks and then task into actions. Figure 5.1 shows a hierarchical structure developed for this pilot study in order to calculate the duration of the actions associated with the "Fluorescent Bulb Replacement" task.

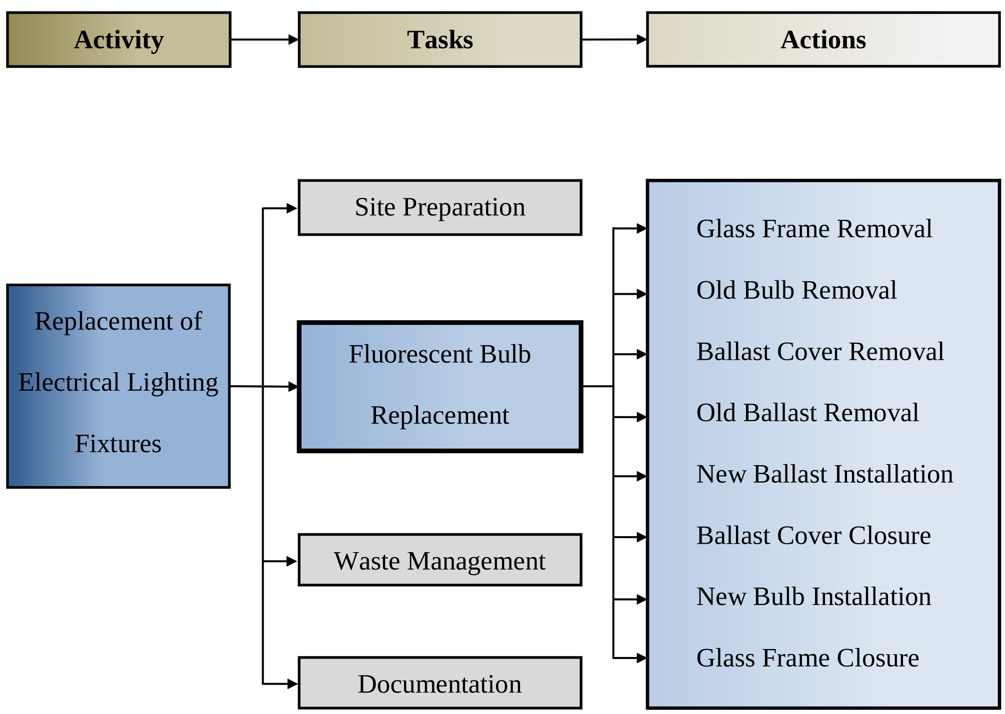


Figure 5.1: Hierarchical Structure of Lighting Fixtures Replacement Activity

The activity "Replacement of Electrical Lighting Fixtures" was selected for analysis given its homogeneity across the construction project and was broken down into four tasks: (1) Site Preparation, (2) Fluorescent Bulb Replacement, (3) Waste Management, and (4) Documentation. The task "Fluorescent Bulb Replacement" was selected for further analysis given its consistency and number of repetitions available and was broken down further into eight actions: (1) Glass Frame Removal, (2) Old Bulb (T12) Removal, (3) Ballast Cover Removal, (4) Old Ballast Removal, (5) New Ballast Installation, (6) Ballast Cover Closure, (7) New Bulb Installation, and (8) Glass Frame Closure.

The hierarchical structure was analyzed from videotape. Figures 5.2-5.9 show the pictures of the veteran electrical worker performing eight actions. Each action consists of movements and the necessary steps and expected duration to sufficiently accomplish the action. The explanations of each step involved in accomplishing the eight actions are described below.

Figure 5.2: Glass Frame Removal

The process of “Fluorescent Bulb Replacement” task proceeds with “Glass Frame Removal” action, which is shown in Figure 5.2. Removing the cover consists of unscrewing or unlocking one edge of the outer cover of the ceiling light fixture, letting it open to one side, and subsequently allowing the other end to hang all while permitting enough space to continue onto the second action. The second sequential action is “Old Bulb (T12) Removal”, which is shown in Figure 5.3.

Figure 5.3: Old Bulb (T12) Removal

A T12 bulb has a diameter of 12/8 inches, which is equivalent to an inch and a half diameter, and the bulb is old and inefficient compared to new ones. The duration for removing bulbs counts from reaching hands to the bulbs, twisting the bulbs to unlock, and then dumping them into the collection box that are hung on either side of the scaffold as shown in the pictures. The sample durations of each action are recorded in spreadsheet as shown in Appendix B.

The third sequential action is "Ballast Cover Removal" which is shown in Figure 5.4. This removing action involves reaching out hands to the ballast cover, unscrewing or unlocking the cover, removing the cover and safely placing that cover over the scaffold so that it is readily available. They put removed cover depending upon their convenience. For example, sometimes the worker places the cover above the base of the scaffold as soon as they remove the cover, sometimes holds the cover between their two legs for some duration and then puts that cover later somewhere over the scaffold, and sometimes places the cover on the side handrail of the scaffold.

Figure 5.4: Ballast Cover Removal

The fourth sequential action is "Old Ballast Removal", which is shown in Figure 5.5. The duration begins when the worker reaches out hands to the ballast, disconnects circuit wires, and inserts push-in wire connectors, unscrews all screws, removes the old ballast, and ends when the worker discards the old ballast into a collector bin placed over the scaffold. The unscrewing may be manual or assisted by use of powered tools depending upon the level of difficulty. Relative to the duration of other actions; removing old ballast has the longest duration.

Figure 5.5: Old Ballast Removal

The fifth sequential action is “New Ballast Installation”, appears in Figure 5.6. The steps for installing new ballast start when the worker grabs new ballast, inserts push-in wire connectors if necessary, connects circuit wires, screws in all screws either manually or using power tools, wraps wires together and manages wires properly. The steps may be interchangeable. For example, the worker sometime screws the ballast first and then connects wires later, and sometimes vice versa. Relative to the duration of other actions, installing new ballast has the second longest duration.

Figure 5.6: New Ballast Installation

The sixth sequential action is “Ballast Cover Closure”, which is shown in Figure 5.7, is closing ballast cover.

Figure 5.7: Ballast Cover Closure

The closing action involves picking up the ballast cover, placing it at an appropriate location, and screwing or locking it properly. As mentioned earlier, screwing in may be done manually or by using power tools. Figure 5.8 shows by using power tools.

The seventh sequential action is “New Bulb (T8) Installation”, which is shown in Figure 5.8, is installing new bulbs. A T8 bulb has 8/8 inches or simply an inch in diameter and has higher efficiency than the T12 bulb. The steps for installing new bulbs comprise grabbing T8 bulbs from the container hung on the side of scaffold, inserting it into the fixture location, twisting bulb to lock in the fixture. While installing T8 bulbs, the worker grabbed two bulbs simultaneously and installed two bulbs into the fixture sequentially in a single step. Figure 5.8 shows the instance of worker installing one bulb while still carrying another bulb in his hand.

Figure 5.8: New Bulb (T8) Installation

The eighth sequential action is “Frame Cover Closure”, which involves closing the frame cover back to its original position. Figure 5.9 shows the instance of frame closure.

Figure 5.9: Frame Cover Closure

In this way the duration of all actions are recorded in a spreadsheet and analyzed. A sample data of 20 repetitions out of 62 repetitions are shown in Appendix B.

5.1.3 Results

From Table 1, a QFM is used to estimate actual system inefficiency. The model uses the input of the factors that influence productivity and assigns severity scores and probabilities of each factor’s occurrence. Thanks to a comprehensive literature review process, a list of productivity-influencing factors at the system level could be generated for the installation. Next, five experts provided severity scores and probabilities of occurrence for each factor. These scores and probabilities were inputs for the QFM to determine system inefficiency estimates.

As discussed in the methodology section, a discrete event simulation yielded operational inefficiency estimates. Using a detailed video analysis, events and their stochastic durations were identified and defined. Time studies were conducted from the video data, and durations were recorded for each contributory and non-contributory action (these terms are explained in DES section below). A sample data after removing non-contributory actions is shown in Appendix B. Based on this categorization of contributory and non-contributory events, simulations were performed to estimate the lower limit of optimal productivity.

5.1.3.1 Actual Productivity

Recorded field data shows that laborers completed 62 stations at an average of 4.5 minutes per station or 13.33 stations per hour. Here the output is measured in stations because each station consists of replacing two old fluorescent lamps with new ones. Since the two bulbs were removed at once during replacement task and a single ballast is enough to operate two bulbs, the unit of stations per hour makes more sense.

5.1.3.2 Qualitative Factor Model

Table 5.2 shows the system inefficiency factors present in the pilot study (those with probability of occurrence different than zero), their severity scores, and their probabilities. Five experts; three researchers, one supervisor, and a worker; sorted the factors that caused system inefficiencies during the pilot study. For instance, the impact due to external weather condition was not in the list since the activity happened inside the school building. Experts provided probability and severity scores for each factors depending on how likely the factors was present and how severe the factors would impact productivity if indeed the factors were present.

During the electrical installation activity, classes were in session at the school. Therefore, the severity score for noise level was observed high due to presence of students. As expected, the severity score for space congestion was high in classroom because the working space was furnished which caused obstruction to the workers. Because of the indoor environment, Table 5.2 shows a severity score for temperature, humidity, and lighting to be relatively low. Though the school had a controlled environment, there were certain variations in temperature and humidity among different zones inside the building. For example, due to students taking showers, humidity was high in locker rooms compared to other room. These variations were considered in Table 5.2.

The estimation of the productivity frontier was 22.32 stations per hour by using the same methodology as in Mani et al. (2014) and using the same data set. When substituting all the required parameters in the qualitative factor model, the estimate of productivity loss due to system inefficiency (Δ'_{si}) is 2.98 stations per hour. When this value is subtracted from the productivity frontier, 19.34 stations per hour is the estimate of the upper limit of optimal productivity (OP_{UL}).

Table 5.2: Severity and Probability Analysis for Productivity Factors

Zone	**Factors**	**Severity Score (S_i)**	**Probability of Occurrence (P_i)**	**Product ($S_i P_i$)**
Classrooms	High humidity	2	0.4	0.8
	Low temperature	2	0.3	0.6
	Low luminance	2	0.3	0.6
	High noise level	2	0.6	1.2
	Space congestion	4	0.8	3.2
Locker Rooms	High humidity	3	0.4	1.2
	Low temperature	2	0.5	1.0
	Low luminance	2	0.4	0.8
	High noise level	4	0.3	1.2
	Restricted access	2	0.6	1.2
	Space congestion	3	0.6	1.8
Corridor/ Hallway	High humidity	1	0.2	0.2
	Low temperature	2	0.3	0.6
	High luminance	2	0.3	0.6
	High noise level	4	0.4	1.6
	Space congestion	1	0.3	0.3
Weight Room/ Training Room	High humidity	2	0.3	0.6
	Low temperature	2	0.3	0.6
	Low luminance	2	0.3	0.6
	High noise level	3	0.6	1.8
	Space congestion	4	0.7	2.4
Family Consumer Science room	High humidity	2	0.3	0.6
	High temperature	2	0.3	0.6
	High luminance	2	0.3	0.6
	High noise level	3	0.4	1.2
	Space congestion	4	0.6	2.4

5.1.3.3 Discrete Event Simulation Model

The actions observed in the field were categorized into: (1) contributory (direct and indirect work), and (2) non-contributory. Contributory actions included those actions that are necessary to accomplish the task—for example, basic actions and movements required to replace bulbs. Non-contributory actions include those that are non-productive in nature, such as unscheduled breaks, late starts and early quits, idle time, and engagement of workers in personal discussions (Heizer & Render, 1996). In this pilot study non-contributory actions identified were sitting idle, spending time using cell phones, chatting with co-workers, dropping tools and wasting time, and doing rework because of inappropriate material management.

5.1.2.3.1 Modeling the Bulb Replacement Process

The bulb replacement process is illustrated schematically in Figure 5.10. The model is very simple and consists of only sequential actions involved in the Fluorescent Bulb Replacement task. Entities arrive at the station where light fixtures need to be replaced; in our case entities are new bulbs and new ballasts. The veteran worker processes the actions. When the worker finishes the replacement task, the worker moves into next station. The time taken for the worker to complete each action is recorded. Here, the process of finishing the task is only considered for the analysis since the objective was to find the efficiency of the worker to complete that particular task. The model could simulate at activity level including site mobilization time and transfer time from one station to another station; however, the data collected were not sufficient to model at activity level. Therefore, the model is analyzed at action level and the entities and resources required to handle that entity are assumed available at all stations.

In order to get a realistic model, it is necessary that it be based on actual field data; the more 'real' data are collected, the more realistic the model becomes (Smith, 1999). Each action shown in Figure 5.10 has 62 repetitions of field data. The duration of each action is recorded in spreadsheets by playing video several times and observing the time. A stopwatch was also used to cross check the durations.

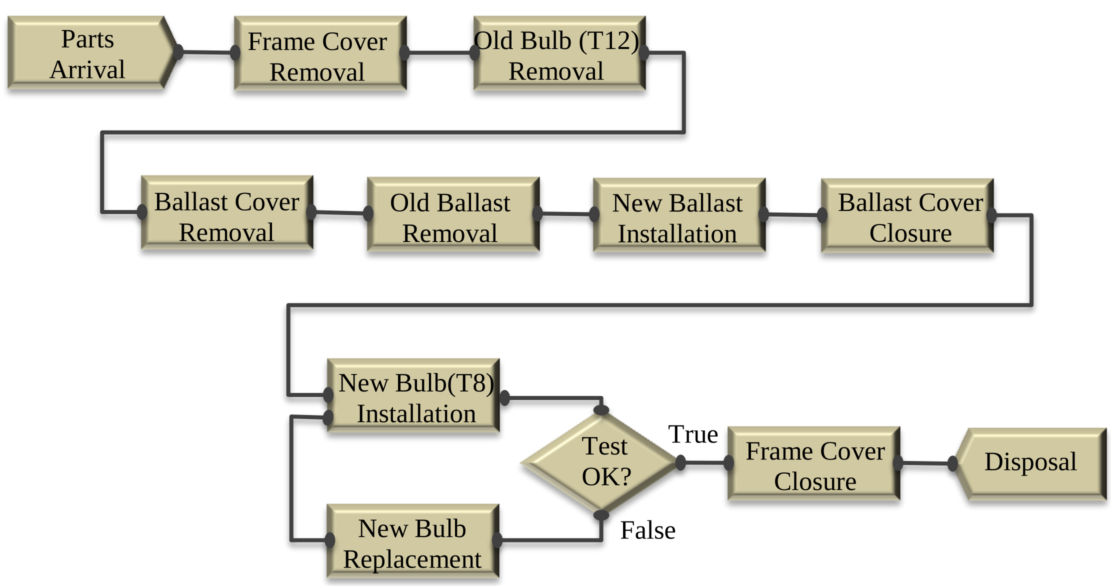


Figure 5.10: Discrete Event Simulation Model of Fluorescent Bulb Replacement Task

5.1.2.3.2 Fitting Probability Distribution to Data

Once the durations of each action are recorded, it is usually necessary to determine which probability distribution fits the sample data. There are many techniques available to fit distributions to the sample data; these are usually goodness-of-fit tests or heuristic graphical techniques. Rockwell Automation is the provider of Arena simulation software (Rockwell Automation, 2013). Arena supports a wide variety of probability distributions including uniform, normal, log-normal, beta, gamma, Weibull, and Erlang (Kelton, Sadowski, & Swets, 2010). Smith (1998) used beta and gamma distributions to model construction data. Input Analyzer in Arena software easily plots distribution curves for a given sample. It provides square error and significance P-value for Chi-square test and Kolmogorov-Smirnov test which serve goodness-of-fit test.

The following illustration shows how to plot distribution curves and choose the best one based on significance P-value, square error and the visual inspection. Based on 62 observations of each action the curves generated from Arena simulation are shown below. Figure 5.3 and Figure 5.4 show histogram of the data and fitted curves along with the expression to represent that curve by using Arena Input Analyzer tool.

Table 5.3: Distribution Curves and Expressions for Different Actions (Part 1)

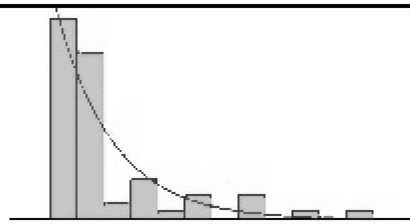
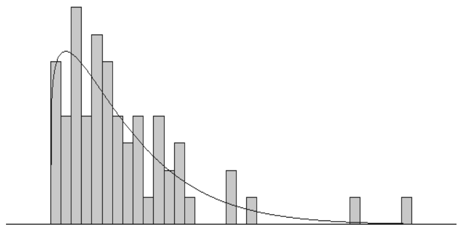
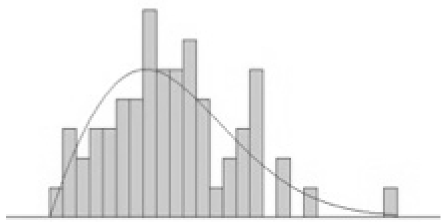
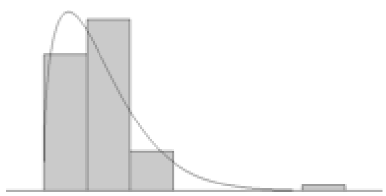
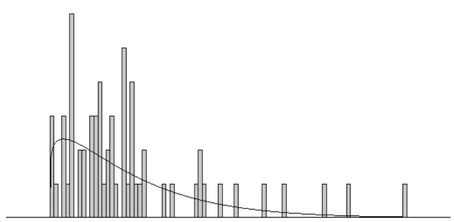
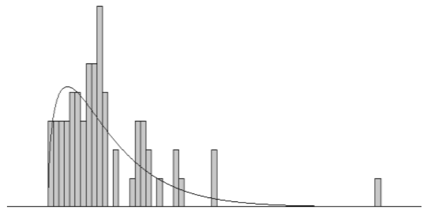
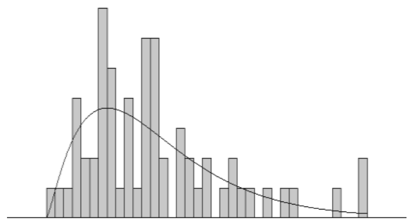
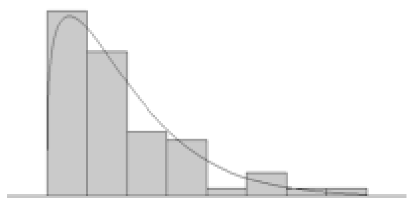
Actions	Distribution Curve	Expression
Glass Frame Removal		Exponential 2.5 + Expo(2.11)
Old Bulb (T12) Removal		Weibull 9.5 + WEIB (7.41, 1.17)
Ballast Cover Removal		Weibull 4.5 + WEIB (10.4, 1.94)
Old Ballast Removal		Weibull 70+WEIB(28.2, 1.38)
New Ballast Installation		Weibull 51.5 + WEIB (20.8, 1.14)

Table 5.4: Distribution Curves and Expression for Different Actions (Part 2)

Actions	Distribution Curve	Expression
Ballast Cover Closure		Gamma 9.5 + GAMM (7.18, 1.49)
New Bulb Installation		Gamma 29.5 + LOGN(9.79 +3.4)
Glass Frame Closure		Erlang 10.5 + ERLA(6.23, 9)

5.1.2.3.3 Model Verification and Validation

Contributory and non-contributory actions were modeled into the DES to represent process workflow. The model was verified with the sequences of actions in the model with the actual sequences in the field. After verifying sequences of actions, the simulation was run under two scenarios: actual (including non-contributory actions) and synthetic (excluding non-contributory actions). The actual scenario was used for model validation while the synthetic scenario was used for estimating the lower limit of the optimal labor productivity.

Simulation results from the actual scenario were compared against field data to calculate the deviation and see if the deviation is within the reasonable limit. Recorded field data show that actual productivity was 13.33 stations per hour. The simulation results from the actual scenario show a completion rate of 13.07 stations per hour. These values represent less than 2% deviation from the recorded field values. Thus the simulation model was validated with face validity: the technique used in determining if the logic in the conceptual model is correct and if a model's input-output relationships are reasonable (Sargent, 2013, Lucko & Rojas, 2010).

5.1.2.3.4 Analysis and Results

The field data were compared to the simulation results from the actual scenario. The simulation results from the actual scenario show a completion rate of 13.07 stations per hour. These results represent less than 2% deviation from recorded field values. The simulation results for the synthetic scenario show a completion rate of 14.32 stations per hour. This is a 7.4% improvement over the results from the actual scenario. This implies that the loss due to operational inefficiency (Δ'_{oi}) is 1.25 station per hour.

The mean values from the actual and the synthetic models were compared to determine if they were statistically different. Using Arena's output analyzer and a 95% confidence interval, a paired-T means comparison test of the null hypothesis that both means were equal concluded that the means were different.

The productivity from this synthetic scenario is taken as an estimate of the lower limit of optimal productivity (OP_{LL}) rather than as the optimal productivity itself because, even when non-contributory actions are excluded, a simulation model that relies on field data cannot eliminate all operational inefficiencies embedded in a construction operation.

5.1.4 Estimation of Optimal Labor Productivity

The average of the upper and lower limits of optimal productivity results in an optimal productivity (OP) of 16.83 stations per hour. Compared to actual average productivity, which is 13.33 stations per hour, the estimate of optimal productivity may seem high. However, recorded field data shows that at one point during the installation, a station was completed in 3.4 minutes, which is equivalent to 17.64 stations per hour if such productivity were sustained. This duration demonstrates that the estimate of 16.83 stations per hour is challenging, but not necessarily out of reach. In summary, during the pilot study, the “Fluorescent Bulb Replacement” tasks achieved 79.2% efficiency (actual recorded productivity as a percentage of estimated optimal productivity).

5.1.5 Pilot Study Conclusions

The pilot study provided valuable lessons. The QFM was found to be effective in modeling system inefficiencies. The DES process was also found to be effective at modeling operational inefficiencies. Therefore, this pilot study demonstrated that the proposed two-prong strategy for estimating optimal labor productivity is adequate when applied to a simple electrical installation with a single worker and sequential tasks.

5.1.6 Pilot Study Limitations and Recommendations

The conclusion drawn from this pilot study is based on the observation and analysis of a single worker and in sequential tasks. The impacts of factors that affect labor productivity in this pilot study were normal due to the controlled environment. The factors identified were also minimal. Therefore, more research is required to:

- Determine the adequacy of the proposed two-prong approach when dealing with more complex construction operations. The pilot study focused on a simple operation performed by a single worker in a highly controlled environment.
- Determine the adequacy of the proposed two-prong approach when dealing with an entire activity. The pilot study focused only on the "Fluorescent Bulb Replacement" task. Data were not collected for the other three tasks that make up the "Lighting Replacement" activity.
- Determine the potential benefits of collecting more detailed information for the two-prong approach. The pilot study only collected data up to the action level, which predictably hides some inefficiency.
- Explore innovative ways of automating data collection and analysis. The proposed two-prong approach, as applied in the pilot study, was time consuming and intensive.

CHAPTER 6

ESTIMATING OPTIMAL PRODUCTIVITY IN AN ACTIVITY WITH MULTIPLE WORKERS AND SEQUENTIAL AND PARALLEL TASKS USING A TWO-PRONG STRATEGY

This chapter presents the feasibility test of the research method in complex operations. The test includes an activity level analysis, where the activity includes multiple tasks and actions. Unlike the pilot study discussed in chapter 5, this advanced study includes multiple workers who perform the activity. The tasks involved in the activity are both sequential and parallel. In many cases, the actions within the task are also both sequential and parallel. Thus, the operations discussed in this chapter are complex enough to test the feasibility of the developed research methodology. The results, analysis and discussion for both qualitative and quantitative analysis are illustrated in the following sections.

6.1 Fabrication of Sheet Metal Ducts: An Advanced Study

The advanced study was conducted at the workshop of the Waldinger Corporation in Omaha, Nebraska. The study was analyzed on “Fabrication of Sheet Metal Ducts” activity that was part of new construction projects at the University of Nebraska Medical Center (UNMC) in Omaha, Nebraska. The ducts fabricated from the workshop are installed as part of exhaust systems in the new building, which was under construction at the UNMC.

The activity has multiple workers involved, both sequential and parallel operations, numbers of repetitions were significant to draw statistical conclusion, the timeline of the study was reasonable, and the daily travel distance to the field was feasible. In addition, the activity involved consistent operations, a work environment that was indoors which made data collection easy, and the level of complexity and the factors affecting labor productivity were feasible to quantify. Though the operations were performed inside the workshop, the temperature or the weather effect to the worksite was not fully controlled since the garage doors were mostly open during the work.

