CONSTRUCTION CREW DESIGN: A LEAN APPROACH

By

Naveen Nerwal

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ABSTRACT

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Construction work is executed by a variety of speciality trades, using group of workers commonly known as crews. Performance of these crews is very crucial to the work being executed and consequently for the overall project performance. Yet decisions regarding how to design a crew (makeup and how work itself will flow) and improve their performance are addressed in an ad hoc fashion, if at all. Also, despite the clear significance of crew design, only a modest scholarly interest in this area has been seen in the last two decades. Developing lean-based guidelines for crew design will allow us to answer questions such as: Can we choreographically design construction work crews, and how? The aim of this research is to address this question by developing lean-based crew design guidelines for construction operations by conducting an extensive literature review focused on “work design/team design” that have well developed theoretical and empirical foundations in Lean Production, Lean Construction, Socio-Technical System theory, and Organizational Psychology. Synthesizing these existing production theories into a new unified model to develop a set of lean-based crew design guidelines that allows experimenting with different crew interactions and interrelations, and not only sizes with the help of using simulation models between discrete event simulation and system dynamics modeling is expected to lead to better overall performance of crews achieving lean construction ideals of minimizing waste and maximizing value for construction operations and projects at large.

Dedicated to

My Loving Parents

&

My Mentor Dr. Tariq Sami Abdelhamid

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1 INTRODUCTION

1.1 Background

Construction industry plays an important role in contributing to the economic health of the United States. According to U.S. Bureau of Economic Analysis, “Construction fell for the sixth consecutive year and the 3.2 percent drop was the smallest since the 3.0 percent drop in 2006” (Teresa L. Gilmore et al 2011) (Figure 1.1).