6.1.1 Data Collection

Three Canon XF100 professional camcorders were used to videotape the operations involved in the "Fabrication of Sheet Metal Ducts" activity at the local workshop of the Waldinger Corporation in Omaha, Nebraska. These cameras were calibrated using Matlab tool (Bai et al., 2008; Sigal et al., 2010) and synchronized with same setting (Delamarre & Faugeras, 1999; Caillette & Howard, 2004).

The fabrication activity consisted of sequential and parallel tasks as well as actions. There were eight tasks involved in the activity. The first two tasks were sequential. The tasks following third up to eighth tasks involved parallel and sequential tasks.

For the first two tasks, all three cameras were placed in three different locations to capture actions performed by crew members in each task. In each crew, there were two to three members except in the delivery task, which had only one worker. Whenever there are parallel tasks going on, the cameras were set up individually to capture each task separately. Wherever possible the cameras were set up in such a way that a single camera could capture multiple tasks and actions simultaneously.

Data were collected at two levels, as previously described in the pilot study as shown in Table 5.1 of Chapter 5. Factors contributing to system inefficiency were collected at the “Fabrication of Sheet Metal Ducts” activity level. Factors contributing to operational inefficiency were analyzed at the action level for the eight different tasks. Altogether there were 43 actions involved in the data collection. The sheet metal used was US Standard 21 Gauge with the dimension of 80.25 inches x 60 inches.

The data were collected in video files, which document all of the tasks, actions, and movements necessary to fabricate sheet metal ducts. The experts’ input on severity and probability of factors that affect labor productivity at the fabrication workshop were also collected via questionnaire survey.

6.1.2 Data Analysis

A hierarchical structure was defined to break down activities into tasks and then task into actions. The activity “Fabrication of Sheet Metal Ducts” was broken down into eight tasks: (1) Roll Bending; (2) Lock Forming, (3) Lock Setting, (4) Tie Rod Installing, (5) Flange Screwing, (6) Sealing, (7) Packing, and (8) Delivery. Each action was further broken down to action levels. For example, the “Roll Bending” action was broken down to six actions: (1) Laying, (2) Marking, (3) Machine Setup, (4) Bending, (5) Dimension Checking, and (6) Stacking.

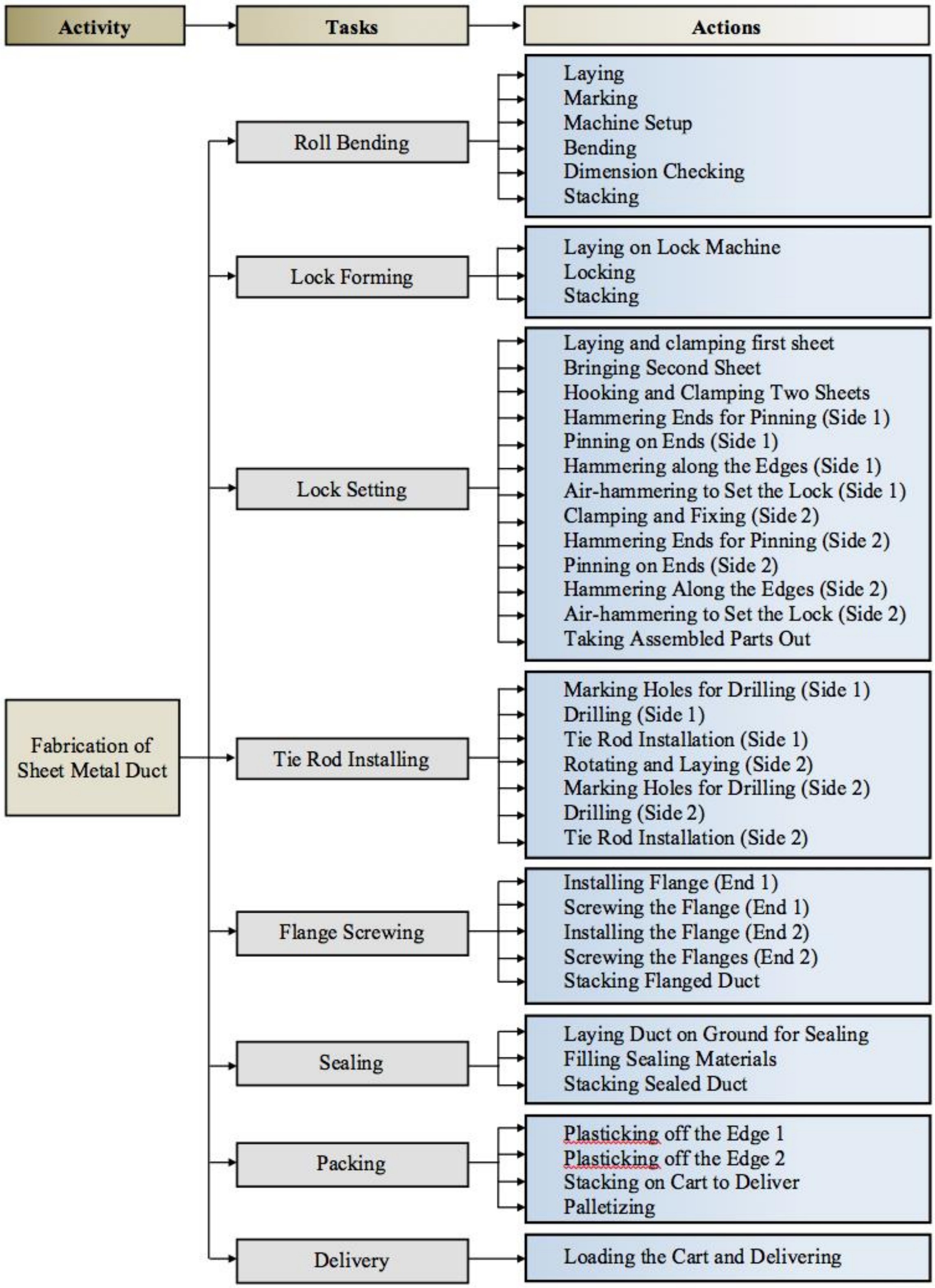


Figure 6.1: Hierarchical Structure of Fabrication of Sheet Metal Duct

Since this first task was performed by two different crews, the sequence of actions was different. Figure 6.1 shows a detailed hierarchical structure of the activity in tasks and actions.

6.1.2.1 Roll Bending Task

The first task involved in the fabrication of sheet metal duct was to form a roll up to one third of the length at one end. The roll bending task consists of the following (refer to Table 6.1) list of the steps necessary for completing this task. The descriptions of each task and actions involved are presented in Table 6.1 below.

Table 6.1: Descriptions of Each Action Involved in Roll Bending Task

Task	**Actions**	**Descriptions**
Roll Bending	Laying	• Grab sheet metal and lay over the table near the roller machine
	Marking	• Mark the sheet in order to roll up to the marked position
	Machine Setup	• Insert sheet to the machine and check if it's ok
	Bending	• Bend the sheet by turning on the machine
	Dimension Checking	• Check dimension to see if the rolled parts is at correct curve
	Stacking	• Lift the curved sheet and moving to the stack station

This task was performed by two crews. There were two members in each crew. Figure 6.2 shows the roll bending task performed by Crew 1. They completed 148 sheets out of 234 sheets in total.

Figure 6.3 shows the roll bending task performed by Crew 2. They completed 86 sheets out of 234 sheets in total in the activity.

Figure 6.2: Roll Bending Task by Crew 1

The Crew 2 performed somewhat differently from the Crew 1, but the actions involved were similar except the order of action steps.

Figure 6.3: Roll Bending Task by Crew 2

6.1.2.2 Lock Forming Task

The second sequential task consists of forming a lock at each end of rolled sheet in order to provide a grip to connect one sheet over another sheet. The grip width was kept half an inch to allow proper grip. Crew 2 completed all 234 sheets. Figure 6.4 shows a snapshot of the lock forming task. This task involves moving rolled sheets from the stack to the lock-forming machine, running each edge to the machine to form grip, and then transferring it to the next stack station that are shown in Table 6.2.

Table 6.2: Descriptions of Each Action Involved in Lock Forming Task

Task	Actions	Descriptions
Lock Forming	Laying Locking Stacking	• Move rolled parts from stacked station to the locker machine • Set lock on each side of sheet metal edges • Hold the locked sheet and move to the stack station

Figure 6.4: Lock Forming Task by Crew 2

6.1.2.3 Lock Setting Task

The lock setting task was the third sequential task involved in the "Fabrication of Sheet Metal Duct" activity. Compared to numbers of actions involved in each tasks of fabrication of sheet metal duct activity, there were significantly more actions associated with this "Lock Setting" task. The detail descriptions are shown in Table 6.3 below.

Table 6.3: Descriptions of Each Action Involved in Lock Setting Task

Task	Actions	Descriptions
Lock Setting	Laying and clamping first sheet	• Move the lock formed sheet metal to lock setting machine and clamp edges
	Bringing second sheet	• Move second sheet from stack to the lock setting station
	Hooking and clamping two sheets	• Assemble both parts together and clamp edges
	Hammering ends for pinning (side 1)	• Grab hammer and punch at both ends in order to facilitate pinning action
	Pinning on ends (side 1)	• Pin with pointed metal on both ends of sheets to hold together
	Hammering along the edges (side 1)	• Grab hammer and punch along the edges so that two sheets grip together
	Air-hammering to set the lock (side 1)	• Grab air-hammer and move along the edges for smooth grip
	Clamping and fixing (side 2)	• After side rotation from side 1 to 2 clamp other side with the rigid frame
	Hammering ends for pinning (side 2)	• Grab hammer and punch at both ends in order to facilitate pinning action
	Pinning on ends (side 2)	• Pin with pointed metal on both ends of sheets to hold together
	Hammering along the edges (side 2)	• Grab hammer and punch along the edges so that two sheets grip together
	Air-hammering to set the lock (side 2)	• Grab air-hammer and move along the edges for smooth grip
	Taking assembled parts out	• Remove assembled parts from the lock station and transfer to flange station

As shown in Table 6.3, the actions involve: laying and clamping first rolled sheet to the rigid frame, moving second sheet to the locking station to hook with the first, hooking and clamping those two sheets together, hammering about one foot length at each ends of side 1 for pinning, pinning the ends at side 1, hammering along the edges manually on side 1, then air-hammering to set the lock properly by using powered air-hammer, and then following the above steps on the side 2.

Once the lock setting was completed in side 1, the next task “Tie Rod Installing” was also performed simultaneously on the side 1 before the duct is rotated to side 2. Thus, as shown in Figure 6.1 earlier, the actions involved in lock setting and tie rod installing tasks were parallel and intermixed. The actions were classified carefully at manageable actions and separated into lock setting and tie rod installing task according to their nature of work.

In this task, worker A of Crew 2 performed “Hammering Along the Edges” and “ air-hammering to set the lock” actions in parallel with worker B, who performed “Drilling” action that was part of “Tie Rod Installing” task. All other actions involved in the lock-setting task were performed by both workers together in sequence. Figure 6.5 shows two crew members of Crew 2 working on lock setting task.

Figure 6.5: Lock Setting Task by Crew 2

6.1.2.4 Tie Rod Installing Task

As mentioned earlier, this task involved actions that were intermixed with the lock-setting task. The actions were separated that were mostly involved in tie rod installation. Crew 2 performed the task. This task involved marking holes for drilling preparation on side 1, drilling holes by powered driller, tie rod installing on side 1, and then following the same steps on side 2 after rotating and laying back to the rigid frame. The detail description of each action is shown below in Table 6. 4.

The important thing to notice here was that when the workers were doing parallel actions, either worker had to wait until the other worker completed his action. Figure 6.6 shows the workers installing the tie rods.

Table 6.4: Descriptions of Each Action Involved in Tie Rod Installing Task

Task	Actions	Descriptions
Roll Bending	Marking holes for drilling (side 1)	• Grab the marker key and place over duct and mark down the location to drill
	Drilling (side 1)	• Grab drill and make holes on duct at the marked location
	Tie rod installation (side 1)	• Insert tie rods and screw them at one ends
	Rotating and laying (side2)	• Take out ducts, rotate from side 1 to side 2 and place to the rigid frame again
	Marking holes for drilling (side 2)	• Grab the marker key and place over duct and mark down the location to drill
	Drilling (side 2)	• Grab drill and make holes on duct at the marked location
	Tie rod installation (side 2)	• Insert tie rods and screw them at other ends

Figure 6.6: Tie Rod Installation Task by Crew 2

Five tie rods were installed in each duct to hold the duct together and make it stable and strong enough to prevent smashing. Each tie rod was screwed from both ends by using a powered screwdriver.

6.1.2.5 Flange Screwing Task

The fifth sequential task was flange fitting and screwing at each end to prevent the duct from bulging and twisting. The flange-screwing task involved fitting flange at one end of the duct, installing it by screws at its perimeter, overturning the duct, and then repeating the same flange screwing at the other end. Finally, the ducts were stacked in preparation for the sealing station. The detailed description of actions steps are mentioned in Table 6. 5.

Table 6.5: Descriptions of Each Action Involved in Flange Screwing Task

Task	**Actions**	**Descriptions**
Flange Screwing	Installing flanges (end 1)	• Grab flange and place over one end of the duct
	Screwing the flanges (end 1)	• Grab screws and insert on the sides of flange using powered tool
	Installing the flanges (end 2)	• Grab flange and place over other end of the duct
	Screwing the flanges (end 2)	• Grab screws and insert on the sides of flange using powered tool
	Stacking flanged duct	• Move the flanged duct to the sealing station

The flange used was already prefabricated and delivered to the workshop from another manufacturing company. Figure 6.7 shows the flange screwing task by Crew 2.

Figure 6.7: Flange Screwing Task by Crew 2

6.1.2.6 Sealing Task

Crew 3 had three crew members and they were involved in the sealing task. The purpose of sealing is to prevent air leakage since it was designed for an exhaust system. All the edges, screw holes, tie rod joints and any other separations or openings were filled with sealer materials. The sealing task consisted of laying the duct on the ground; filling joints and separations with sealer material, and then stacking after completion. The detailed description is shown in Table 6.6, which follows.

Table 6.6: Descriptions of Each Action Involved in the Sealing Task

Task	**Actions**	**Descriptions**
Sealing	Laying duct on ground for sealing	• Move duct and place over the ground to seal the joints and holes
	Filling sealing materials	• Fill sealer with the help of brush to each joints and holes
	Stacking sealed duct	• Move the duct after sealing to the packing station

The three crew members worked independently and in parallel. However, the task was performed in parallel with the packing task that required two crew members to perform. Therefore, if one crew member out of three finished sealing then they stacked the finished duct to one side and, if the stack was more than three ducts, then two workers would stop sealing work and continue the packing task. Figure 6.8 shows a member putting sealer material along the joints of flanges and ducts.

Figure 6.8: Sealing Task by Crew 3

6.1.2.7 Packing Task

The packing task involved plasticking off both edges of the duct, stacking them on a cart, and then palletizing for delivery. The detail description is shown in Table 6.7.

Table 6.7: Descriptions of Each Action Involved in Packing Task

Task	Actions	Descriptions
Packing	Plasticking off the edge 1	• Place adhesive plastic to cover the opening of the duct and flange portion
	Plasticking off the edge 2	• Overturn the duct and repeat plasticking off the other side
	Stacking on cart to deliver	• Move the duct and place over wooden cart for palletizing
	Palletizing	• Bind the stack of ducts with the aid of pallets

The task required two crew members. These members were from the previous Crew 3. For example, if the workers in Crew 3 were named Worker 3, Worker 4, and Worker 5, then the two crew members to handle the task would either be mostly Worker 3 and Worker 4, or Worker 3 and Worker 5. The instances of Worker 4 and Worker 5 were very rare. Therefore, Worker 3 of Crew 3 was mostly involved in the packing task. Figure 6.9 shows Workers 4 and 5 of Crew 2 completing the packing task. Since the task was performed after having more than three sealed ducts, the task is assumed as parallel with the sealing task.

Figure 6.9: Packing Task by Crew 3

6.1.2.8 Delivery Task

The final task was to deliver the packed ducts. The package was of two batch sizes, one with three ducts and the other with six ducts. The batch sizes were determined based on the cart and crew members available. However, about 80% were the three ducts batch size. A truck driver was involved in delivery. Therefore, Crew 4 consisted of only one crew member.

Table 6.8: Descriptions of Each Action Involved in Delivery Task

Task	Actions	Descriptions
Packing	Loading the cart and delivering	• Load the batch of ducts and deliver

Figure 6.10: Deliver Task by Crew 4

6.1.3 Results

As described in research methodology in Chapter 4, system inefficiencies were estimated using the QFM, and operational inefficiencies were estimated using the DES. The following sections illustrate the results for actual productivity, losses due to system inefficiencies, losses due to operational inefficiencies, estimates of the upper limit of optimal productivity, estimates of the lower limit of optimal productivity, and finally the estimate of optimal productivity.

6.1.3.1 Actual Productivity

The field records show that altogether 234 plain metal sheets were used to make 117 ducts for the entire exhaust system. Four crews were involved in the fabrication of sheet metal duct activity. Crew 1 had two members, Crew 2 had two members, Crew 3 had three members, and Crew 4 had one member. Therefore, eight crew members were involved in completing 117 ducts in 97.45 hours (350808 seconds) as shown in Table 6.9.

Table 6.9: Actual Productivity Calculation of Fabrication of Sheet Metal Duct Activity

Tasks	**Crews**	**Total Time**
Roll Bending	Crew 1	16262.00
	Crew 2	9062.00
Lock Forming	Crew 2	18282.00
Lock Setting, Tie Rod Installing, Flange Installing	Crew 2	122862.00
Sealing	Crew 3	134198.00
Packing	Crew 3	47544.00
Delivery	Crew 4	2598.00
Total Duration		350808.00
Total Duration in Minutes		5846.80
Total Number of Ducts (number)		117.00
Production Rate (Minutes/Duct)		49.97
Actual Productivity (Ducts/Crew-hour)		**1.20**
(All units are in seconds unless specified)		

As shown in Table 6.9, Crew 2 was involved in five tasks: roll bending, lock forming, lock setting, tie rod installing, and flange installing. Crew 2 completed 86 out of 234 metal sheets in the roll bending task. The remaining 148 metal sheets were roll bent by Crew 1. Since the same crew performed lock setting, tie rod installing, and flange installing; the duration is measured from start of lock setting to finish of flange installing. Using Ducts/Crew-hour as a unit of labor productivity, the actual productivity measured was 1.20 Ducts/Crew-hour for fabrication of sheet metal duct activity.

6.1.3.2 Qualitative Factor Model

From the questionnaire survey collected from experts regarding the factors affecting labor productivity to the fabrication of sheet metal activity at the workshop, the results are shown in Tables 6.10 and 6.11. The factors affecting labor productivity are organized based on affinity groups discussed in Chapter 2. Out of 14 affinity groupings, eight groups are only mentioned in the table that had a significance score other than zero on the same row. A zero attributed to both severity and probability of occurrence would result in a zero value that does not contribute to the analysis. There were some cases where the expert's score was zero on either the severity category or the probability category that would also make a product of zero. These were still counted on the QFM because that can occur in reality. For example, high wind may have severe impact on fabrication of sheet metal duct but the probability of occurrence at the site may be zero. There were 14 experts: six people in management, six skilled workers, and two researchers. Therefore, the data in Table 6.10 and Table 6.11 is the result of all 14 experts. The sample of individual expert's score is attached in the Appendix B.

The data on the severity score, though average of 14 experts' score, is rounded to the nearest whole number since the scale was from "0" as *no impact* to "5" as *very high impact*.

Table 6.10: Severity and Probability Results (Part 1)

Serial No.	**Factors affecting labor productivity**	**Severity Score (S_i)**	**Probability of Occurrence (P_i)**	**Product (S_iP_i)**
1	**Environmental Factors**			
	High temperature	3	0.48	1.31
	High humidity	3	0.47	1.31
	High wind	2	0.20	0.38
	Heavy rainfall	2	0.23	0.39
	Cold temperature	2	0.32	0.58
2	**Site Condition**			
	High noise level	4	0.74	2.59
	Excess lighting (brightness of light)	2	0.29	0.55
	Insufficient lighting	3	0.35	0.97
	Space congestion	4	0.66	2.69
	Site layout	3	0.39	1.03
3	**Manpower**			
	Fatigue (restless, tired)	3	0.42	1.44
	Poor health condition	3	0.30	0.91
	Family issues	2	0.25	0.55
	Quality of artisanship	3	0.62	1.94
	Lack of experience	4	0.40	1.50
	Absenteeism	4	0.36	1.30
	Misunderstanding among workers	3	0.37	1.21
4	**External Factors**			
	Interference from other trades	3	0.36	1.14
	Availability of skilled worker	3	0.49	1.48
	Increase in the price of materials	3	0.31	0.88
	Implementation of government laws	3	0.23	0.61

Table 6.11: Severity and Probability Results (Part 2)

Serial No.	Factors affecting labor productivity	Severity Score (S_i)	Probability of Occurrence (P_i)	Product (S_iP_i)
5	**Materials**			
	Shortage of materials	4	0.33	1.16
	Poor material quality (e.g. defects, broken)	3	0.30	0.94
	Poor material storage	4	0.34	1.18
	Difficulty in tracking material	3	0.26	0.89
	Safety (possible injury due to sharp edges)	4	0.55	1.93
6	**Tools and Equipment**			
	Maintenance of tools and equipment	4	0.51	2.00
	Lack of tools and equipment	4	0.47	1.91
7	**Technical Factors**			
	Complex design of unusual shapes and heights	3	0.42	1.37
	Incomplete and illegible drawing	4	0.31	1.31
8	**Management Factors**			
	Inadequate supervision	3	0.24	0.70
	Overstaffing	3	0.26	0.68
	Management practices	3	0.29	0.87
	Incompetent supervisors	3	0.22	0.61
	Supervision delays	3	0.21	0.58

The probability score is rounded to two decimal figures because it is represented as a percentage. For example, probability score of 0.48 represents 48%. Similarly, the final product is also rounded to two decimal places. Therefore, the data on “product” column may not give same answer when data on "severity score" is multiplied by data on "probability of occurrence."

During the "Fabrication of Sheet Metal Ducts" activity, the major factors affecting labor productivity were high noise level and space congestion. Since the fabrication was performed inside the workshop, obviously the high noise and space congestion would affect more than expected than other factors. On the other hand, high wind, high humidity, and cold temperature did not have much effect on labor productivity since the work environment was inside the workshop. The management factors had interesting results; though management personnel mentioned very high impact in the questionnaire, the skilled workers did not mention management factors as having very high impact. Although the average scores between the two groups were not statistically significant because of less data, it is something to consider in future analysis. The data on management factors were scored as less than 30% likely to be present at the worksite and, when the factors were present, they had only medium impact on labor productivity.

The data were analyzed according to the equation illustrated in QFM. As shown in the equation, in order to calculate the losses due to system inefficiencies, value of productivity frontier and lower limit of optimal productivity are required. The estimation of the productivity frontier was 2.83 ducts per crew-hour by using the same methodology in Mani et al. (2014) and using the same data set. When substituting all the required parameters in qualitative factor model, the estimate of productivity loss due to system inefficiency (Δ'_{si}) is 0.39 ducts per crew-hour. When this value is subtracted from the productivity frontier, 2.44 ducts per crew-hour is the estimate of the upper limit of optimal productivity (OP_{UL}).

6.1.3.3 Discrete Event Simulation Model

A layout for flow diagram of fabrication system is shown in Figures 6.11 and 6.12. The system modeled consisted of parts arrival station, six working stations, four stacking stations, and a departure station. The roll bending station, lock forming station, lock setting and tie rod installing station had powered machine and tools to perform the tasks, while other stations used manual tools and equipment. Individual parts were processed until the lock forming station, and then two sheets were processed afterwards to form a single duct. Figures 6.13 to 6.18 show the DES developed to resemble the actual workflow of the system. These figures are screenshot of the model generated in Arena by using corresponding Arena dialogue boxes. The actions observed in the field were again categorized into: (1) contributory (direct and indirect work), and (2) non-contributory as was described in Chapter 5.

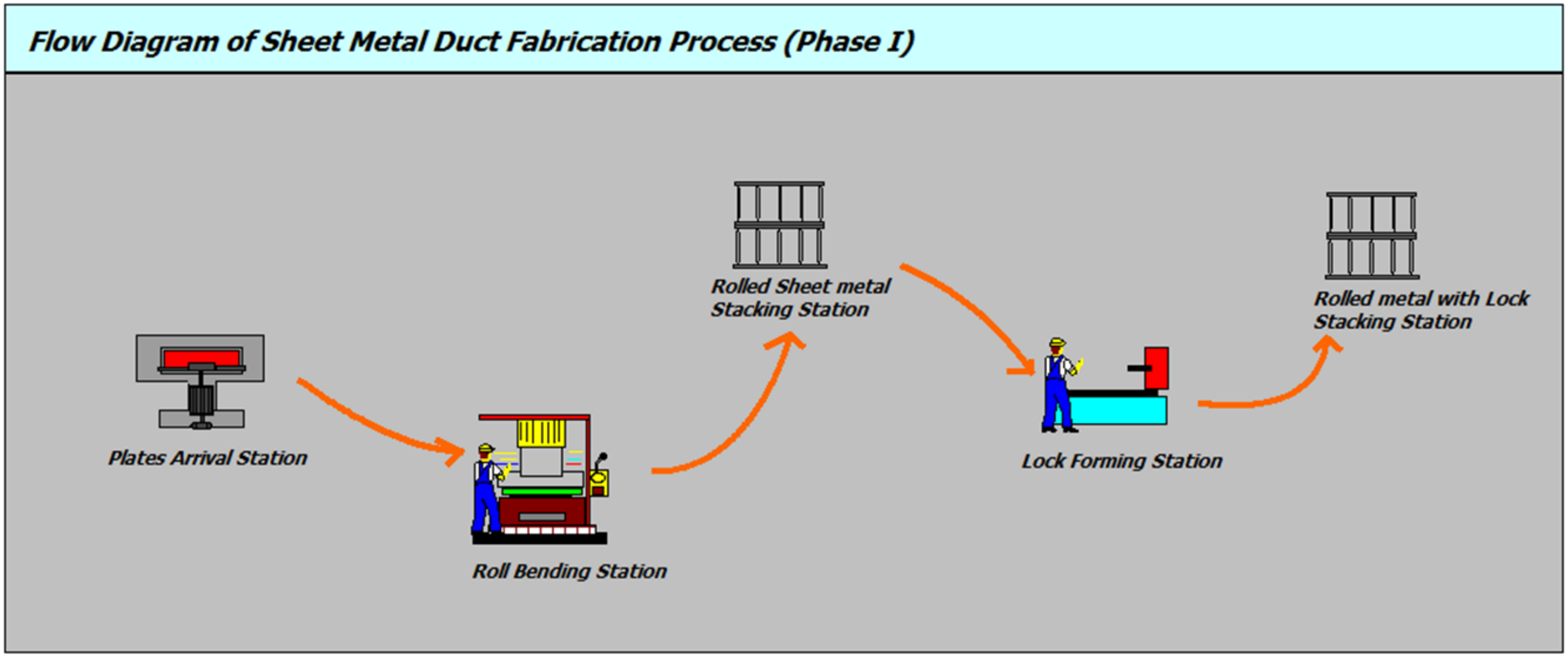


Figure 6.11: Flow Diagram of Tasks in Metal Duct Fabrication Process (Phase I)

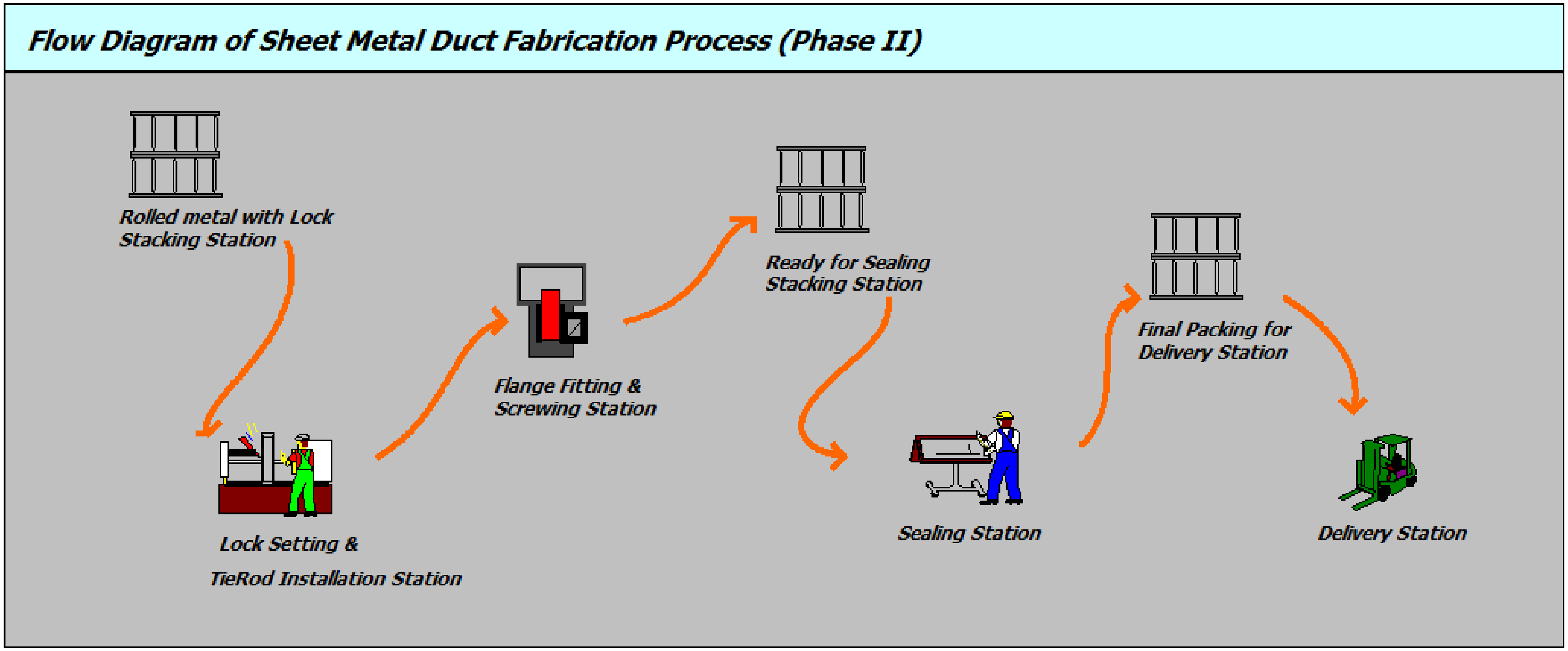


Figure 6.12: Flow Diagram of Tasks in Metal Duct Fabrication Process (Phase II)

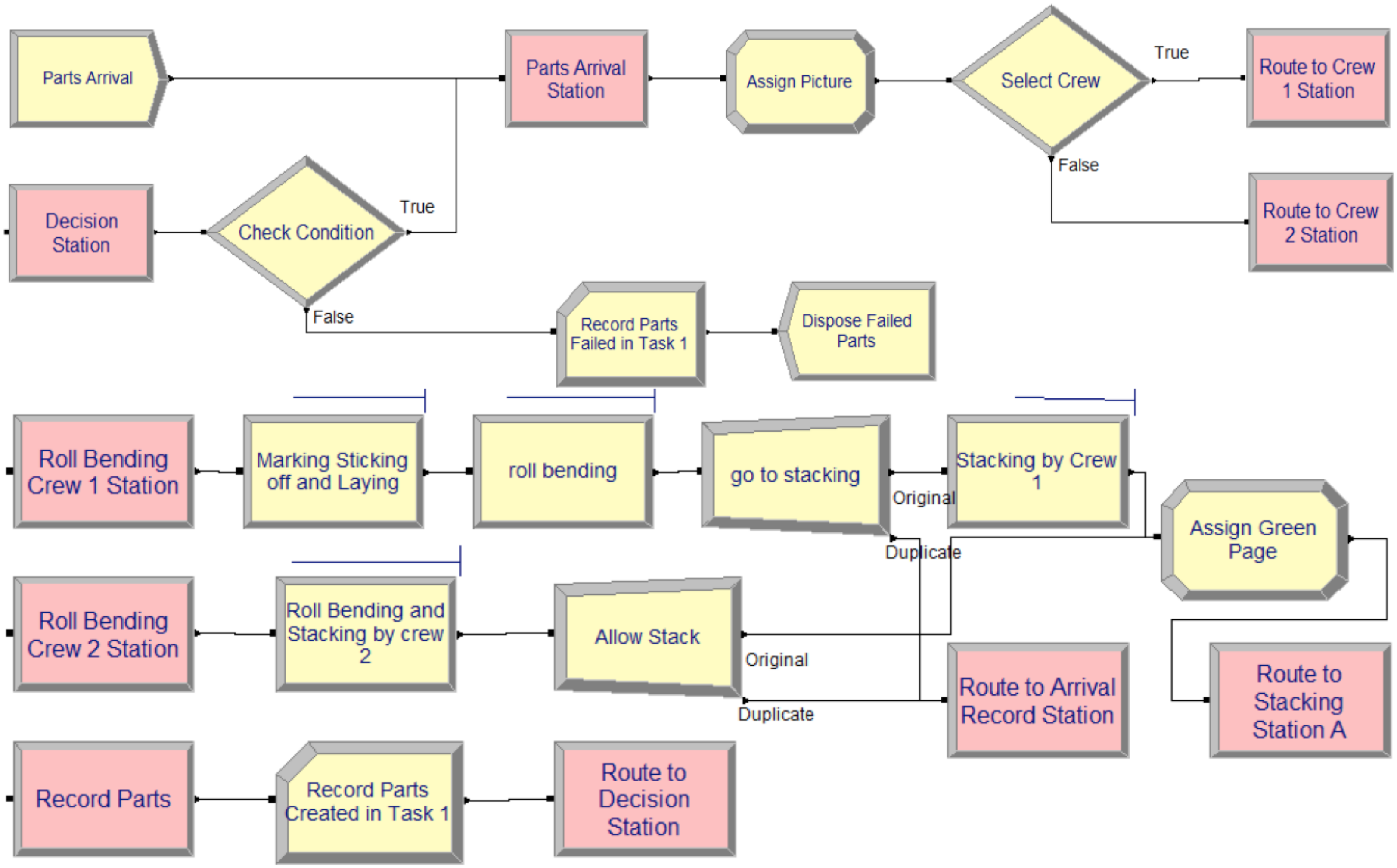


Figure 6.13: Discrete Event Simulation Model of Metal Duct Fabrication Process (Part 1)

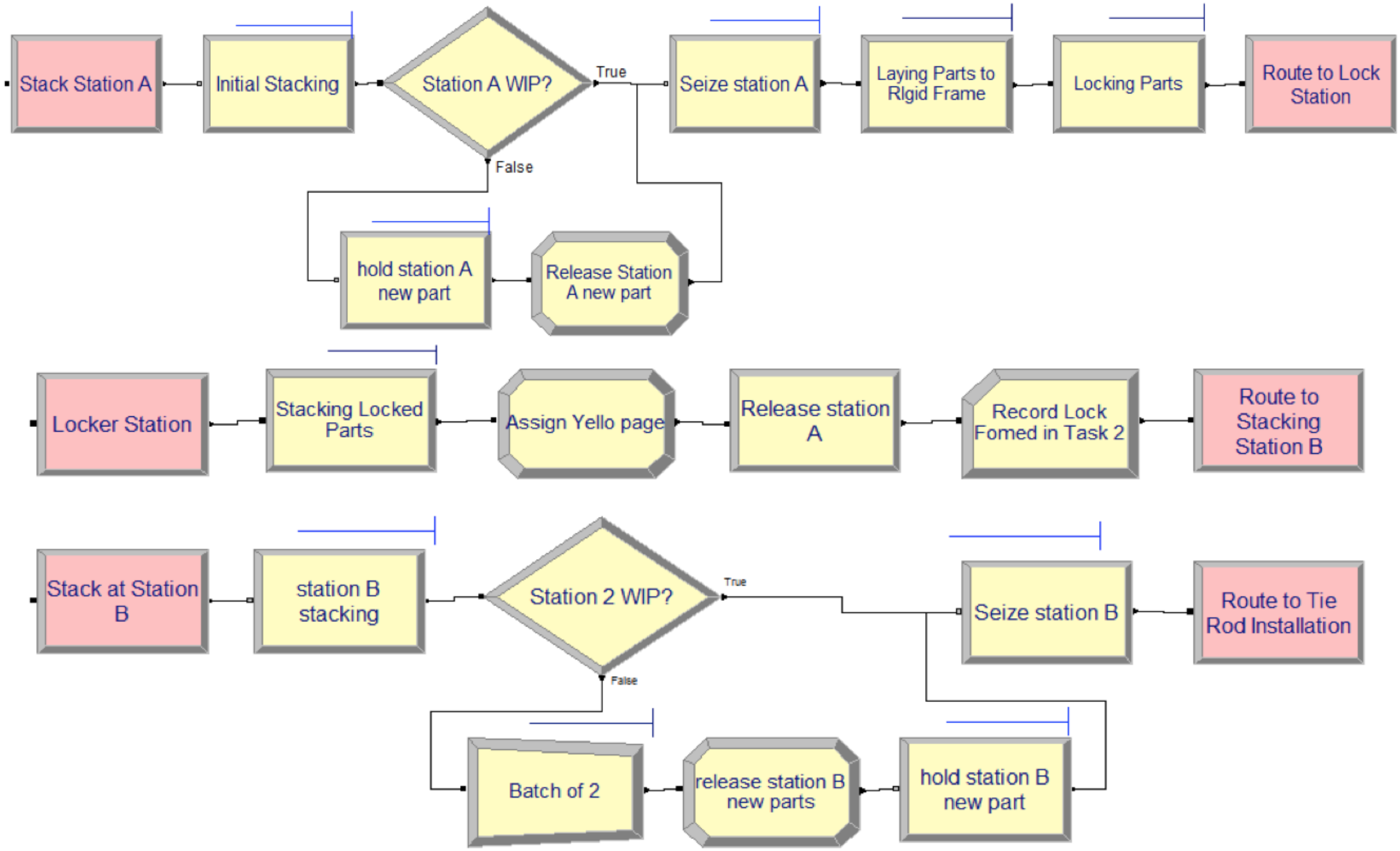


Figure 6.14: DES Model of Metal Duct Fabrication Process (Part 2)

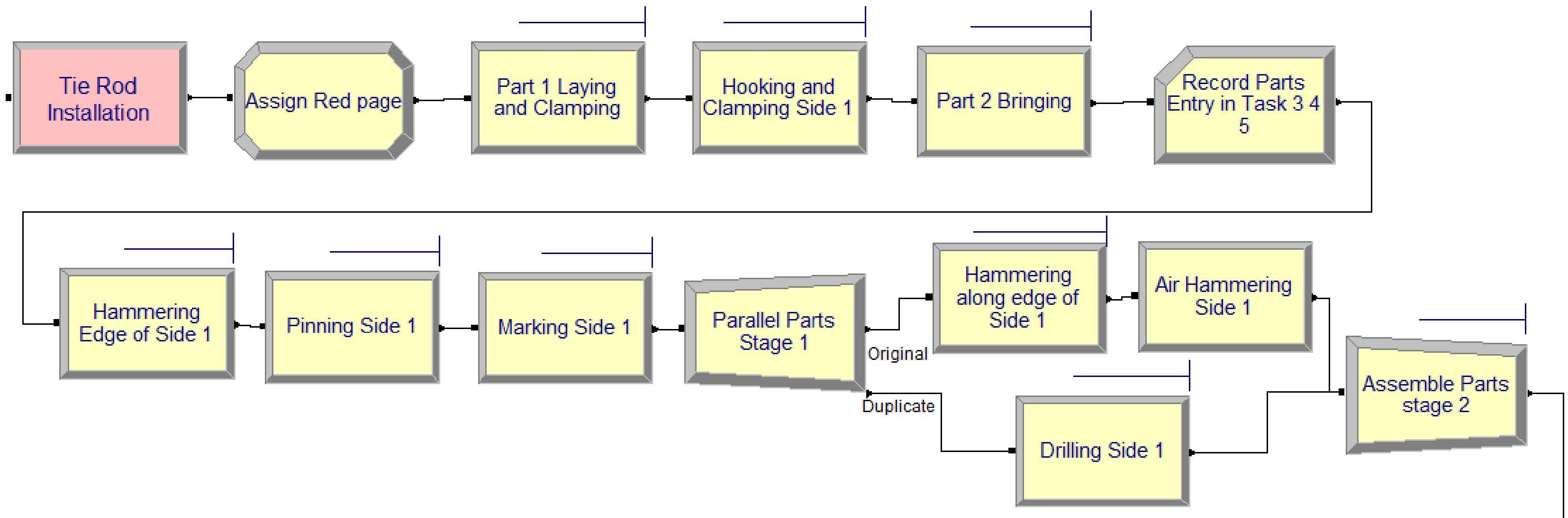


Figure 6.15: DES Model of Metal Duct Fabrication Process (Part 3)

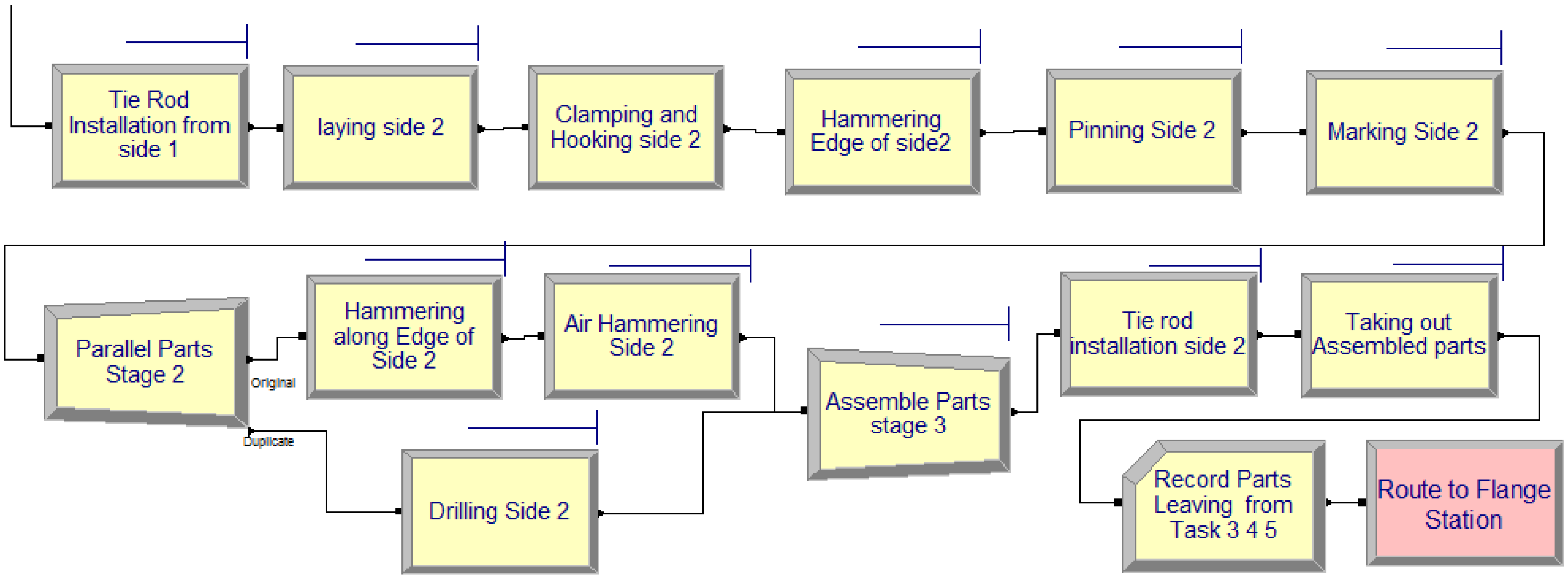


Figure 6.16: DES Model of Metal Duct Fabrication Process (Part 4)

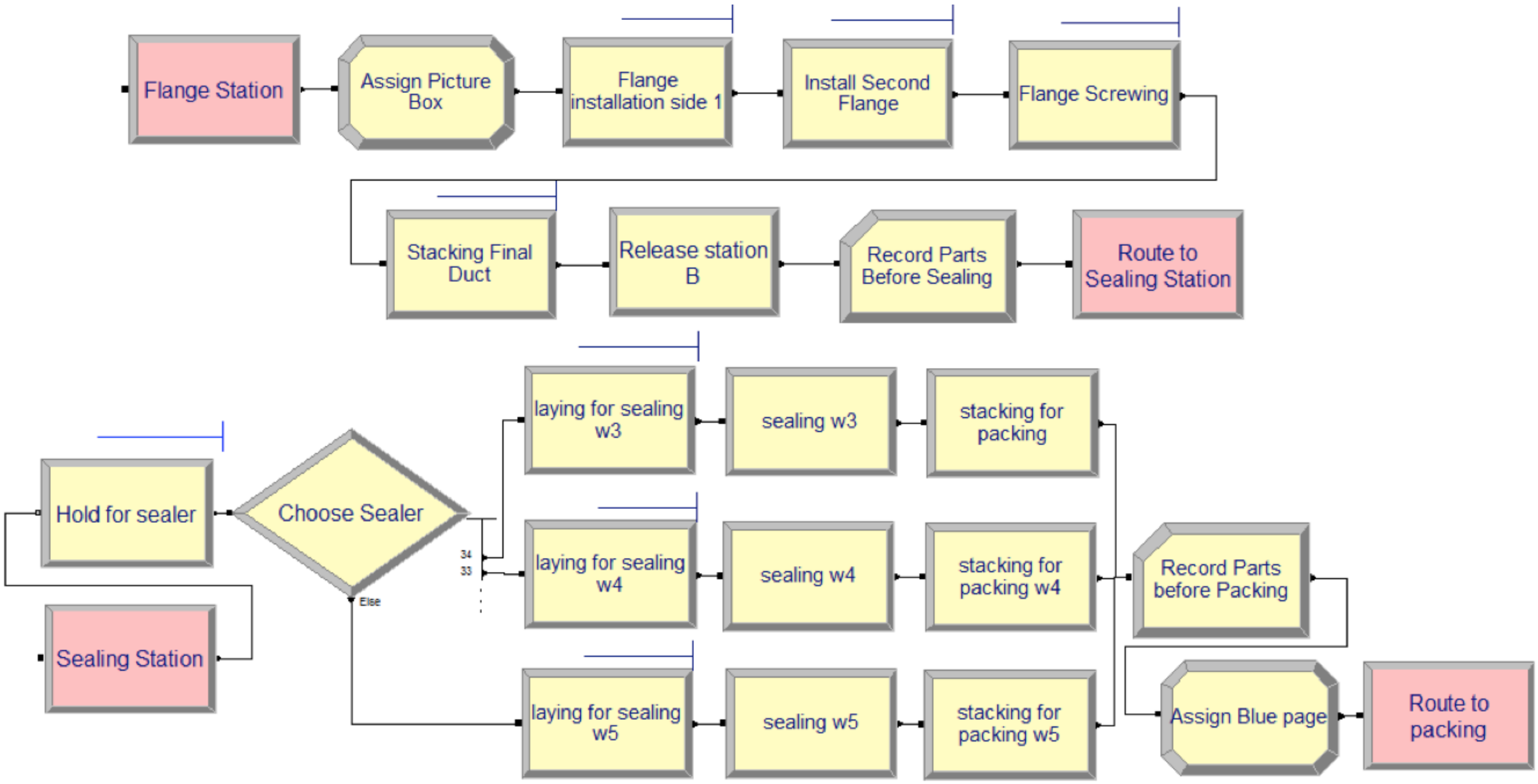


Figure 6.17: DES Model of Metal Duct Fabrication Process (Part 5)

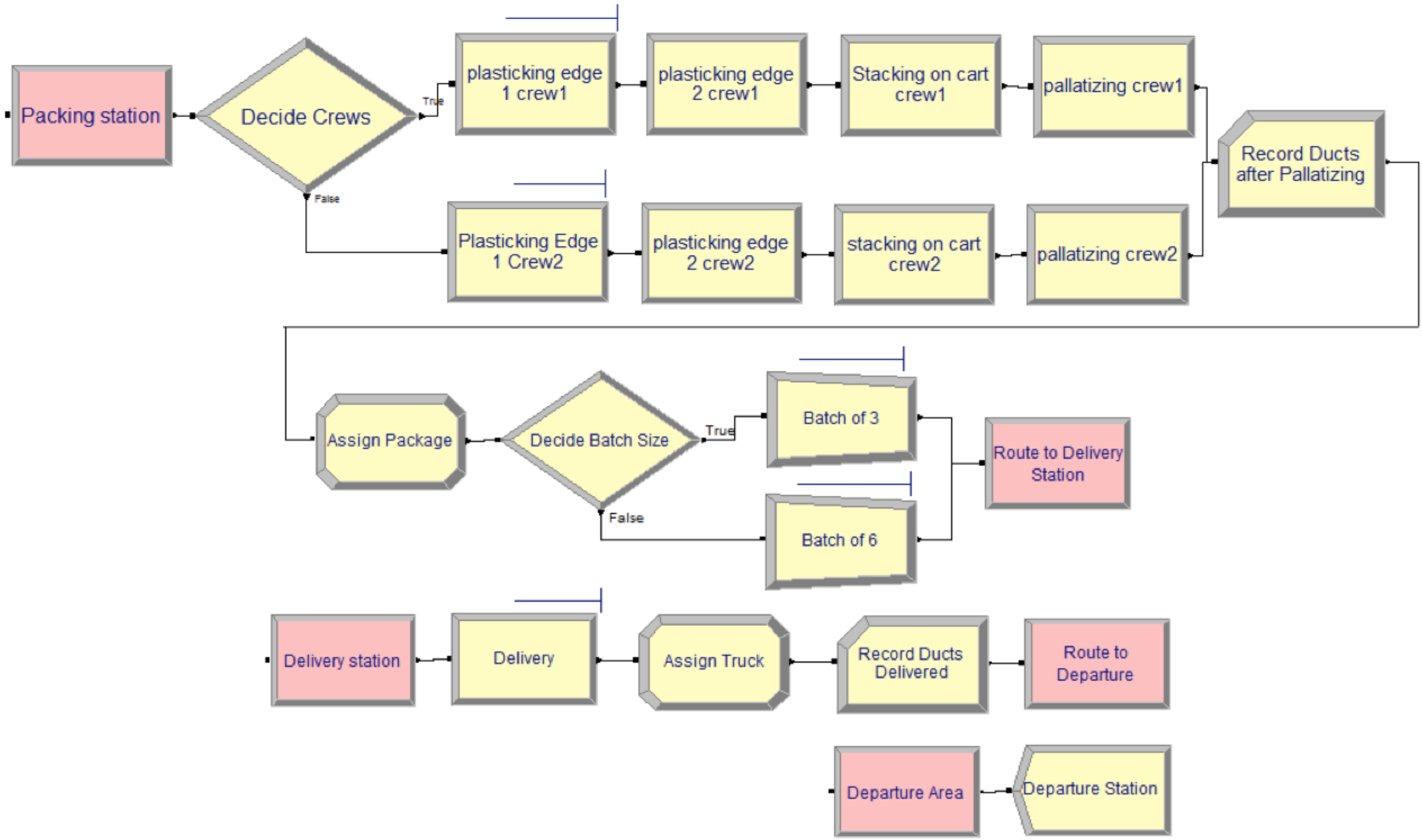


Figure 6.18: DES Model of Metal Duct Fabrication Process (Part 6)

6.1.3.3.1 The Modeling Approach

The simulation model often depends on the availability of data type and the system's complexity. There are many ways to model a system or a portion of system in simulation. Experienced modelers say that there are multiple ways to model a system, but they are invalid if they fail to capture the required system details correctly (Kelton et al., 2010).

The first step to development of a modeling approach was to collect and analyze the data used to specify the input parameters and the distributions. This required the definition of a data structure, the segmentation of the system into submodels, or the development of control logic. A DES model of "Fabrication of Sheet Metal Ducts" activity was developed using Arena simulation from Rockwell Automation (Rockwell Automation, 2013). Arena modules were chosen to capture the operation of the system at an appropriate level of detail.

For the sheet metal fabrication system, the data structure from the collected field data and the assumptions have affected the model design to a limited extent. Different model logics are considered to mimic the original workflow at the field. Route modules are used to control the flow of parts through the system. Decision modules are used to decide the conditions of logic reflecting the real scenario at field. Process modules are used to regulate the duration for each event to process by using appropriate goodness of fit distribution curve. Similarly, other modules are used to better mimic the real workflow and collect the required information for analysis.

6.1.3.3.2 Building a Model

The fabrication of sheet metal duct system was built in Arena by using its basic process panel, advanced process panel, and advanced transfer panel. The complete model is shown in Figures 6.13 to 6.18. The modules used in building the model in Arena were: one Create, 10 Assign, 49 Process, four Hold, two Seize, two Release, eight Record, seven Decide, five Batch, four Separate, 14 Station, 13 Route, and two Departure modules. Each module contains data structure that is based on the logic of the simulation model. Each process module had different distribution parameters that were calculated using an input analyzer tool of Arena. The brief description of the model is described in later sections. Since the process is complex enough to represent real model, some assumptions were made to simplify the simulation model. The assumptions are illustrated below.

Assumptions in model

a. Goodness of fit curve is based on data with no outliers. Special cases are illustrated in section “fitting distribution curves” with examples.
b. Multiple actions are modeled into a single process module when all workers within a crew perform sequential actions. However, if there are parallel actions requiring a single worker for each action then they are modeled with the parallel process module with each worker assigned as resources to the modules.
c. If an operation requires two workers to complete an action then the duration is considered contributory for both workers even if any worker within the crew has to wait for certain duration that cannot be used in any other productive actions.

For example, Crew 1 consists Worker A and Worker B. If there is an instance where Worker A is sufficient to finish action X while Worker B sits idle till the action X is complete because Worker B has no choice to get involved in any other productive actions, then, in such situation both workers are considered contributory actions.

d. If two workers are assigned to accomplish an action, then the action is assigned with two resources in the process module though in a few instances only one worker may be performing the action. However, these cases should be less than 10% of the entire operation. Otherwise, they are modeled differently. The 10% is arbitrarily chosen to reduce the complexity of the entire simulation.

e. The instances of deciding contributory and non-contributory are based on literature and data analyzer. There are some cases where workers move parts due to site conditions, congestion, and worker's comfort. In these complex cases, the contributory duration is based on the average of the entire repetitions of the action.

6.1.3.3.4 Fitting Distribution Curves

The Input Analyzer in Arena was used to fit a probability distribution to the field data. The Input Analyzer provides numerical estimates of the appropriate parameters, or it seeks fitting a number of distributions to the data and selects the most appropriate one. The Input Analyzer is a standard tool that accompanies Arena and is designed specifically to fit a distribution to the observed data, provide estimates of their parameters, and measure how well they fit the data (Kelton et al., 2010).

The curves are chosen based on square error, P-value for Chi-square test and Kolmogorov-Smirnov test. P-value higher than 0.05 is chosen as a good fitted curve. The special cases for choosing best fitted curves for data having outliers are described below with examples.

Special Case 1: Outlier replaced by most likely average value

The following curve is a probability distribution curve fitted for observed data on hammering action of lock setting task. As shown in Figure 6.19, the data has an outlier and the distribution summary result from Arena input analyzer with a corresponding p-value for Chi Square Test less than 0.005. The distribution summary from Input Analyzer is shown in Table 6.12. In such case, the outlier is replaced by most likely value among the data, which is considered as the average value. The curve shown in Figure 6.20 is the best fitted curve after the outlier replacement with an average value so that the total observation is still the same. The corresponding distribution summary of Figure 6.20 is shown in Table 6.13. The Chi Square test in Table 6.13 is 0.326 that is clearly above the significance value of 0.05. Therefore, the new curve fitted as a good fit. This is how the best fitted curve was selected for the observed data that had outlier.

Figure 6.19: Probability Distribution with Outlier

Table 6.12: Distribution Summary with Outlier

Distribution	Weibull
Expression	18+WEIB (13.6, 1.21)
Square Error	0.001653
Chi Square Test	
Number of Intervals	3
Degrees of freedom	6
Test Static	0.601
Corresponding P-value	< 0.005
Number of Data Points	117
Min Data Value	18
Max Data Value	125

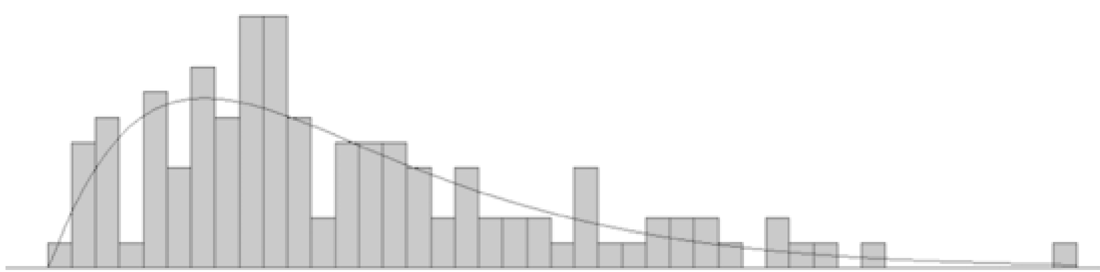


Figure 6.20: Probability Distribution after Outlier Replaced by Likely Average Value

Table 6.13: Distribution Summary after Outlier Replaced by Likely Average Value

Distribution	Gamma
Expression	17.5+GAMM (6.09, 2.07)
Square Error	0.006831
Chi Square Test	
Number of Intervals	9
Degrees of freedom	6
Test Static	7.09
Corresponding P-value	0.326
Number of Data Points	117
Min Data Value	18
Max Data Value	60

Special Case 2: Outlier replaced by most likely average value plus change of curve

The second case for selecting fitted curve for data that had an outlier was also checked according to square error generated by Arena Input Analyzer. The following curve is a probability distribution curve fitted for observed data on air-hammering action of the lock setting task. As shown in Figure 6.21, the data has an outlier. The distribution summary result from Arena input analyzer shows that its corresponding p-value for Chi Square Test is less than 0.005 that is shown in distribution summary in Table 6.14. In such a case, the outlier is replaced by average value. The curve shown in Figure 6.22 is the fitted curve after the outlier was replaced by the average value. The distribution summary shown in Table 6.15 reveals that the Chi Square Test is still less than 0.005, which is not the best fitted curve. Therefore, the new curve is fitted by checking the next curve that was ranked in summary table according to least square error. Figure 6.23 is the fitted curve after replacing the curve by the one that was ranked one step down in the summary table generated according to square error by Arena input analyzer summary report. The summary shown in Table 6.16 clearly shows that the new fitted curve has Chi Square value of 0.093, which is greater than 0.05. This is how best fitted curve was selected for the observed data when the curve did not satisfy the criteria after the outlier was replaced by the average value.

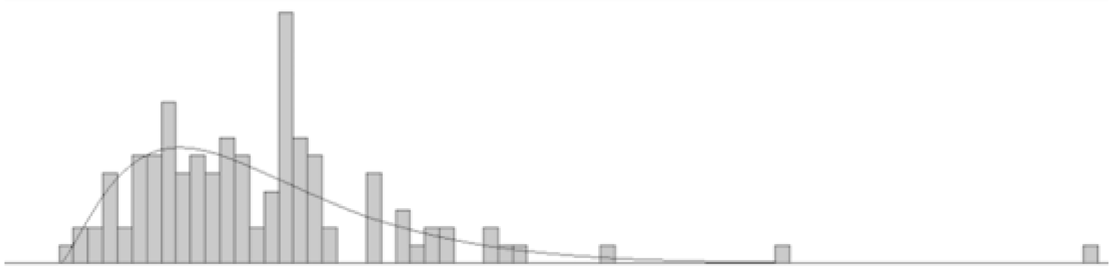


Figure 6.21: Probability Distribution with Outlier and Least Square Error

Table 6.14: Distribution Summary with Outlier and Least Square Error

Distribution	Gamma
Expression	19.5+GAMM (5.69, 2.44)
Square Error	0.01313
Chi Square Test	
Number of Intervals	9
Degrees of freedom	6
Test Static	23.4
Corresponding P-value	< 0.005
Number of Data Points	117
Min Data Value	20
Max Data Value	90

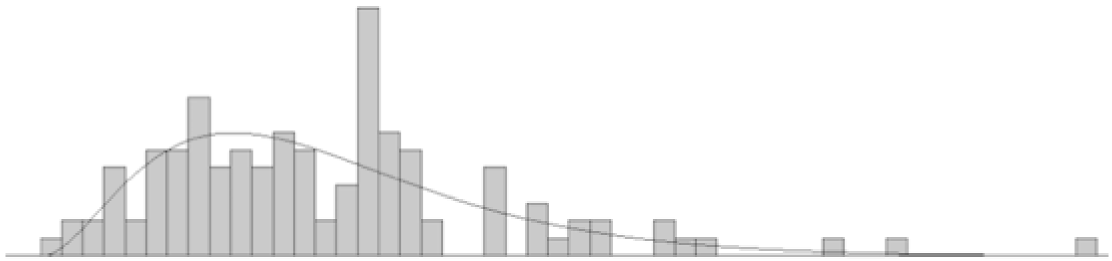


Figure 6.22: Probability Distribution after Outlier Replaced by Likely Average Value

Table 6.15: Distribution Summary after Outlier being Replaced by Likely Average Value

Distribution	Erlang
Expression	19.5+ERLA (4.55, 3)
Square Error	0.012787
Chi Square Test	
Number of Intervals	9
Degrees of freedom	6
Test Static	19.6
Corresponding P-value	< 0.005
Number of Data Points	117
Min Data Value	20
Max Data Value	69

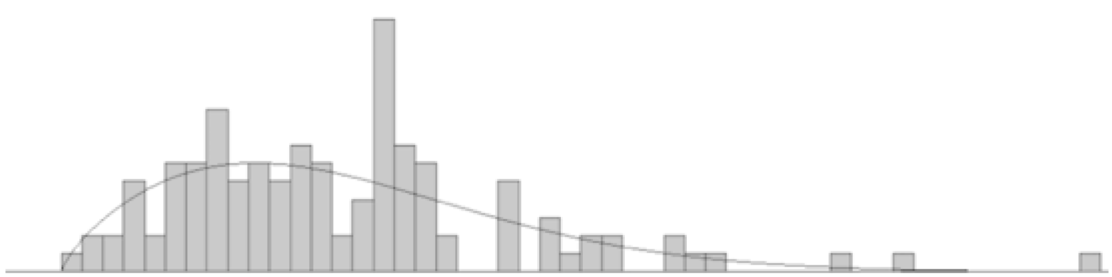


Figure 6.23: Probability Distribution Replaced by Curve with Least Square Error

Table 6.16: Distribution Summery after Replaced by Curve having Least Square Error

Distribution	Weibull
Expression	19.5+WEIB (15.3, 1.72)
Square Error	0.012943
Chi Square Test	
Number of Intervals	10
Degrees of freedom	7
Test Static	12.3
Corresponding P-value	0.093
Number of Data Points	117
Min Data Value	20
Max Data Value	69

The selections of curves for all actions are presented below from Table 6.17 to Table 6.22. As mentioned earlier, the goodness of fit was based on Chi Square Test, Kolmogorov-Smirnov test and least square error. If any distribution fitted to the observed data were not satisfactory then they followed the same logic that was illustrated in special cases to get a reasonable goodness of fit curve.

Four steps were followed to use Input Analyzer to fit a probability distribution to the observed data (Kelton et al., 2010). They were:

a. Create a text file containing the data values,
b. Fit one or more distributions to the data,
c. Select which distribution fits data best, and
d. Copy the expression generated by the Input Analyzer into the appropriate field in the Arena model.

Table 6.17: Distribution Curves for Roll Bending Task

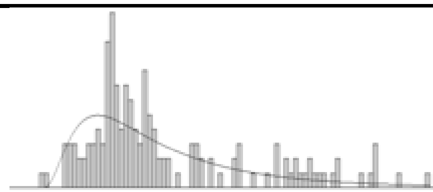
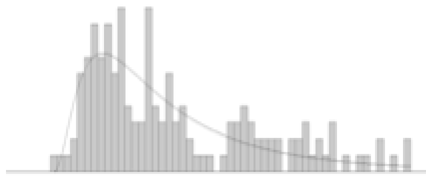
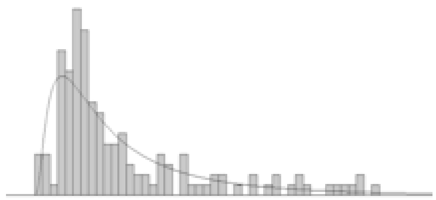
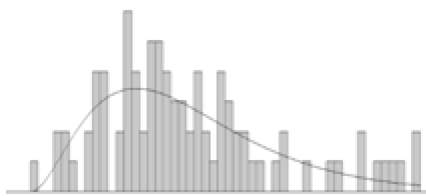
Actions	Distribution Curve	Name and Expression
Marking, Sticking off and Laying (Crew 1)		Lognormal 25.5 + LOGN(67.8, 3.4)
Setting, Roll Bending, and Checking Dimension (Crew 1)		Lognormal 44.5 + LOGN(79.2, 47.5)
Stacking (Crew 1)		Lognormal 37.5 + LOGN(83.1, 25.4)
Laying, Marking, Setting, Bending, Checking, and Stacking (Crew 2)		Erlang 65.5 + ERLA(18.78, 28)

Table 6.18: Distribution Curves for Lock Forming Task

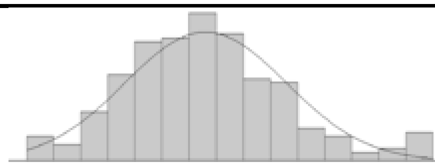
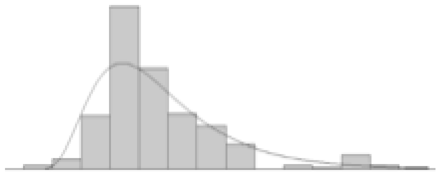
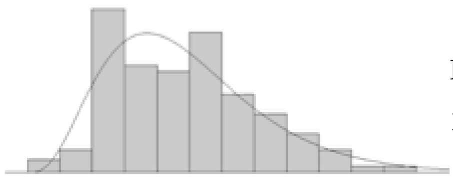
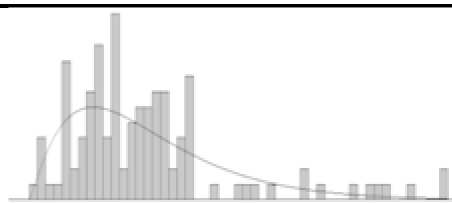
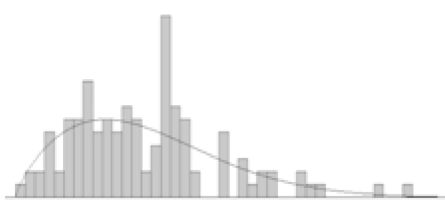
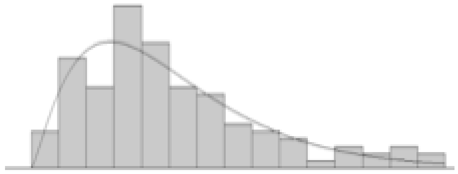
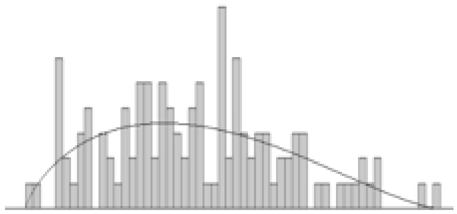
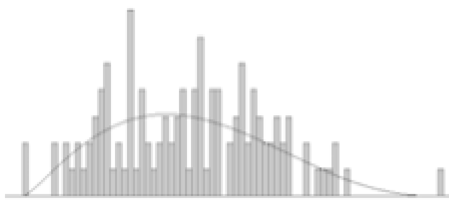
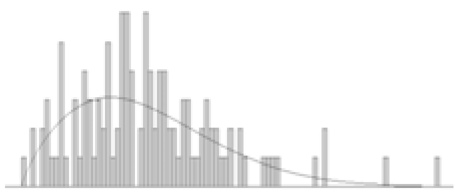
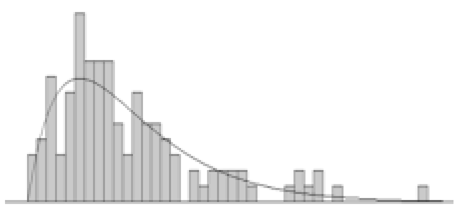
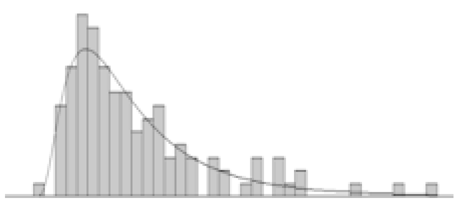
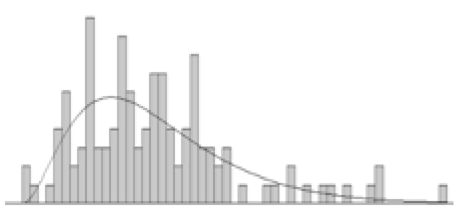
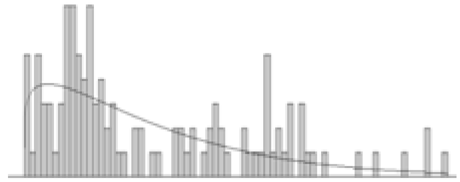
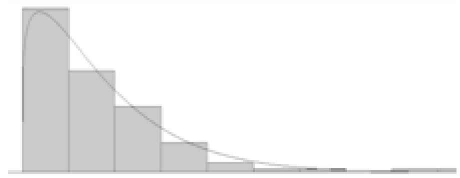
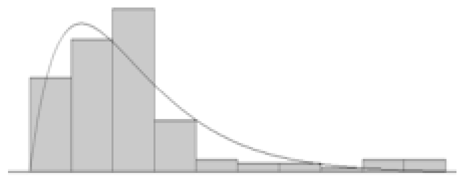
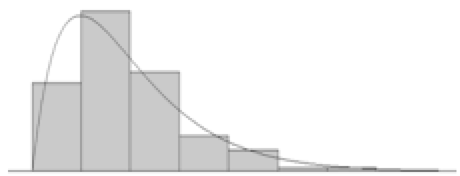
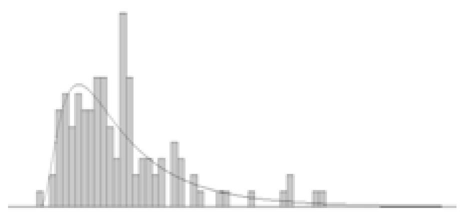
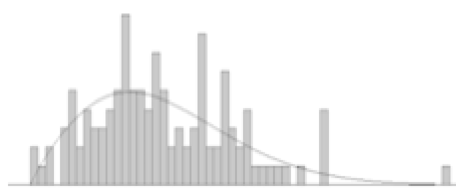
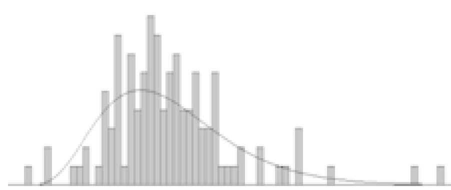
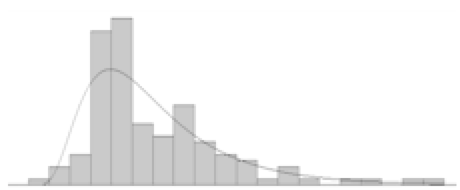
Actions	Distribution Curve	Name and Expression
Laying Parts to Lock Machine		Normal NORM(28, 2.97)
Lock Forming Parts		Lognormal 29.5 + LOGN(9.79 +3.4)
Stacking		Erlang 10.5 + ERLA(6.23, 9)

Table 6.19: Distribution Curves for Lock Setting, Tie Rod Installing and Flange Screwing Tasks

Actions	Distribution Curve	Name and Expression
Air Hammering along Side 1		Gamma 29.5 + GAMM(16.62, 3.17)
Air Hammering along Side 2		Weibull 31.5 + WEIB(27.3, 1.72)

Bringing Part 2		Gamma 11.5 + GAMM(4.24, 2.27)
Clamping and Fixing Side 2		Beta 33.5 + 56*BETA(7.72, 2.45)
Drilling Side 1		Beta 32.5 + 72*BETA(12.31, 5.52)
Drilling Side 2		Weibull 51.5 + WEIB(40.3, 1.77)
Hammering along Edge of Side 1		Erlang 15.5 + ERLA(15.48, 18)
Hammering along Edge of Side 2		Lognormal 11.5 + LOGN(19.59, 7.35)
Hammering End of Side 1		Erlang 16.5 + ERLA(11.54, 10.5)

Hooking and Clamping Side 1		Weibull 25.5 + WEIB(33.5, 7.16)
Installing Flange at End 1		Weibull 33 + WEIB(54.6, 1.18)
Installing Flange at End 2		Erlang 56 + ERLA(57.5, 2)
Laying and Clamping Part 1		Erlang 16 + ERLA(10.8, 5)
Laying Side 2		Lognormal 20.5 + LOGN(34.3, 11.9)
Marking Side 1		Weibull 17.5 + WEIB(29.6, 5.87)
Marking Side 2		Erlang 8.5 + ERLA(4.49, 5)
Pinning Side 1		Lognormal 6.5 + LOGN(19.14, 3.6)

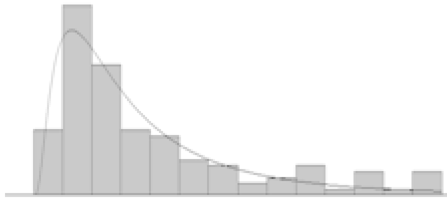
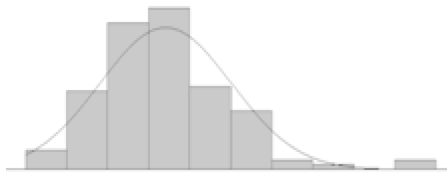
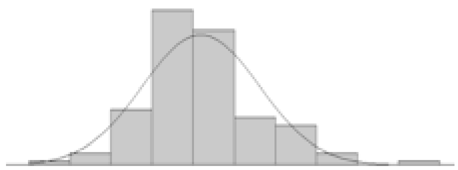
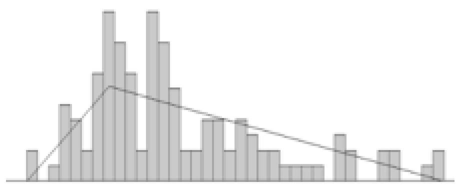
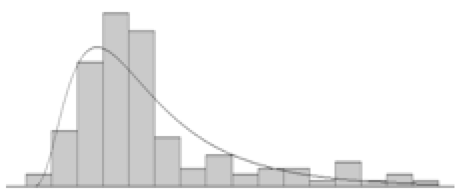
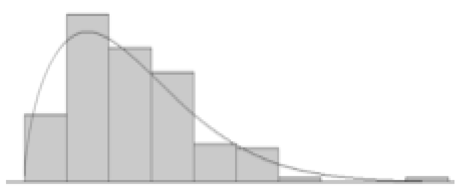
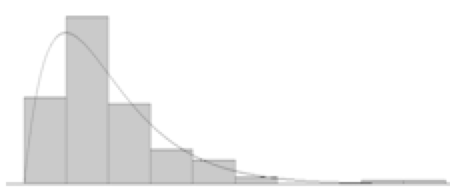
Pinning Side 2		Lognormal 8.5 + LOGN(4.11, 4.4)
Screwing Flange at End 1		Erlang 10.5 + ERLA(6.23, 9)
Screwing Flange at End 2		Lognormal 29.5 + LOGN(9.79 +3.4)
Stacking Duct		Triangular TRIA(130, 148, 178.4)
Taking Out to Flange Station		Lognormal 15.5 + LOGN(4.92, 3.38)
Tie Rod Installing at Side 1		Weibull 151 + WEIB(71.5, 5.58)
Tie Rod Installing at Side 2		Erlang 47 + ERLA(28.8, 10)

Table 6.20: Distribution Curves for Sealing Task

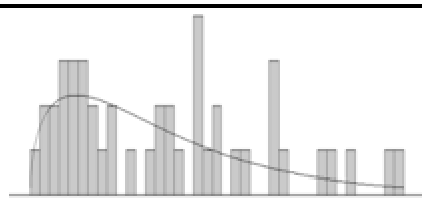
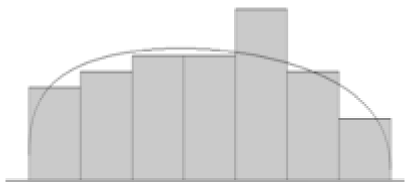
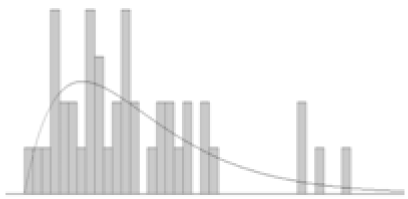
Actions	Distribution Curve	Name and Expression
Laying Duct for Sealing		Weibull 18.5 + WEIB(93.4, 0.96)
Sealing		Beta 546 + 835*BETA(19.26, 1.36)
Stacking		Gamma 6.5 + GAMM(25.3, 4.5)

Table 6.21: Distribution Curves for Packing Task

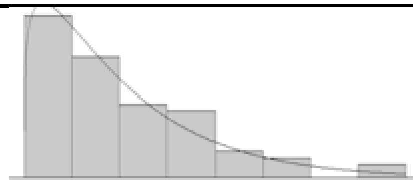
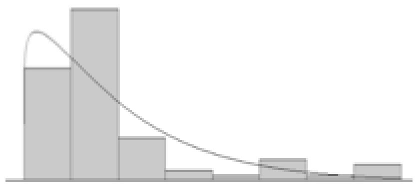
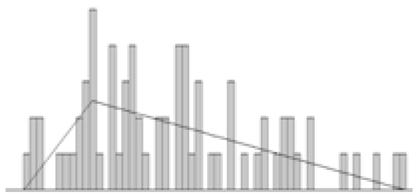
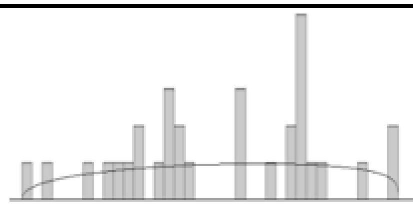
Actions	Distribution Curve	Name and Expression
Plasticking Edge 1		Beta 27 + 170*BETA(11.91, 0.72)
Plasticking Edge 2		Weibull 41 + WEIB(76.9, 1.11)
Stacking		Triangular TRIA(23.5, 53.9, 81.5)

Table 6.22: Distribution Curves for Packing Task

Actions	Distribution Curve	Name and Expression
Delivery		Beta 13.5 + 37*BETA(1.4, 1.24)

6.1.3.3.4 Pieces of the Simulation Model

Since the model is based on actual workflow at the field, the simulation is built upon terminating conditions. The simulation model is developed in such a way that it terminates creating new parts to flow inside the model once the production reaches the limit. In the field, only 234 sheet metal parts were processed to create 117 ducts. Two sheet metal parts were required for fabricating one duct. Therefore, conditional modules were modeled to verify if the conditional statements were being met or not. Figure 6.24 shows a sample of the Decide module used in Arena simulation to check condition.

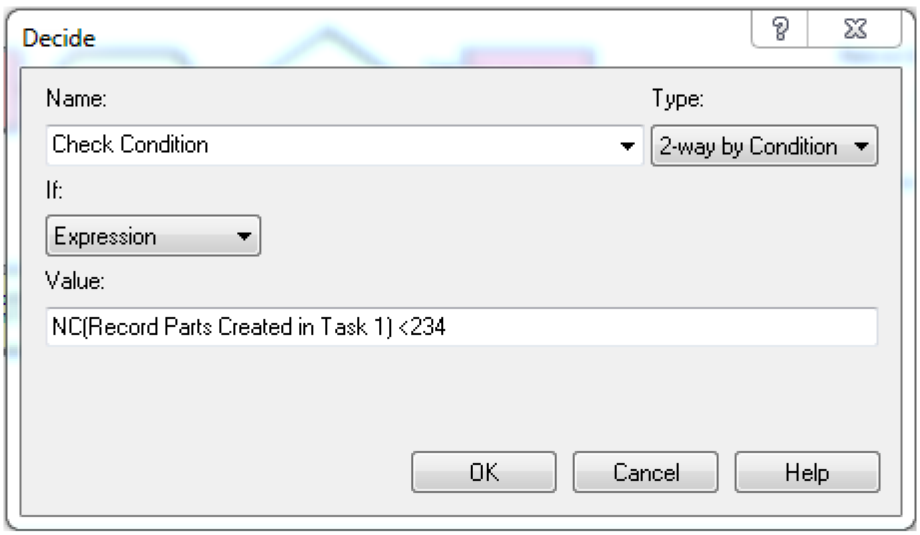


Figure 6.24: Decide Module Used for Controlling Parts' Creation

For illustration, the first task "Roll Bending" is described here in detail. Parts arrive at the arrival station as shown in Figure 6.13. Two crew members grab the metal sheet from the arrival station, move it near the roller machine and laying over the table in front of the roller machine. One of the two crew members marks the where the sheet is to be precisely bent. Then they both feed the sheet into the roller machine and turn on the machine to start roll-bending process. Once it reaches the mark, the rolling process is reversed and it is rolled back out of the machine. Next, they check the dimensions of the curve and verify its shape. Finally, they take that rolled sheet and move it to a stack station. Then they get a new sheet and repeat the process. Crew 1 followed the process exactly while Crew 1 followed a slightly different process. Instead of working sequential actions together, Crew 1 performed some actions in parallel. For example, while one crew member stacked a roll of sheet metal, the other crew member headed toward the parts arrival station and marked the sheet metal for the roll bending position. Next, they stick off the sheet and placed over the table in front of the roller machine. Then both crew members start roll bending actions by turning on the roller machine, reversing the roller motion, turning off the roller once it is done, and then checking the shape of the curve. Since two crews were involved in the roll bending task and the process of doing the task was different, the model was modified accordingly.

The creation of the part at the “Part Arrival” happens one time. The remaining parts are then created by duplication when needed. This is shown in Figure 6.13. This was so there was no queue built up at the arrival station that would have caused if the arrival process had any distribution curves. Instead, all 234 sheet metal parts were already at the workstation and the crew had access to the parts whenever needed. So, in order to distinguish between original and duplicate parts, each part leaving the “Parts Arrival Station” module is assigned a unique picture. Then it proceeds with “Select Crew” module, which decides whether the parts go to Crew 1 or Crew 2. Since, 148 parts were handled by Crew 1 and rest by Crew 2, the two-way conditional expression was entered in the “Select Crew” decide module by allowing only 148 parts to be processed by Crew 1 and the other 86 parts by the Crew 2. An example of this conditional module is shown in Figure 6.25. However, for the significance value for Arena simulation, these numbers were multiplied by ten and run for significance test analysis.

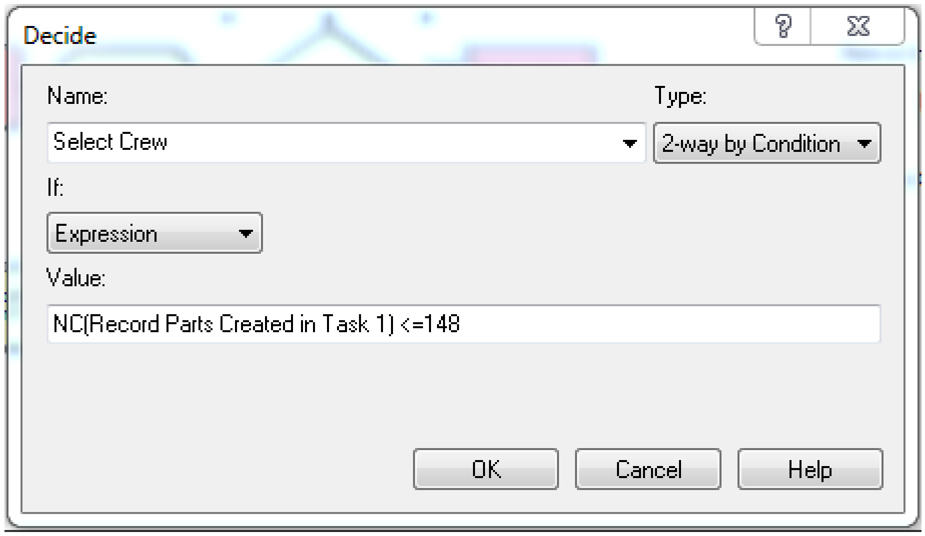


Figure 6.25: An Example of Decision Module for Selecting Crew

After crew selection, the parts are routed to the designated crew. If it is Crew 1 then the parts goes through "Marking, Sticking off, and Laying" process module where one crew member is assigned as a resource, action logic is assigned as "Seize Delay Release" and the delay type is recorded by an expression generated as shown in Table 6.17. Once a part enters the process module, it seizes resources, delays for certain duration according to the distribution curve, and then releases resource once completed. This is the "Seize Delay Release" module. In this case, Crew member 1 of Crew 1 was involved in marking, sticking off, and laying processes. Then both Crew member 1 and Crew member 2 of Crew 1 get involved in the roll bending process. After that, Crew member 1 goes for the marking, sticking, and laying process while Crew member 2 goes for the stacking process. Therefore, the actions performed by both crew members are parallel except for the roll bending process. Figure 6.26 shows and an example of assigning Crew member 1as a resource to complete marking, sticking off, and laying processes.

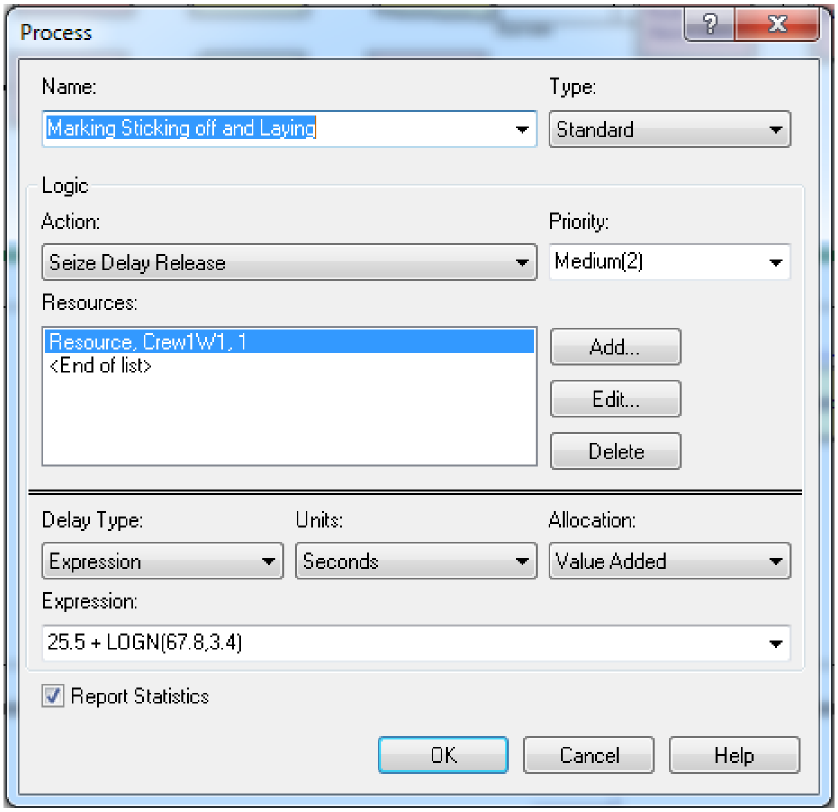


Figure 6.26: A Process Module in Arena with Single Resource

Figure 6.27 shows and example of assigning Crew member 1 and Crew member 2 as resources to complete a roll bending actions in Arena simulation.

In order to mimic this parallel process, original and duplicate parts were created by using separate modules from the advance process panel in Arena as shown in Figure 6.11a. The separate module “Go to Stacking” sends original parts for stacking while duplicate part was routed to the record station to keep track of how many parts were created. The record module “Record Parts Created in Task 1” shown in Figure 6.11a does the record-keeping task. The part is again routed to a decision station where it goes to the “Check Condition” module to check if the created part exceeds 234.

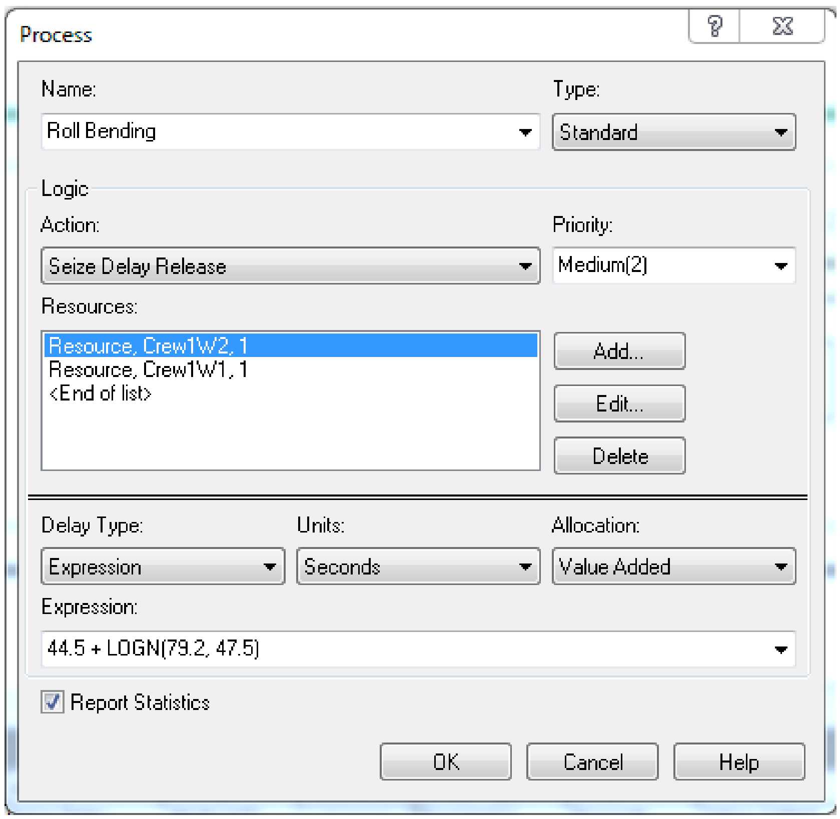


Figure 6.27: A Process Module in Arena with Double Resource

If it does, then the decide module will stop sending parts and the creating new parts process terminates. However, the parts already in the system will continue through the simulation process. This is how duplicate parts acts as new parts for simulation in a terminating condition. On the other hand, the original part is assigned a unique picture to identify it later in subsequent process modules. Once assigned a picture, in this case a green page, it is routed to stack at "Stacking Station A." The process followed for Crew 2 is similar to that shown in Figure 6.13 with the only difference being that Crew 2 performs all processes together; therefore, the distribution is represented by a single curve.

6.1.3.3.5 Animation

Animation is a part of the verification and validation process. Figure 6.28 shows an animation model for sheet metal fabrication activity. Different pictures were assigned to an entity flowing from parts arrival station to delivery station in order to keep track of an entity flowing inside the animation. The animation model was developed inside the Arena window by using draw tools.

The animation was run in various conditions as described in the "verification and validation" section. Two-hundred thirty-four parts were used to fabricate 117 ducts. However, for the significance test, the parts were increased tenfold so that 2340 parts were simulated to fabricate 1170 ducts. The reason was to minimize the variation in data, decrease the standard deviation, and increase the confidence interval so that the outputs are reliable enough to interpret at the significance value. The replication number was 100, which was enough for the significance test. The number can be calculated if needed as described in Arena (Kelton et al., 2010).

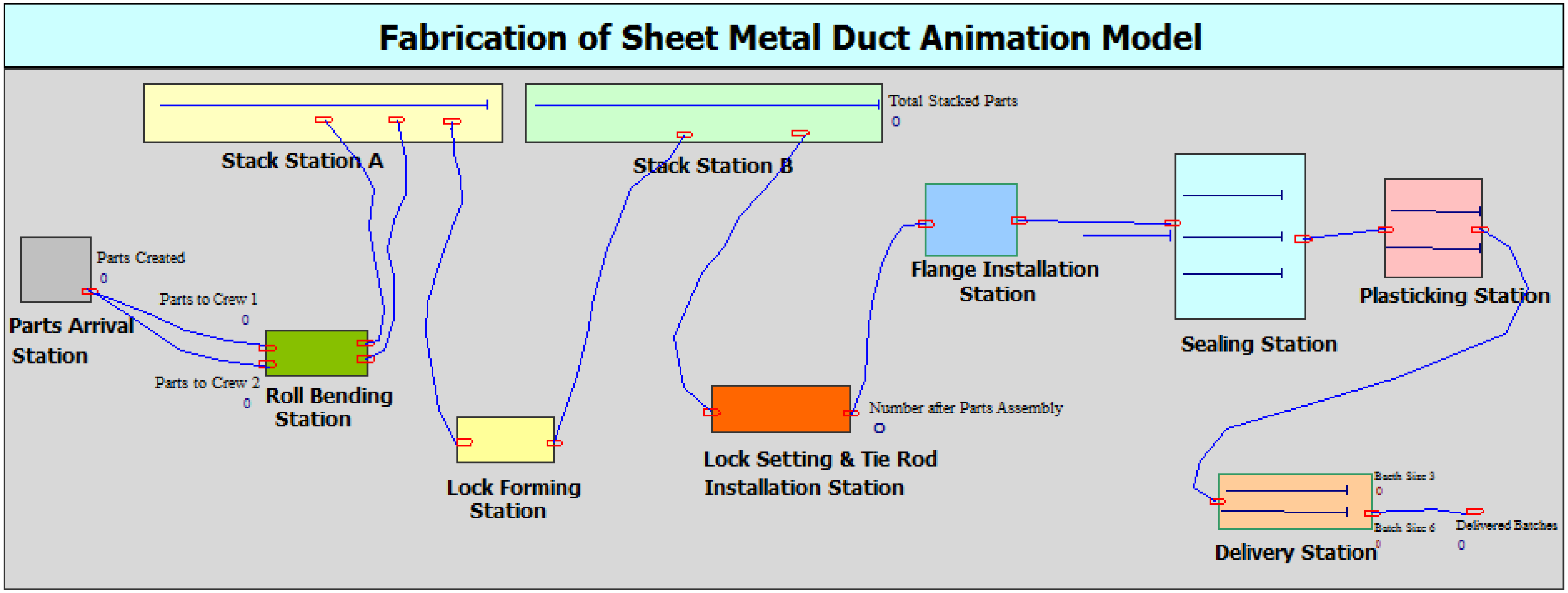


Figure 6.28: Animation Model for Fabrication of Sheet Metal Duct Activity

6.1.3.3.6 Verification and Validation

Verification is the process of ensuring that the Arena model behaves in the way it was intended according to modeling assumptions. It is easy when the model is straightforward and the size of simulation is small containing few logic and process modules. For example, the simulation developed in pilot study was a simple model. Developing more realistically sized models is very challenging, and ensuring 100% accuracy is a much more difficult process. Arena produces an error message if any variable is undefined, if there is a duplicate name, if a logic connector has been isolated, or if parts have been created but not disposed. These features of Arena helped in debugging the model. Once the model gets a no error message it is run to see that parts are created as intended, they move through the system as intended and the logic is performing accurately. The following points were used in model verification of duct fabrication system.

a. First, a single entity was allowed to enter the system and tested to make sure that it followed the model logic and the data were accurate.
b. Since at least two sheets were required to construct a duct, four entities were allowed at second trial to ensure the output was two ducts.
c. The same crew members were intentionally assigned parallel actions to check that the model throws an error.
d. Logic was tested to see if it generates appropriate output by modifying the resources assigned to complete the actions. For example, the lock-forming task needs two crew members. It was tested to see if the duration took longer when only one crew member was assigned.

e. Decide modules were carefully checked by allowing too many parts to enter. For example, 234 metal parts were allowed to process through the roll-bending task as in the real case. The condition was checked against this limit. If it does then model is not verified.

f. The fabrication system model consisted of parallel tasks and some actions within a task were parallel. The entities were checked if they flow in parallel as intended.

g. The model was also checked by replacing different probability distributions by constant values to see if the system behavior was accurate.

h. Animation was performed to see if the flow of entities matched with the real workflow from the field.

i. The outputs were also checked if all the units entered in the system were consistent as specified.

j. Finally, the model was checked to see how it behaves under extreme conditions. For example, introducing only one resource throughout the system, allowing zero parts to begin with and allowing more parts than needed in the truncated system.

Validation is the process of ensuring that the model behaves the same as the real system (Kelton et al., 2010). The model was verified by checking all the conditions previously mentioned. Animation was developed to see if the model behaved the same as the workflow in the field. Animation helped to visualize how the system actually worked and matched the real system. The animation was observed for bottlenecks in the model that did not occur in the real system.

Resource utilization was also checked to ensure they were within the confidence limit of the actual resource utilization. This was done by cross checking the arena report on resource utilization against the spreadsheet data and analyzed by tracking the utilization of individual crew members.

The most important validation was a comparison of the simulation results with the actual data. The deviation was less than 2%, which was within the 95% confidence interval. Since the data were insufficient to provide half width for each output, the data were multiplied by 10 times and the replication were made 100 times so that there is no risk of warm up period and insignificant result. This way the model result was cross-validated to see if all the individual outputs were within the 95% confidence interval limit.

6.1.3.3.7 Analysis

The field data were compared to the simulation results from the actual scenario. For the significance value, instead of 234 data points in the field, simulation data were made 2340 (i.e. 10 times the original data). Table 6.23 shows the analysis of discrete-event simulation outputs. The simulation results from the actual scenario show a completion rate of 1.23 ducts per crew-hour. These results represent less than 3% deviation from recorded field values. The simulation results for the synthetic scenario show a completion rate of 1.7 ducts per crew-hour. This is a 38% improvement over the results from the actual scenario. This implies that the loss due to operational inefficiency (Δ'_{oi}) is 0.5 ducts per crew-hour.

Table 6.23: Discrete Event Simulation Outputs

Description	Number of Ducts	Total Time (Sec)	Time per Duct (Min)	Productivity (Ducts/Crew-hour)	Difference from Actual Productivity
Actual Productivity	117	350808.00	49.97	1.20	2.50%
Actual Scenario	1170	3429971.2	48.86	1.23	
Synthetic Scenario	1170	2470937.7	35.20	1.70	38.21%

The mean values from the actual and the synthetic models were compared to determine if they were statistically different. Using Arena's Output Analyzer and a 95% confidence interval, a paired-T means comparison test of the null hypothesis that both means were equal concluded that the means were different.

The productivity from this synthetic scenario is taken as an estimate of the lower limit of optimal productivity (OP_{LL}) rather than as the optimal productivity itself because even when non-contributory actions are excluded, a simulation model that relies on field data cannot eliminate all operational inefficiencies embedded in a construction operation.

6.1.4 Estimation of Optimal Labor Productivity

The average of the upper and lower limits of optimal productivity results in an optimal productivity (OP) of 2.07 ducts per crew-hour. Compared to actual average productivity, which is 1.20 ducts per crew-hour, the estimate of optimal productivity may seem high. However, recorded field data shows that for a few instances during the activity, crews completed with a productivity of 2.10 ducts per crew-hour. This duration demonstrates that the estimate of 2.07 ducts per crew-hour is challenging, but not necessarily out of reach. Table 6.24 shows the summary of optimal labor productivity calculation. In summary, during the advanced study, the “fabrication of sheet metal ducts” activity achieved 58% efficiency (actual recorded productivity as a percentage of estimated optimal productivity). The efficiency seems very low because of heavily congested workplace, frequent management interruption, frequent chatting with co-workers, parallel works being slowed down because of dependence on others.

Table 6.24: Estimation of Optimal Productivity in Fabrication of Sheet Metal Duct Activity

Description	**Number of Ducts**	**Total Time (Sec)**	**Time per Duct (Min)**	**Productivity (Ducts/Crew-hour)**
Actual Productivity	117	350808.00	49.97	1.20
Productivity Frontier	117	148941.00	21.22	2.83
Lower Limit of Optimal Productivity	117	247093.77	35.20	1.70
System Inefficiencies			3.36	0.39
Operational Inefficiencies			14.77	0.50
Upper Limit of Optimal Productivity			24.57	2.44
Estimate of Optimal Productivity			**29.89**	**2.07**

6.1.5 The Advanced Study Conclusions

The Qualitative Factor Model was found to be effective in modeling system inefficiencies in a complex activity. The discrete event simulation was also found to be effective at modeling operational inefficiencies. Therefore, this advanced study demonstrated that the proposed two-prong strategy for estimating optimal labor productivity is adequate when applied to an activity with multiple workers and sequential and parallel tasks.

6.1.6 The Advanced Study Limitations and Recommendations

The conclusion drawn from this advanced study is based on the observation and analysis of multiple workers performing activities in a semi-controlled working environment inside a manufacturing workshop. The impacts of factors that affect labor productivity in this advanced study were determined from experts within the workshop. The severity score and probability score required for determining system inefficiencies were solely dependent on experts' judgment and their experiences. On the other hand, DES was used solely to estimate operational inefficiencies. The other limitations on this advanced study are as follows:

a. In some cases, detailed movements of workers were difficult to discuss especially when the visibility from the camera was obstructed by stacks of ducts around workers.
b. Only three cameras were used in the field. Therefore, when three or more workers were performing parallel tasks and their workspace is congested then one's details may be captured very well in one camera while another's movement was less detailed.
c. The cameras were set up closely to the workspace where workers perform their tasks. This had caused some discomfort to the workers who otherwise could have moved freely on their own way.
d. The data points were not the same repetitions because of parallel actions performed by workers: some workers complete fast while other take longer.

The following points are recommended for future studies based on findings from advanced study.

a. Multiple cameras should be placed to capture each individual's actions. Surveillance cameras could be better when things have to be captured from some heights that may not be possible from a regular camera tripod.
b. For parallel actions, cameras may be placed in a location that can capture wide range of actions.
c. Avoid placing the cameras in close vicinity of workers' movement zone as much as possible.
d. Explore alternative ways to capture the actions and movements of each worker efficiently and effectively within the appropriate budget.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the results from the pilot study and the advanced study illustrated in the previous chapters. The pilot study concluded that the research method is feasible and justifiable in a simple electrical installation with a single worker in a controlled working environment. The advanced study concluded that the research method is applicable in a complex labor-intensive operation with multiple workers performing sequential and parallel tasks and actions. The advanced study suggested that the two-prong strategy methodology could be expanded to not only construction industry, but also in manufacturing operations.

7.1 Findings and Contributions

The major findings with respect to the research hypotheses stated in Chapter 1 are discussed in three major aspects as follows:

a. Applicability

The two-prong strategy research method is applicable to any labor-intensive construction operations with crews of multiple workers performing sequential and parallel processes. The pilot study proved that it is applicable in a simple electrical replacement activity. The advanced study showed that it is applicable in a fabrication of sheet metal duct activity. Both activities were of different trades but involved labor-intensive operations. These results show that the research methodology is applicable to both single worker crews and multiple workers crews with both serial and parallel processes.

b. Scalability

The two-prong strategy research method is scalable. For example, the research method was still feasible when the level of study was increased from task level in the pilot study to the activity level in the advanced study. When comparing the pilot study to the advanced study, the analysis increased from studying one task to eight tasks, one worker to eight workers, eight actions to 43 actions, and 62 data points to 5031 data points at action level. The research method was also found scalability regarding degree of complexity. The research method was successful when scaled from sequential actions to sequential and parallel actions as it was analyzed in the advanced study. It was also found to be successful when the tasks were sequential and parallel according to the results from the advanced study.

c. Adaptability

The research method was tested in two working conditions, one indoor with controlled environment and the other semi-controlled environment since all the doors, gates, and ventilation window were partly opened. In both conditions, the research method is feasible since the environment only affects the system inefficiencies that are incorporated by the QFM. Therefore, the research would be adaptable to outside working conditions.

7.1.1 Major Differences Between the Pilot and the Advanced Studies

Though the common goal of the research was to test the feasibility in both simple and complex labor-intensive operations, the major differences between the pilot and the advanced study are illustrated in the following categories.

a. Level of study

The pilot study was analyzed at the task level. The task was to replace old light bulbs with new ones. Due to lack of data points and consistency in the data, the pilot study was only considered at task level, which was further broken down into action level. In the Advanced study, the analysis was performed at activity level. Sufficient data points were available and the data points were consistent throughout the study. The activity was then further broken down into tasks and then into actions.

b. Number of tasks and actions

There was only one task analyzed in the pilot study whereas there were eight tasks involved in the advanced study. The advanced study analyzed fabrication of a sheet metal duct from a plain metal sheet and the process involved eight different tasks. These tasks in the advanced study were further analyzed into 43 actions in total that vary in number of actions in each task. Unlike sequential actions in pilot study, the actions involved in advanced study included sequential and parallel actions.

c. Number of workers

The pilot study was conducted by two workers: one novice and the other veteran. Depending on the consistency and availability of data points, only actions performed by the veteran worker were analyzed. Thus, a single worker is considered in the pilot study. In the advanced study, eight skilled workers completed the fabrication of sheet metal duct activity. There were eight tasks. Tasks 1, 2, 3, 4, and 5 included two workers in each task. Tasks 6 and 7 included three workers, and Task 8 had only one worker.

d. Complexity

The pilot study dealt with only actions that were sequential within a task. For example, “Glass Frame Removal” action has to be completed in order to begin “Old Bulb Removal” action and it has to follow “Ballast Cover Removal” to proceed “Old Ballast Removal” and so on sequentially. On the other hand, there were eight tasks and forty-three actions in the advanced study. The tasks were sequential and parallel, and the actions within a task were also sequential and parallel. For example, tasks such as “Lock Setting”, “Tie Rod Installing” and “Flange Screwing” were parallel with “Sealing”, “Packing” and “Delivery” tasks. Moreover, “Sealing”, “Packing” and “Delivery” tasks were also parallel in a few cases because there were three crew members and each task needed at most two crew members. In addition, most actions in the advanced study were parallel. For example, “hammering along the edges” and “air-hammering to set the lock” actions within the “Lock Setting” task were parallel with “Drilling” action. Therefore, the analysis of advanced study was very complex and time consuming.

e. Work environment

The pilot study was conducted in a controlled work environment. All the actions involved in the electrical light replacement activity were performed inside the school building. Though the work environment was indoors, there were different zones such as classrooms, locker rooms, hallways. that had different temperature, lighting condition, and humidity. Classroom and locker rooms had an issue of space congestion and locker rooms with humidity. Because of fixed furniture around the classrooms and locker rooms, the camera setup was affected to some extent. In the advanced study, the work environment was semi-controlled. The workspace was within the mechanical workshop but had all doors; gates and ventilation opened that allowed the external effect of such items as temperature, humidity, and luminance inside the workshop.

f. System inefficiencies

The system inefficiencies found in the pilot study were humidity, temperature, luminance, space congestion, noise, and restricted access. Five experts provided severity scores and probabilities of occurrence for each factor. These scores and probabilities were inputs for the QFM to determine system inefficiency estimates. In the advanced study, 35 factors were listed in eight different categories that were mentioned as affinity grouping described in Chapter 2. Those main categories were environmental factors, site condition, manpower, external factors, materials, tools and equipment, technical factors, and management factors. Fourteen experts provided their opinions about how likely the factors were present and the consequences or impact of the factors present in the field.

g. Operational inefficiencies

Operational inefficiencies were observed to be more prevalent in an advanced study with multiple workers in sequential and parallel operations. Major factors that contributed higher operational inefficiencies in the advanced study were space congestion, workers interference, chatting, and psychological factors among the parallel workers. Therefore, operational inefficiencies were more significant issues in the advanced study when compared with the pilot study. However, since the pilot study assumed that worker availability at the workstation all the time, the mobility effect was ignored for the analysis.

In essence, the pilot and the advanced study were different in many ways. Table 7.1 shows the summary of the difference between pilot study and advanced study.

Table 7.1: Difference Between Pilot Study and Advanced Study

Category	Pilot Study	Advanced Study
Level of study	Task level	Activity level
Number of tasks	1	8
Number of workers	1	8
Number of actions	8	43
Number of outputs	62 stations	117 ducts
Complexity	Sequential actions	Sequential and parallel tasks as well as actions
Working environment	Controlled	Semi-controlled
Movement	Restricted within the scaffold	Workers move freely within each station and between stations
System Inefficiencies	6 factors	35 factors
Number of experts	5	14

7.1.2 Feedback Implementation From Pilot Study to Advanced Study

The first lesson learned from the pilot study was that there was a high variance between actual average value and the simulated value in the sequential tasks. Data must be carefully checked when analyses are based on sequential data since all durations are accumulated together in sequential actions. This feedback was carefully implemented in the advanced study because it had thousands of data values to analyze. The result of this feedback helped minimize the effect of variability in the data analysis of the advanced study. The advanced study had many parallel tasks and actions. This study found that variability is more of an issue with sequential data than parallel data.

The second lesson learned from the pilot study was the camera setup. The height of camera, position, and the distance from the worker influenced data extraction in the pilot study. Some of the data had to be discarded because of unclear and obstructed views. In addition, the pilot study involved a lot of actions that involved only hand movement and finger movement that made data extraction longer than it should take if the movements were distinct. Therefore, the fabrication of sheet metal duct activity was chosen because it involved lots of physical motion from one place to another, distinct hand and body motion as well as the number of repetitions were also significantly larger than the pilot study. Cameras were set up at appropriate locations to minimize possible obstruction from camera view.

The third lesson learned from the pilot study was that workers felt uncomfortable when cameras were very close to them or when the camera was focusing on their face with a cameraman sitting beside the camera. This feedback was minimized in the advanced study by placing cameras at reasonable distances. Additionally, once the camera was no camera operator was necessary. The camera operators made routine checks to verify the recording storage and sufficient battery.

7.1.3 Qualitative Factor Model for Estimating System Inefficiency

The Qualitative Factor Model was found effective in estimating system inefficiencies in both the pilot study and the advanced study. The model determined that the impact of system inefficiencies is part of a two-prong strategy to estimate upper limit of optimal productivity. This model used severity score and probability of occurrence as factors that affect labor productivity during the field operation. Experts were used to provide those scores. These severity scores were based on a Likert scale from scale “0” to “5” (“0”=no impact; “1”=very low impact; “2”=low impact; “3”=medium impact; “4”=high impact; and “5”=very high impact). The model proved effective in both controlled and semi-controlled environments. The implications show that it can be used in outdoor environments because the model is designed to accommodate every situation and environment.

7.1.4 Simulation Model for Estimating Operational Inefficiencies

The second prong of a two-prong strategy was to estimate lower limit of optimal productivity for which losses due to operational inefficiencies had to be incorporated. DES was found successful in estimating operational inefficiencies in both the pilot and advanced study or in complex labor-intensive operations. The simulation model was very simple in the pilot study that modeled sequential actions of a task. The simulation model in the advanced study modeled a complex operation that included sequential and parallel tasks and actions. The DES was modeled by using Arena simulation from Rockwell Automation. The model was effective in modeling a single worker performing sequential actions and modeling multiple workers performing sequential and parallel tasks and actions.

7.1.5 A Two-prong Strategy for Estimating Optimal Productivity

The implications of a two-prong strategy for estimating optimal productivity were successful in both the pilot study and advanced study. The first prong implemented a top-down analysis in which optimal productivity was estimated by introducing system inefficiencies into productivity frontier. This top-down analysis resulted in an upper limit of optimal productivity estimation. Subsequently, the second prong implemented a bottom-up analysis in which optimal productivity was estimated by filtering out operational inefficiencies from actual productivity. The bottom-up analysis resulted in a lower limit of optimal productivity estimation. The average of the upper and lower thresholds of optimal productivity provided the best estimate of optimal productivity.

The pilot study was conducted in an electrical light replacement activity and the advanced study in a fabrication of sheet metal ducts activity. This shows that the strategy is applicable in other labor-intensive trades to estimate optimal productivity.

An accurate estimation of optimal labor productivity would allow project managers to determine the efficiency of their labor-intensive construction operations by comparing actual versus optimal rather than actual versus historical productivity.

7.2 Research Conclusions

This research proposed and validated a novel concept of estimating optimal productivity in labor-intensive construction operations. By defining optimal labor productivity as the level of sustainable productivity that may be achieved in the field under good management and typical field conditions, the research emphasized an absolute benchmark for gauging efficiency by comparing actual with optimal rather than actual with historical productivity.

Accurate estimation of optimal productivity allows project managers to determine the absolute (unbiased) efficiency of their labor-intensive construction operations by comparing actual vs. optimal rather than actual vs. historical productivity. For example, actual productivity equal to 95% of average historical productivity does not necessarily mean that the operation is efficient but only that the efficiency of the operation is in line with historical averages. Indeed, the operation now and then could be significantly inefficient if it is well below optimal productivity. Therefore, the proposed concept of estimating optimal labor productivity plan to replace historical cost since the historical cost may not be reliable.

As there is currently a vacuum within the realm of optimal productivity estimation, the proposed research would create a heretofore tool with which the construction industry could accurately examine and improve labor-intensive operations. Since the proposed two-prong approach does not depend upon past productivity data for assessing current operations, it has the potential to create a dynamic means by which project managers could measure and assess productivity for any type of labor-intensive operation, regardless of whether managers possess historical productivity data. However, one would not do this with all activities, that would be cost prohibited, but one would do this with key activities: those that are very expensive, or those that are very repetitive so that if improvements in productivity are found the benefits can be spread over and be significant, or for those which no historical data is available. This adaptability within the approach could foreseeably transform the construction industry by obviating uncertainty within productivity metrics and priming the industry for greater innovation in labor-intensive operations. Further case studies will be conducted for it's significance.

This research contributes to the body of knowledge in construction engineering and management by introducing a two-prong strategy for estimating optimal labor productivity in labor-intensive construction operations and reporting on a pilot study and an advanced study from simple electrical operation with single worker to fabricating sheet metal duct with multiple workers. The proposed two-prong strategy for estimating optimal labor productivity was successfully applied in the pilot study and advanced studies. The following points are further conclusions of this dissertation:

a. The research methodology is scalable and can be useful from simple labor-intensive operations to complex labor-intensive operations.
b. The research method is feasible in sequential and/or parallel tasks or actions.
c. The research method is robust enough to support application in more complex cases than just one worker and serial processes.
d. The QFM is an effective tool to estimate system inefficiencies.
e. The DES is an effective to model operational inefficiencies.

With regard to the research hypotheses formulated in Chapter 1, the following conclusions are made based on the pilot and advanced studies:

Hypothesis 1: The proposed two-prong approach for estimating optimal labor productivity is applicable to complex construction operations with crews of multiple workers performing both sequential and parallel processes.

Result of Success: The proposed two-prong approach was found to be scalable, practical, and reliable for estimating optimal productivity in complex construction activities. Therefore, a novel and validated tool is available for project managers to evaluate the efficiency of their construction operations.

Hypothesis 2: The use of QFM, which incorporates severity scores and a probability technique, is best for evaluating system inefficiencies that requires subjective evaluation in complex construction operations.

Result of Success: Introduction of the QFM justified estimating the system inefficiencies in simple or complex construction operations. Thus, the QFM is available to evaluate any factors that need subjective evaluation in labor productivity.

7.3 Research Limitations

The limitations of this research are listed below.

a. The methodology was only tested in controlled and semi-controlled environments. Further research should also include assessment in open environments.

b. System inefficiencies depend on expert judgments. Besides management experts, this research also used skilled workers to give their opinion on severity score and probability of occurrence of factors that affect labor productivity.

c. Physiological and psychological statuses of workers were not monitored. During work activities, workers often stretch their arms and take breaks. However, workers were not asked their physiological conditions to assess the reason for breaks and body stretches. This remained unmeasured.

d. Discrete event simulation is primarily used for operational inefficiencies. Other techniques such as agent-based simulation remained untested.

e. Casual relationships that are among the factors affecting labor productivity were not examined.

f. The data extraction was done manually, which was very time consuming and could include human error. However, video data was advantageous for reexamination of activities.

g. The study only tested in simple electrical replacement activity and fabrication of sheet metal ducts. Exploring more work situations is warranted.

h. The methodology was only tested in a case study basis with only two processes and that therefore these results may not be typical of what would happen in other processes. However, the methodology is robust enough to support application in more complex cases than just one worker and serial processes.

7.4 Research Recommendations

To overcome limitations, this research listed the following recommendations.

a. Conduct feasibility tests in outdoor working environments.

b. Explore use of other simulation techniques to quantify operational inefficiencies.

c. Provide clear instructions and definitions of factors having multiple meanings in the questionnaire survey before getting experts' opinion.

d. Keep field notes as detailed as possible about items that are difficult to capture in video recordings.

e. Keep track of weather information such as temperature, and humidity.

f. Explore the automation techniques in data collection and extraction.

CHAPTER 8

FUTURE RESEARCH

This chapter explores the future steps of expanding research on this topic. Since the proposed methodology for estimating optimal productivity in labor-intensive construction operations is new and focuses on establishing absolute benchmark rather than traditional approach of a relative benchmark, more exploration and efforts are recommended for future research. The following areas will be explored for future research:

i. Incorporate safety and worker health in the decision-making process using physiological status monitoring technologies by extending the same framework

A physiological status monitoring system includes a wearable circumferential band around the body that detects respiratory and blood circulation system by using sensors. Research has been conducted to monitor construction workers' activities by deploying nonintrusive real-time worker location sensing (RTWLS) and physiological status monitoring (PSM) technology (Cheng et al., 2013). The study utilized fusion of data from continuous remote monitoring of construction worker' location and physiological status. These techniques will be implemented in the two-prong strategy to incorporate safety and workers' health in optimization decision-making process.

The following Figure 8.1 is an example of BioHarness marketed by Zephyr Technology that can provide real-time visibility into the physical status of personnel operating in high stress and extreme environments. Many devices are now able to measure the physiological status, which may be very useful in estimating system and operational inefficiencies.

Figure 8.1: BioHarness

(Source: Zephyr Technology Corporation)

Physiological statuses utilized in estimating inefficiencies can include:

- Heart rate
- Posture
- Activity level
- Peak Acceleration
- Breathing rate
- R-R interval
- EKG

Similarly, a team of researchers at Korea Advanced Institute of Science and Technology (KAIST) in Daejeon, South Korea has developed a flexible, wearable polymer sensor that can directly measure the degree and occurrence of goose bumps, technically known as "piloerection," on the skin, which are caused by sudden changes in body temperature or emotional states.

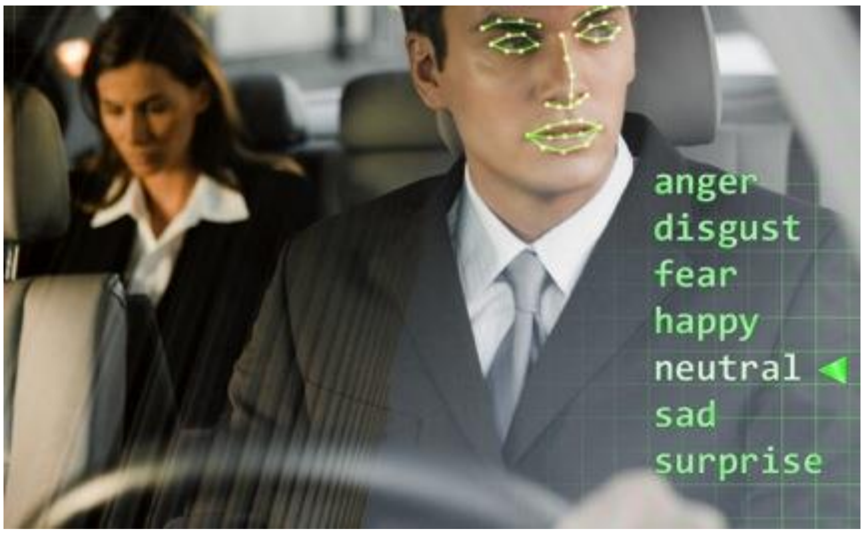


Figure 8.2: Emotional States

(Source: https://wtvox.com/2014/06/wearable-tech-step-toward-emotion-detectors)

All of these innovations could be used for data collection and developing a decision process for defining system and operational inefficiencies. The result will also be beneficial for advancing the understanding of productivity and safety levels of construction processes.

ii. Accommodate streams of data from the proliferation of technologies such as cell phones, unmanned aerial vehicles (UAV), low-cost GPS, and ubiquitous internet access into the same framework

Simulation and visualization have dramatically improved project monitoring and decision-making processes in construction projects. However, outdoor construction, involving labor intensive operations, equipment and large budgets, is yet to benefit from the advancement of such data driven decision systems. With the proliferation of technologies such as low-cost Global Positioning System (GPS), cell phones, unmanned aerial vehicles (UAV), and ubiquitous Internet access, the process of outdoor construction operation management can be improved significantly.

One of the challenges in collecting data in outdoor environment is camera setup. It gets complicated when stationary cameras are unable to capture all the workers' actions and movement. For collecting data in the outdoor environment, drones and other UAVs can be very useful. Drones have been getting attention in capturing videos where setting up camera tripods on the ground is impossible. Figure 8.3 shows a sample of a drone that has a camera hung from the body of the Drone.

Figure 8.3: Drone with Attached Camera

(Source: http://techpp.com/2014/01/29/cheap-drones/)

This equipment can be remotely monitored and manipulated over the construction site to collect data. This might be too costly to operate for data collection so its use should be limited to situation that cannot be collected with regular cameras. The videotape recorded from the Drone can be easily available in real time via access to the Internet. Many GPS tracking devices can also be used to collect data to analyze system and operational inefficiencies to estimate optimal productivity of the operation.

iii. Advance a tested novel theoretical concept and replace status quo productivity metrics by introducing a novel approach for assessing the efficiency of labor-intensive construction process

The research result based on the pilot study and the advanced study has shown that the two-prong strategy for estimating optimal productivity is valid, and it provides an absolute benchmark for gauging performance. Future research will be performed in order to gain more validation by applying it to different labor-intensive trades. If successful, then it will help in replacing status quo productivity metrics by introducing a novel two-prong strategy for assessing the efficiency of labor-intensive operation. For example, the cost comparison based on historical data may not be reliable, but by comparing with the optimal would allow the project managers a realistic cost, because the proposed two-prong approach does not depend upon the past productivity data for assessing current operations. The two-prong approach relies on assessing current operations and the productivity metrics based on current data would obviate uncertainty within productivity metrics and thus, leads the industry for greater innovation in labor-intensive operations.

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APPENDIX A

ADDITIONAL LIST OF FIGURES

The following list of figures relates to the advanced study. Figures A.1 to A.3 refer to Arena outputs simulated with 2340 inputs and 100 replications. Figures A.4 to A.10 refer to instances of non-contributory events.

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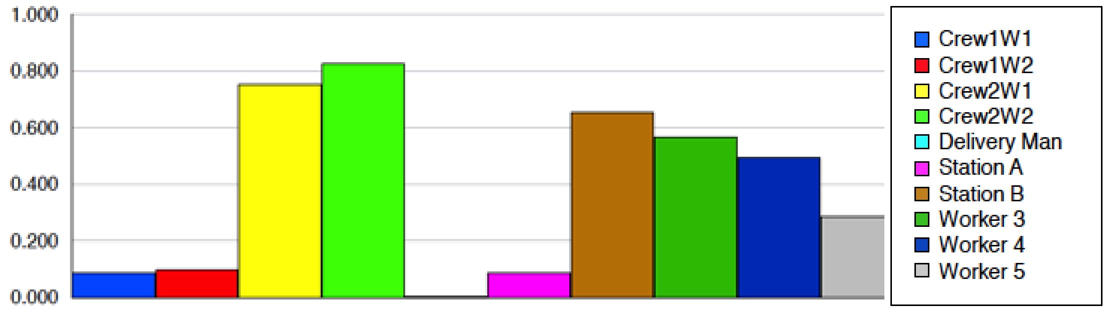
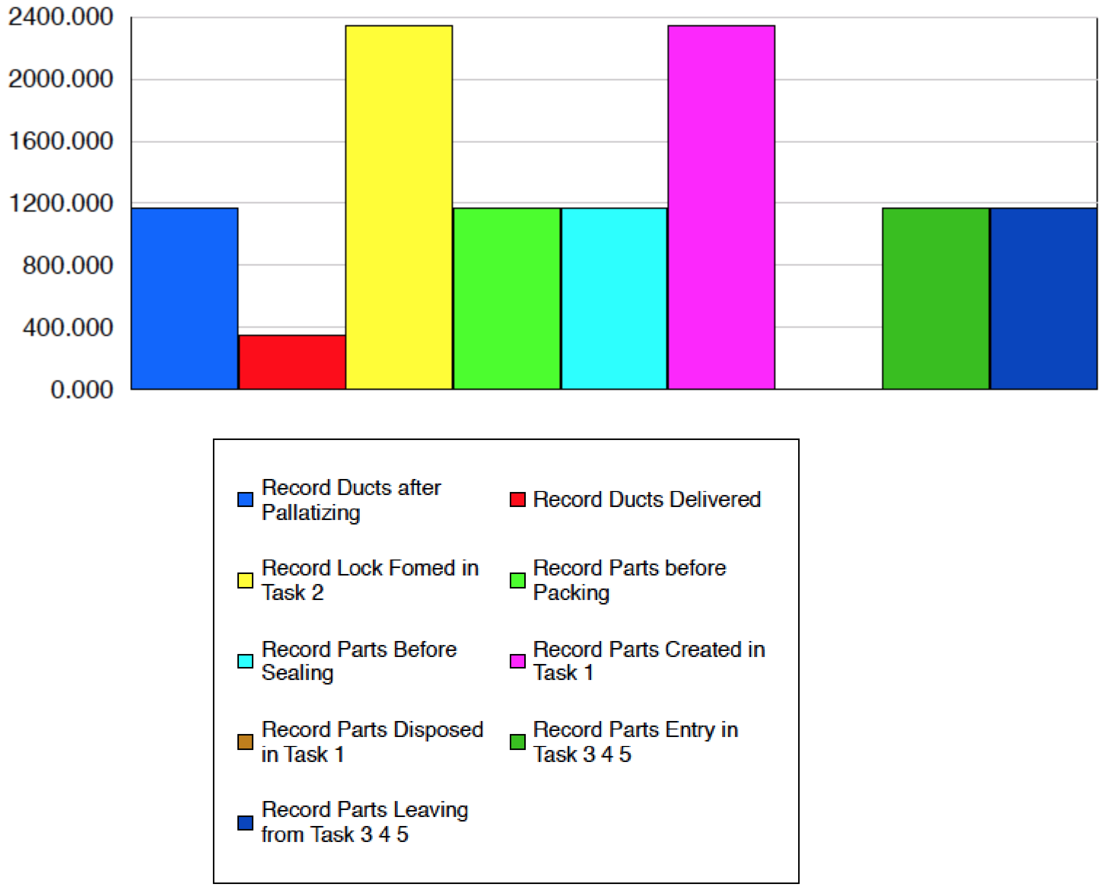


Figure A.1: Resource Utilization



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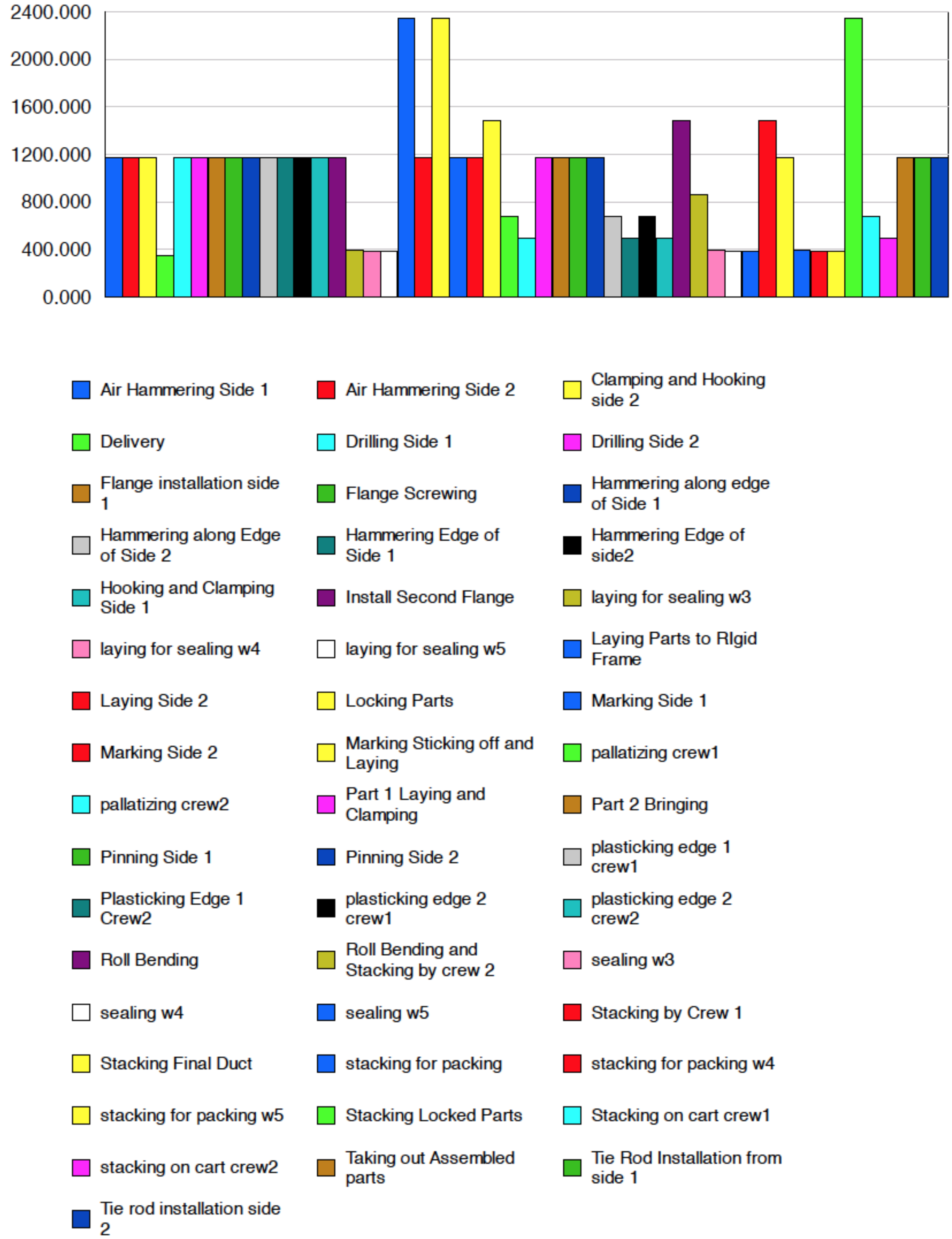

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APPENDIX B

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Table B.1: Sample Data with Non-Contributory Duration in Pilot Study

Serial No	Frame Cover Removal	Old Bulb (T12) Removal	Ballast Cover Removal	Old Ballast Removal	New Ballast Installation	Ballast Cover Closure	New Bulb (T8) Installation	Frame Cover Closure	Total Duration
1	8	20	20	125	110	50	52	4	390
2	4	10	22	88	72	26	19	3	246
3	4	15	15	127	89	28	20	3	304
4	4	10	16	84	57	18	24	3	220
5	3	20	12	128	52	19	20	3	262
6	4	25	14	206	72	22	15	3	367
7	4	25	19	150	57	14	31	3	310
8	4	10	16	86	57	30	19	3	233
9	3	11	12	83	64	14	29	3	228
10	3	19	14	151	180	15	50	3	445
11	3	11	20	87	63	15	24	4	238
12	3	16	13	94	52	70	34	4	298
13	4	18	15	89	56	33	23	4	255
14	3	14	18	79	60	26	28	4	246
15	4	15	16	104	55	40	30	4	283
16	4	17	20	94	73	19	40	4	287
17	4	10	24	92	59	27	31	4	268
18	3	16	15	108	67	40	28	5	300
19	4	13	16	112	80	33	33	3	313
20	4	12	20	88	67	34	29	4	278

Table B.2: Sample Data without Non-Contributory Durations in Pilot Study

Serial No	Frame Cover Removal	Old Bulb (T12) Removal	Ballast Cover Removal	Old Ballast Removal	New Ballast Installation	Ballast Cover Closure	New Bulb (T8) Installation	Frame Cover Closure	Total Duration
1	4	20	20	92	110	27	49	4	327
2	4	10	22	88	72	26	19	3	246
3	4	15	15	127	89	28	20	3	304
4	4	10	16	84	57	18	24	3	220
5	3	12	12	93	52	19	20	3	219
6	4	11	14	206	72	22	15	3	353
7	4	18	19	104	57	14	31	3	257
8	4	10	16	86	57	30	19	3	233
9	3	11	12	83	64	14	29	3	228
10	3	19	14	107	120	15	25	3	316
11	3	11	20	87	63	15	24	4	238
12	3	16	13	94	52	70	34	4	298
13	4	18	15	89	56	33	23	4	255
14	3	14	18	79	60	26	28	4	246
15	4	15	16	104	55	40	30	4	283
16	4	17	20	94	73	19	40	4	287
17	4	10	24	92	59	27	31	4	268
18	3	16	15	108	67	40	28	5	300
19	4	13	16	112	80	33	33	3	313
20	4	12	20	88	67	34	29	4	278

Table B.3: Sheet Metal Roll Bending Task by Crew 1

Serial No.	Marking, Sticking off and Laying by Crew1 W1 (Col. A)	Setting, Bending and Dimension Checking by Crew 1 (Col. B)	Stacking Parts by Crew1 W2 (Col. C)
1	12	49	19
2	24	48	18
3	23	48	15
4	32	60	18
5	24	45	28
6	22	49	29
7	39	47	23
8	21	47	21
9	35	55	18
10	36	53	20
11	17	53	20
12	30	47	31
13	45	51	27
14	19	49	21
15	34	49	17

Table B.4: Sheet Metal Roll Bending Task by Crew 2

Serial No.	Laying	Marking	Setting	Bending	Checking Dimension	Stacking
1	4	16	13	29	13	15
2	7	14	9	29	11	8
3	5	21	14	27	3	9
4	6	14	9	28	2	7
5	6	22	6	27	1	8
6	6	25	9	28	2	8
7	6	15	7	27	3	9
8	7	18	10	26	2	9
9	9	18	8	29	2	9
10	8	20	6	28	1	9
11	7	19	10	27	2	11
12	7	21	8	28	2	9
13	9	19	8	29	3	9
14	6	15	9	28	1	12
15	6	17	19	28	5	19

Table B.5: Sheet Metal Lock Forming Task by Crew 2

Serial No.	Laying	Locking	Stacking
1	18	48	11
2	17	39	13
3	23	35	13
4	19	32	13
5	20	32	11
6	19	32	10
7	16	33	11
8	19	32	13
9	24	31	11
10	17	32	11
11	18	31	10
12	18	35	15
13	22	33	11
14	21	33	11
15	18	32	13

Table B.6: Lock Setting of Two Sheets at Side 1 by Crew 2

Serial No.	Laying and clamping part 1 (W2)	Bringing Part 2 (W2)	Hooking and Clamping (W1W2)	Hammering ends side 1 (W2)	Pinning Side1 (W2)
1	74	19	48	25	11
2	87	15	66	22	19
3	24	13	55	33	14
4	30	16	60	34	11
5	32	15	71	40	16
6	55	17	74	17	10
7	58	18	55	25	10
8	41	20	11	26	8
9	40	13	61	27	11
10	60	12	68	36	11
11	22	16	95	37	13
12	49	17	70	40	13
13	34	21	64	27	8
14	65	20	54	21	11
15	23	18	64	29	15

Table B.7: Tie Rod Installation Side 1 by Crew 2

Serial No.	Marking Side1 (W1W2)	Hammering along Side 1 (W2)	Air-hammering Side 1 (W2)	Drilling side 1	Tie Rod Installation Side 1 (W1W2)
1	24	33	28	47	48
2	36	35	35	59	63
3	28	23	28	65	86
4	32	35	29	77	50
5	31	41	38	74	109
6	23	26	28	66	54
7	27	40	49	100	77
8	23	24	59	64	95
9	30	22	33	69	86
10	30	28	28	57	129
11	32	21	35	71	93
12	44	28	36	74	74
13	34	20	24	73	117
14	33	18	33	61	96
15	31	26	24	55	86

Table B.8: Lock Setting of Two Sheets at Side 2 by Crew 2

Serial No.	Laying side 2 (W1W2)	Clamping and fixing (W1W2)	Hammering Side 2 (W2)	Pinning Side 2 (W2)
1	31	42	20	12
2	30	202	27	12
3	38	50	27	16
4	31	89	41	11
5	60	60	24	11
6	42	77	48	15
7	38	68	32	8
8	30	60	40	11
9	24	69	27	18
10	37	60	32	18
11	25	52	27	11
12	36	58	25	18
13	43	50	23	10
14	34	42	26	22
15	28	45	26	15

Table B.9: Tie Rod Installation Side 2 by Crew 2

Serial No.	Marking Side 2 (W1W2)	Hammering along Side 2 (W2)	Air-hammering Side 2 (W2)	Drilling Side 2 (W1)	Tie Rod Installation Side 2 (W1W2)
1	21	32	28	61	135
2	20	31	29	61	87
3	32	19	30	60	149
4	28	23	41	86	70
5	22	15	46	76	47
6	34	26	26	94	95
7	12	35	28	96	73
8	27	22	32	70	65
9	36	23	37	53	63
10	33	24	25	72	103
11	38	23	35	59	107
12	30	28	33	83	64
13	28	21	26	59	94
14	45	26	44	71	75
15	35	25	35	54	78

Table B.10: Flange Installation by Crew 2

Serial No.	Taking out (W1W2)	Installing Flange (W1W2)	Screwing Flange (W1)	Installing flanges (W1W2)	Screwing next (W1W2)	Stacking Assembled Parts (W1W2)
1	9	22	135	22	173	24
2	7	22	145	43	128	8
3	54	15	144	44	147	21
4	11	18	136	41	178	20
5	18	24	123	48	169	20
6	10	19	122	38	150	28
7	10	20	110	41	124	37
8	7	16	111	46	178	11
9	7	14	127	39	153	30
10	9	22	201	46	133	15
11	8	19	122	57	137	21
12	10	27	145	53	163	17
13	8	25	141	58	171	15
14	8	24	127	78	178	13
15	17	19	125	52	120	10

Table B.11: Sealing Sheet Metal Ducts

Serial No.	Laying			Sealing			Stacking		
	W1	W2	W3	W1	W2	W3	W1	W2	W3
1	22	12	12	977	1655	712	10	11	22
2	11	10	12	671	1923	612	4	8	21
3	11	9	14	874	1286	729	8	10	34
4	12	13	14	788	1109	1043	5	11	25
5	12	10	36	681	1109	740	6	9	65
6	11	10	37	1268	960	920	25	10	25
7	33	10	33	868	960	803	15	11	83
8	15	12	55	1556	1014	695	16	12	25
9	20	10	50	1620	1043	1202	15	14	27
10	8	29	39	1386	1032	765	13	37	11
11	15	29	34	1080	1150	796	18	20	11
12	10	46	19	940	1148	893	7	15	14
13	9	19	21	822	1151	674	11	24	19
14	13	24	136	730	740	740	16	18	23
15	10	20	21	967	728	920	7	21	22

Table B.12: Palletizing and Packing Sheet Metal Ducts

Serial No.	Plasticking Edge 1		Plasticking Edge 2		Stacking		Palletizing
	W3 / W4	W3 / W5	W3 / W4	W3 / W5	W3 / W4	W3 / W5	
1	27	125	66	297	18	55	328
2	47	25	69	301	19	62	583
3	42	103	55	74	26	34	437
4	36	43	53	58	26	27	434
5	54	45	46	280	31	31	626
6	51	175	49	92	17	39	434
7	85	216	109	245	17	64	525
8	133	239	110	84	14	30	418
9	156	190	108	93	37	25	757
10	80	180	153	122	50	38	502
11	90	111	147	105	39	29	464
12	42	146	137	96	26	40	428
13	68	140	188	88	25	38	604
14	88	160	130	78	32	50	609
15	70	160	181	92	38	22	535

Table B.13: Delivery of Sheet Metal Ducts

Serial No.	Uploading Batches of Duct to Delivery Truck
1	42
2	35
3	29
4	20
5	40
6	35
7	30
8	22
9	35
10	25
11	43
12	41
13	29
14	28
15	14

Table B.14: Sample Data Entry for Fabrication of Sheet Metal Ducts Activity

Worker ID	SN	Laying on roll table			Marking for curved edge			Setting			Bending			Checking Dimensions			Stacking		
		Start	End	Duration	Start	End	Duration	Start	End	Duration	Start	End	Duration	Start	End	Duration	Start	End	Duration
Worker 1	50				0:26	0:50	0:24												
Worker 2																			
Together		0:15	0:25	0:10				0:51	0:59	0:08	1:00	1:28	0:28	1:29	1:30	0:01	1:31	1:41	0:10
Worker 1	51				1:58	2:16	0:18												
Worker 2																	2:59	3:08	0:09
Together		1:42	1:51	0:09				2:17	2:25	0:08	2:26	2:56	0:30	2:57	2:58	0:01			
Worker 1	52				3:18	3:32	0:14												
Worker 2																			
Together		3:09	3:17	0:08				3:33	3:46	0:13	3:47	4:16	0:29	4:17	4:18	0:01	4:19	4:32	0:13
Worker 1	53				4:48	5:02	0:14												
Worker 2																			
Together		4:33	4:47	0:14				5:03	5:13	0:10	0:00	0:27	0:27	0:28	0:29	0:01	0:30	0:41	0:11
Worker 1	54				1:26	1:50	0:24												
Worker 2																			
Together		0:42	0:50	0:08				1:51	1:59	0:08	2:00	2:28	0:28	2:29	2:30	0:01	2:31	2:49	0:18
Worker 1	55				3:04	3:24	0:20												
Worker 2																			
Together		2:50	3:03	0:13				3:25	3:36	0:11	3:37	4:04	0:27	4:05	4:06	0:01	4:07	4:23	0:16

Table B.15: Sample Questionnaire used in the Advanced Study (Part 1)

No.	**Factors affecting labor productivity**	**Impact score**						**How likely is this factor present in this activity (in percentage %)**
		0	**1**	**2**	**3**	**4**	**5**	
1	**Environmental Factors**							
	High temperature							
	High humidity							
	High wind							
	Heavy rainfall							
	Cold temperature							
2	**Site Condition**	**0**	**1**	**2**	**3**	**4**	**5**	
	High noise level							
	Excess lighting (brightness of light)							
	Insufficient lighting							
	Space congestion							
	Site layout							
3	**Manpower**	**0**	**1**	**2**	**3**	**4**	**5**	
	Fatigue (restless, tired)							
	Poor health condition							
	Family issues							
	Quality of craftsmanship							
	Lack of experience							
	Absenteeism							
	Misunderstanding among workers							

Table B.16: Sample Questionnaire used in the Advanced Study (Part 2)

No.	Factors affecting labor productivity	Impact score						How likely is this factor present in this activity (in percentage %)
		0	1	2	3	4	5	
4	**External Factors**							
	Interference from other trades							
	Availability of skilled worker							
	Increase in the price of materials							
	Implementation of government laws							
5	**Materials**	**0**	**1**	**2**	**3**	**4**	**5**	
	Shortage of materials							
	Poor material quality (defects, broken etc.)							
	Poor material storage (inappropriate storage, long distance)							
	Difficulty in tracking material (lack of periodic supervision)							
	Safety (possible injury due to sharp edges)							
6	**Tools and Equipment**	**0**	**1**	**2**	**3**	**4**	**5**	
	Maintenance of tools and equipment							
	Lack of tools and equipment							
7	**Technical Factors**	**0**	**1**	**2**	**3**	**4**	**5**	
	Complex design of unusual shapes and heights							
	Incomplete and illegible drawing							
8	**Management Factors**	**0**	**1**	**2**	**3**	**4**	**5**	
	Inadequate supervision							
	Overstaffing							
	Management practices							
	Incompetent supervisors							
	Supervision delays							

Table B.17: Data Structure of Process Modules used in Arena Simulation

Process - Basic Process										
	Name	Type	Action	Priority	Resources	Delay Type	Units	Allocation	Expression	Report Statistics
1	Marking Sticking off and Laying	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Second	Value Added	25.5 + LOGN(67.8,3.4)	☑
2	Roll Bending	Standard	Seize Delay Release	Medium(2)	2 rows	Expression	Second	Value Added	44.5 + LOGN(79.2, 47.5)	☑
3	Stacking by Crew 1	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Second	Value Added	37.5 +LOGN (83.1, 25.4)	☑
4	Roll Bending and Stacking by crew 2	Standard	Seize Delay Release	Medium(2)	2 rows	Expression	Second	Value Added	65.5 +ERLA(18.78,28)	☑
5	Laying Parts to RIgid Frame	Standard	Seize Delay Release	Medium(2)	2 rows	Expression	Second	Value Added	NORM(28 , 2.97)	☑
6	Locking Parts	Standard	Seize Delay Release	Medium(2)	2 rows	Expression	Second	Value Added	29.5+LOGN(9.79,3.4)	☑
7	Stacking Locked Parts	Standard	Seize Delay Release	Medium(2)	2 rows	Expression	Second	Value Added	10.5+ERLA(6.23,9)	☑
8	Part 1 Laying and Clamping	Standard	Seize Delay Release	High(1)	1 rows	Expression	Second	Value Added	16+ERLA(10.8,5)	☑
9	Part 2 Bringing	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Second	Value Added	11.5+GAMM(4.24,2.27)	☑
10	Hooking and Clamping Side 1	Standard	Seize Delay Release	Medium(2)	2 rows	Expression	Second	Value Added	25.5+WEIB(33.5,7.16)	☑
11	Hammering Edge of Side 1	Standard	Seize Delay Release	Medium(2)	2 rows	Expression	Second	Value Added	16.5+ERLA(11.54,10.5)	☑
12	Pinning Side 1	Standard	Seize Delay Release	Medium(2)	2 rows	Expression	Second	Value Added	6.5+LOGN(19.14,3.6)	☑
13	Marking Side 1	Standard	Seize Delay Release	Medium(2)	2 rows	Expression	Second	Value Added	17.5+WEIB(29.6,5.87)	☑
14	Hammering along edge of Side 1	Standard	Seize Delay	Medium(2)	1 rows	Expression	Second	Value Added	15.5+ERLA(15.46,18)	☑
15	Air Hammering Side 1	Standard	Delay Release	Medium(2)	1 rows	Expression	Second	Value Added	29.5+GAMM(16.62,3.17)	☑
16	Drilling Side 1	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Second	Value Added	32.5+72*BETA(12.31,5.52	☑
17	Tie Rod Installation from side 1	Standard	Seize Delay Release	Medium(2)	2 rows	Expression	Second	Value Added	151+WEIB(71.5,5.58)	☑
18	Laying Side 2	Standard	Seize Delay	Medium(2)	2 rows	Expression	Second	Value Added	20.5+LOGN(34.3,11.9)	☑
19	Clamping and Hooking side 2	Standard	Delay Release	Medium(2)	2 rows	Expression	Second	Value Added	33.5+56*BETA(7.72,2.45)	☑
20	Hammering Edge of side2	Standard	Seize Delay Release	Medium(2)	2 rows	Expression	Second	Value Added	17.5+GAMM(16.09,2.07)	☑

Table B.18: Data Structure of Process Modules used in Arena Simulation

Process - Basic Process

	Name	Type	Action	Priority	Resources	Delay Type	Units	Allocation	Expression	Report Statistics
21	Pinning Side 2	Standard	Seize Delay Release	Medium(2)	2 rows	Expression	Second	Value Added	8.5+LOGN(4.11,4.4)	☑
22	Marking Side 2	Standard	Seize Delay Release	Medium(2)	2 rows	Expression	Second	Value Added	8.5+ERLA(4.49,5)	☑
23	Hammering along Edge of Side 2	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Second	Value Added	11.5+LOGN(19.59,7.35)	☑
24	Air Hammering Side 2	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Second	Value Added	31.5+WEIB(27.3,1.72)	☑
25	Drilling Side 2	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Second	Value Added	51.5+WEIB(40.3,1.77)	☑
26	Tie rod installation side 2	Standard	Seize Delay Release	Medium(2)	2 rows	Expression	Second	Value Added	47+ERLA(28.8,10)	☑
27	Taking out Assembled parts	Standard	Seize Delay Release	Medium(2)	2 rows	Expression	Second	Value Added	15.5+LOGN(4.92,3.38)	☑
28	Flange installation side 1	Standard	Seize Delay Release	Medium(2)	2 rows	Expression	Second	Value Added	33+WEIB(54.6,1.18)	☑
29	Install Second Flange	Standard	Seize Delay Release	Medium(2)	2 rows	Expression	Second	Value Added	56+ERLA(57.5,2)	☑
30	Flange Screwing	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Second	Value Added	TRIA(130,148,178.4)	☑
31	Stacking Final Duct	Standard	Seize Delay Release	Medium(2)	2 rows	Expression	Second	Value Added	TRIA(35,50,65.5)	☑
32	laying for sealing w3	Standard	Seize Delay	Medium(2)	1 rows	Expression	Second	Value Added	6.5+GAMM(49.49,14.5)	☑
33	sealing w3	Standard	Delay	Medium(2)	1 rows	Expression	Second	Value Added	690+EXPO(788)	☑
34	stacking for packing	Standard	Delay Release	Medium(2)	1 rows	Expression	Second	Value Added	3.5+ERLA(6.59,28)	☑
35	laying for sealing w4	Standard	Seize Delay	Medium(2)	1 rows	Expression	Second	Value Added	18.5+WEIB(93.4,0.957)	☑
36	sealing w4	Standard	Delay	Medium(2)	1 rows	Expression	Second	Value Added	TRIA(2291,2.76e+003,3.2	☑
37	stacking for packing w4	Standard	Delay Release	Medium(2)	1 rows	Expression	Second	Value Added	7.5+22*BETA(4.911,0.45)	☑
38	laying for sealing w5	Standard	Seize Delay	Medium(2)	1 rows	Expression	Second	Value Added	15+WEIB(126.6,1.11)	☑
39	sealing w5	Standard	Delay	Medium(2)	1 rows	Expression	Second	Value Added	546+835*BETA(19.26,1.3	☑
40	stacking for packing w5	Standard	Delay Release	Medium(2)	1 rows	Expression	Second	Value Added	6.5+GAMM(25.3,4.5)	☑

Table B.19: Data Structure of Process Modules used in Arena Simulation

Process - Basic Process

	Name	Type	Action	Priority	Resources	Delay Type	Units	Allocation	Expression	Report Statistics
41	plasticking edge 1 crew1	Standard	Seize Delay	Medium(2)	2 rows	Expression	Second	Value Added	27+170*BETA(11.912,	☑
42	Plasticking Edge 1 Crew2	Standard	Seize Delay	Medium(2)	2 rows	Expression	Second	Value Added	25+GAMM(94.7,1.22)	☑
43	plasticking edge 2 crew1	Standard	Delay	Medium(2)	2 rows	Expression	Second	Value Added	46+158+BETA(4.983,1.43	☑
44	Stacking on cart crew1	Standard	Delay	Medium(2)	2 rows	Expression	Second	Value Added	14+WEIB(79.9,1.14)	☑
45	plasticking edge 2 crew2	Standard	Delay	Medium(2)	2 rows	Expression	Second	Value Added	41+WEIB(76.9,1.11)	☑
46	stacking on cart crew2	Standard	Delay	Medium(2)	2 rows	Expression	Second	Value Added	TRIA(23.5,53.9,81.5)	☑
47	pallatizing crew1	Standard	Delay Release	Medium(2)	2 rows	Expression	Second	Value Added	TRIA(361,468,919)	☑
48	pallatizing crew2	Standard	Delay Release	Medium(2)	2 rows	Expression	Second	Value Added	TRIA(361,468,919)	☑
49	Delivery	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Second	Value Added	13.5+37*BETA(1.4,1.24)	☑

Table B.20: Data Structure of Record Module used in Arena Simulation

Station - Advanced Transfer

	Name	Station Type	Station Name	Parent Activity Area	Associated Intersection	Report Statistics
1	Packing station	Station	pack station			☑
2	Stack Station A	Station	Stacking Station A			☑
3	Stack Station B	Station	Stacking Station B			☑
4	Flange Installation Station	Station	Flange Station			☑
5	Sealing Station	Station	Sealing Station			☑

Table B.21: Data Structure of Advanced Transfer Modules

Station - Advanced Transfer

	Name	Station Type	Station Name	Parent Activity Area	Associated Intersection	Report Statistics
1	Packing station	Station	pack station			☑
2	Stack Station A	Station	Stacking Station A			☑
3	Stack at Station B	Station	Stacking Station B			☑
4	Sealing Station	Station	Sealing Station			☑
5	Parts Arrival Station	Station	Arrival Station			☑
6	Roll Bending Crew 1 Station	Station	Crew 1 Station			☑
7	Roll Bending Crew 2 Station	Station	Crew 2 Station			☑
8	Record Parts	Station	Arrival Record Station			☑
9	Decision Station	Station	Decision Station			☑
10	Locker Station	Station	Locker Station			☑
11	Flange Station	Station	Flange Station			☑
12	Delivery station	Station	Delivery station			☑
13	Departure Area	Station	Departure Area			☑
14	Tie Rod Installation	Station	Tie Rod Station			☑

Table B.22: Data Structure of Record Modules used in Arena Simulation

Record - Basic Process

	Name	Type	Value	Record into Set	Counter Name
1	Record Parts Created in Task 1	Count	1		Record Parts Created in Task 1
2	Record Parts Disposed in Task 1	Count	1		Record Parts Disposed in Task 1
3	Record Lock Fomed in Task 2	Count	1		Record Lock Fomed in Task 2
4	Record Parts Entry in Task 3 4 5	Count	1		Record Parts Entry in Task 3 4 5
5	Record Parts Leaving from Task 3 4 5	Count	1		Record Parts Leaving from Task 3 4 5
6	Record Parts Before Sealing	Count	1		Record Parts Before Sealing
7	Record Parts before Packing	Count	1		Record Parts before Packing
8	Record Ducts after Pallatizing	Count	1		Record Ducts after Pallatizing
9	Record Ducts Delivered	Count	1		Record Ducts Delivered

Table B.23: Data Structure of Route Modules used in Arena Simulation

Route - Advanced Transfer

	Name	Route Time	Units	Destination Type	Station Name
1	Route to packing	0.25	Seconds	Station	pack station
2	Route to Stacking Station A	0.25	Seconds	Station	Stacking Station A
3	Route to Stacking Station B	0.25	Seconds	Station	Stacking Station B
4	Route to Flange Station	0.25	Seconds	Station	Flange Station
5	Route to Sealing Station	0.25	Seconds	Station	Sealing Station

Table B.24: Data Structure of Queue Modules (Part 1)

Queue - Basic Process

	Name	Type	Shared	Report Statistics
1	Part 1 Laying and Clamping.Queue	First In First Out	☐	☑
2	Hooking and Clamping Side 1.Queue	First In First Out	☐	☑
3	Drilling Side 1.Queue	First In First Out	☐	☑
4	Laying Side 2.Queue	First In First Out	☐	☑
5	Marking Side 2.Queue	First In First Out	☐	☑
6	Drilling Side 2.Queue	First In First Out	☐	☑
7	Tie rod installation side 2.Queue	First In First Out	☐	☑
8	Flange Screwing.Queue	First In First Out	☐	☑
9	laying for sealing w3.Queue	First In First Out	☐	☑
10	laying for sealing w4.Queue	First In First Out	☐	☑
11	laying for sealing w5.Queue	First In First Out	☐	☑
12	plasticking edge 1 crew1.Queue	First In First Out	☐	☑
13	Plasticking Edge 1 Crew2.Queue	First In First Out	☐	☑
14	Delivery.Queue	First In First Out	☐	☑
15	Pinning Side 2.Queue	First In First Out	☐	☑
16	Air Hammering Side 2.Queue	First In First Out	☐	☑
17	Flange installation side 1.Queue	First In First Out	☐	☑
18	Install Second Flange.Queue	First In First Out	☐	☑
19	Marking Sticking off and Laying.Queue	First In First Out	☐	☑
20	Roll Bending.Queue	First In First Out	☐	☑
21	Stacking by Crew 1.Queue	First In First Out	☐	☑
22	Roll Bending and Stacking by crew 2.Queue	First In First Out	☐	☑
23	Initial Stacking.Queue	First In First Out	☐	☑
24	Stacking Locked Parts.Queue	First In First Out	☐	☑
25	Locking Parts.Queue	First In First Out	☐	☑

Table B.25: Data Structure of Queue Modules (Part 2)

Queue - Basic Process

	Name	Type	Shared	Report Statistics
25	Locking Parts.Queue	First In First Out	☐	☑
26	Laying Parts to RIgid Frame.Queue	First In First Out	☐	☑
27	Part 2 Bringing.Queue	First In First Out	☐	☑
28	Hammering Edge of Side 1.Queue	First In First Out	☐	☑
29	Pinning Side 1.Queue	First In First Out	☐	☑
30	Marking Side 1.Queue	First In First Out	☐	☑
31	Hammering along edge of Side 1.Queue	First In First Out	☐	☑
32	Tie Rod Installation from side 1.Queue	First In First Out	☐	☑
33	Hammering Edge of side2.Queue	First In First Out	☐	☑
34	Hammering along Edge of Side 2.Queue	First In First Out	☐	☑
35	Assemble Parts stage 2.Queue	First In First Out	☐	☑
36	Assemble Parts stage 3.Queue	First In First Out	☐	☑
37	Taking out Assembled parts.Queue	First In First Out	☐	☑
38	Stacking Final Duct.Queue	First In First Out	☐	☑
39	Seize station A.Queue	First In First Out	☐	☑
40	hold station A new part.Queue	First In First Out	☐	☑
41	station B stacking.Queue	First In First Out	☐	☑
42	Seize station B.Queue	First In First Out	☐	☑
43	hold station B new part.Queue	First In First Out	☐	☑
44	Hold for sealer.Queue	First In First Out	☐	☑
45	Batch of 2.Queue	First In First Out	☐	☑
46	Batch of 3.Queue	First In First Out	☐	☑
47 ▶	Batch of 6.Queue	First In First Out	☐	☑

Table B.26: Data Structure of Separate Modules used in Arena Simulation

Separate - Basic Process

	Name	Type	Cost to Duplicates	# of Duplicates
1 ▶	Allow Stack	Duplicate Original	50	1
2	Parallel Parts Stage 1	Duplicate Original	50	1
3	Parallel Parts Stage 2	Duplicate Original	50	1

Table B.27: Time per Entity at 100 Replications (figures are in unit of time in Second)

VA Time Per Entity	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Air Hammering Side 1	82.1645	0.17	79.8329	84.0172	36.1868	298.03
Air Hammering Side 2	55.8786	0.09	54.8717	56.9249	31.5228	146.70
Clamping and Hooking side 2	76.0038	0.04	75.6103	76.5115	44.1567	88.6433
Delivery	33.0045	0.11	31.7474	34.4728	13.5008	50.4991
Drilling Side 1	82.1986	0.04	81.6963	82.6898	47.7081	101.35
Drilling Side 2	87.4275	0.11	86.2494	88.6552	51.5541	206.58
Flange installation side 1	84.7053	0.25	82.1729	87.5034	33.0027	517.04
Flange Screwing	152.08	0.06	151.34	152.78	130.15	178.24
Hammering along edge of Side 1	293.79	0.41	289.69	299.05	131.07	788.87
Hammering along Edge of Side 2	31.0849	0.04	30.5250	31.5643	14.6862	101.69
Hammering Edge of Side 1	132.03	0.21	129.55	134.43	52.1557	373.82
Hammering Edge of side2	50.6273	0.13	49.2717	52.1953	19.8238	235.86
Hooking and Clamping Side 1	56.8671	0.03	56.3915	57.1815	31.8246	73.2144
Install Second Flange	171.07	0.52	163.85	176.79	63.4679	1061.13
laying for sealing w3	724.48	2.01	706.18	749.28	287.91	2187.15
laying for sealing w4	113.42	1.00	102.40	124.27	18.5006	1059.36
laying for sealing w5	137.32	1.04	124.97	149.23	15.0044	1048.10
Laying Parts to RIgid Frame	28.0023	0.01	27.8562	28.1302	14.0959	41.4245
Laying Side 2	54.7821	0.06	53.6635	55.4685	28.1827	168.00
Locking Parts	39.2915	0.02	39.1245	39.5008	31.7990	74.6167
Marking Side 1	44.9390	0.03	44.5359	45.4216	21.7731	61.9493
Marking Side 2	30.9362	0.06	30.3153	31.5904	12.8140	107.03
Marking Sticking off and Laying	93.3102	0.02	93.1178	93.5199	80.0938	110.67
pallatizing crew1	582.30	0.89	572.37	592.06	362.02	917.05
pallatizing crew2	582.26	1.03	569.16	594.87	362.05	916.17
Part 1 Laying and Clamping	70.0770	0.15	68.0343	72.0442	26.4628	292.40
Part 2 Bringing	21.1332	0.03	20.7255	21.5832	12.2952	80.5121
Pinning Side 1	25.6443	0.02	25.3450	25.8832	14.9263	51.4303
Pinning Side 2	12.5840	0.03	12.2192	12.9529	8.5486	100.29
plasticking edge 1 crew1	187.37	0.08	186.50	188.32	100.32	197.00
Plasticking Edge 1 Crew2	139.40	0.85	129.13	151.47	25.0026	1082.45
plasticking edge 2 crew1	204.78	0.00	204.76	204.79	204.15	205.00
plasticking edge 2 crew2	114.56	0.56	108.30	122.30	41.0062	824.46
Roll Bending	123.81	0.26	120.44	127.08	49.8114	800.33
Roll Bending and Stacking by crew 2	591.49	0.63	585.35	598.88	328.14	1172.01
sealing w3	1479.27	8.14	1382.97	1573.66	690.00	9755.24
sealing w4	2757.97	1.92	2730.18	2781.37	2295.15	3218.26
sealing w5	1326.43	0.48	1318.79	1331.78	998.59	1380.99
Stacking by Crew 1	120.52	0.13	118.73	121.84	61.1809	373.83
Stacking Final Duct	50.1525	0.04	49.7786	50.6757	35.0281	65.4241
stacking for packing	188.06	0.36	182.21	191.57	95.4964	390.52
stacking for packing w4	27.6666	0.02	27.4170	27.9113	10.8793	29.5000
stacking for packing w5	120.51	0.59	112.24	127.80	26.4019	582.58
Stacking Locked Parts	66.6024	0.08	65.3881	67.3502	26.8465	222.08
Stacking on cart crew1	90.3473	0.54	82.8333	96.2759	14.0097	790.33
stacking on cart crew2	52.9897	0.12	51.4599	54.4996	23.7176	81.4592
Taking out Assembled parts	20.3989	0.02	20.1797	20.6911	15.7151	72.6562
Tie Rod Installation from side 1	217.08	0.08	215.83	217.96	155.48	260.34
Tie rod installation side 2	335.38	0.54	329.47	341.31	137.21	930.79

Table B.28: Number of Entities at 100 Replications (Part 1)

Number In	Average	Half Width	Minimum Average	Maximum Average
Air Hammering Side 1	1170.00	0.00	1170.00	1170.00
Air Hammering Side 2	1170.00	0.00	1170.00	1170.00
Clamping and Hooking side 2	1170.00	0.00	1170.00	1170.00
Delivery	347.00	0.00	347.00	347.00
Drilling Side 1	1170.00	0.00	1170.00	1170.00
Drilling Side 2	1170.00	0.00	1170.00	1170.00
Flange installation side 1	1170.00	0.00	1170.00	1170.00
Flange Screwing	1170.00	0.00	1170.00	1170.00
Hammering along edge of Side 1	1170.00	0.00	1170.00	1170.00
Hammering along Edge of Side 2	1170.00	0.00	1170.00	1170.00
Hammering Edge of Side 1	1170.00	0.00	1170.00	1170.00
Hammering Edge of side2	1170.00	0.00	1170.00	1170.00
Hooking and Clamping Side 1	1170.00	0.00	1170.00	1170.00
Install Second Flange	1170.00	0.00	1170.00	1170.00
laying for sealing w3	396.79	3.21	355.00	442.00
laying for sealing w4	385.86	3.39	339.00	430.00
laying for sealing w5	387.35	2.99	355.00	421.00
Laying Parts to RIgid Frame	2340.00	0.00	2340.00	2340.00
Laying Side 2	1170.00	0.00	1170.00	1170.00
Locking Parts	2340.00	0.00	2340.00	2340.00
Marking Side 1	1170.00	0.00	1170.00	1170.00
Marking Side 2	1170.00	0.00	1170.00	1170.00
Marking Sticking off and Laying	1481.00	0.00	1481.00	1481.00
pallatizing crew1	678.49	3.53	645.00	720.00
pallatizing crew2	491.51	3.53	450.00	525.00
Part 1 Laying and Clamping	1170.00	0.00	1170.00	1170.00
Part 2 Bringing	1170.00	0.00	1170.00	1170.00
Pinning Side 1	1170.00	0.00	1170.00	1170.00
Pinning Side 2	1170.00	0.00	1170.00	1170.00
plasticking edge 1 crew1	678.49	3.53	645.00	720.00
Plasticking Edge 1 Crew2	491.51	3.53	450.00	525.00
plasticking edge 2 crew1	678.49	3.53	645.00	720.00
plasticking edge 2 crew2	491.51	3.53	450.00	525.00
Roll Bending	1481.00	0.00	1481.00	1481.00
Roll Bending and Stacking by crew 2	859.00	0.00	859.00	859.00

Table B.29: Number of Entities at 100 Replications (Part 2)

Number In	Average	Half Width	Minimum Average	Maximum Average
sealing w3	396.79	3.21	355.00	442.00
sealing w4	385.86	3.39	339.00	430.00
sealing w5	387.35	2.99	355.00	421.00
Stacking by Crew 1	1481.00	0.00	1481.00	1481.00
Stacking Final Duct	1170.00	0.00	1170.00	1170.00
stacking for packing	396.79	3.21	355.00	442.00
stacking for packing w4	385.86	3.39	339.00	430.00
stacking for packing w5	387.35	2.99	355.00	421.00
Stacking Locked Parts	2340.00	0.00	2340.00	2340.00
Stacking on cart crew1	678.49	3.53	645.00	720.00
stacking on cart crew2	491.51	3.53	450.00	525.00
Taking out Assembled parts	1170.00	0.00	1170.00	1170.00
Tie Rod Installation from side 1	1170.00	0.00	1170.00	1170.00
Tie rod installation side 2	1170.00	0.00	1170.00	1170.00

Table B.30: Counter

Count	Average	Half Width	Minimum Average	Maximum Average
Record Ducts after Pallatizing	1170.00	0.00	1170.00	1170.00
Record Ducts Delivered	347.00	0.00	347.00	347.00
Record Lock Fomed in Task 2	2340.00	0.00	2340.00	2340.00
Record Parts before Packing	1170.00	0.00	1170.00	1170.00
Record Parts Before Sealing	1170.00	0.00	1170.00	1170.00
Record Parts Created in Task 1	2340.00	0.00	2340.00	2340.00
Record Parts Disposed in Task 1	1.0000	0.00	1.0000	1.0000
Record Parts Entry in Task 3 4 5	1170.00	0.00	1170.00	1170.00
Record Parts Leaving from Task 3 4 5	1170.00	0.00	1170.00	1170.00

Table B.31: Resource Usage

Instantaneous Utilization	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Crew1W1	0.08664426	0.00	0.08436034	0.08863694	0.00	1.0000
Crew1W2	0.0975	0.00	0.0949	0.1002	0.00	1.0000
Crew2W1	0.7525	0.00	0.7302	0.7681	0.00	1.0000
Crew2W2	0.8258	0.00	0.8011	0.8441	0.00	1.0000
Delivery Man	0.00308589	0.00	0.00294158	0.00325563	0.00	1.0000
Station A	0.08458175	0.00	0.08160979	0.08655715	0.00	1.0000
Station B	0.6559	0.00	0.6361	0.6704	0.00	1.0000
Worker 3	0.5680	0.00	0.5526	0.5800	0.00	1.0000
Worker 4	0.4961	0.00	0.4460	0.5443	0.00	1.0000
Worker 5	0.2831	0.00	0.2617	0.3013	0.00	1.0000

Number Busy	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Crew1W1	0.08664426	0.00	0.08436034	0.08863694	0.00	1.0000
Crew1W2	0.0975	0.00	0.0949	0.1002	0.00	1.0000
Crew2W1	0.7525	0.00	0.7302	0.7681	0.00	1.0000
Crew2W2	0.8258	0.00	0.8011	0.8441	0.00	1.0000
Delivery Man	0.00308589	0.00	0.00294158	0.00325563	0.00	1.0000
Station A	0.08458175	0.00	0.08160979	0.08655715	0.00	1.0000
Station B	0.6559	0.00	0.6361	0.6704	0.00	1.0000
Worker 3	0.5680	0.00	0.5526	0.5800	0.00	1.0000
Worker 4	0.4961	0.00	0.4460	0.5443	0.00	1.0000
Worker 5	0.2831	0.00	0.2617	0.3013	0.00	1.0000

Number Scheduled	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Crew1W1	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Crew1W2	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Crew2W1	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Crew2W2	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Delivery Man	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Station A	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Station B	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Worker 3	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Worker 4	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Worker 5	1.0000	0.00	1.0000	1.0000	1.0000	1.0000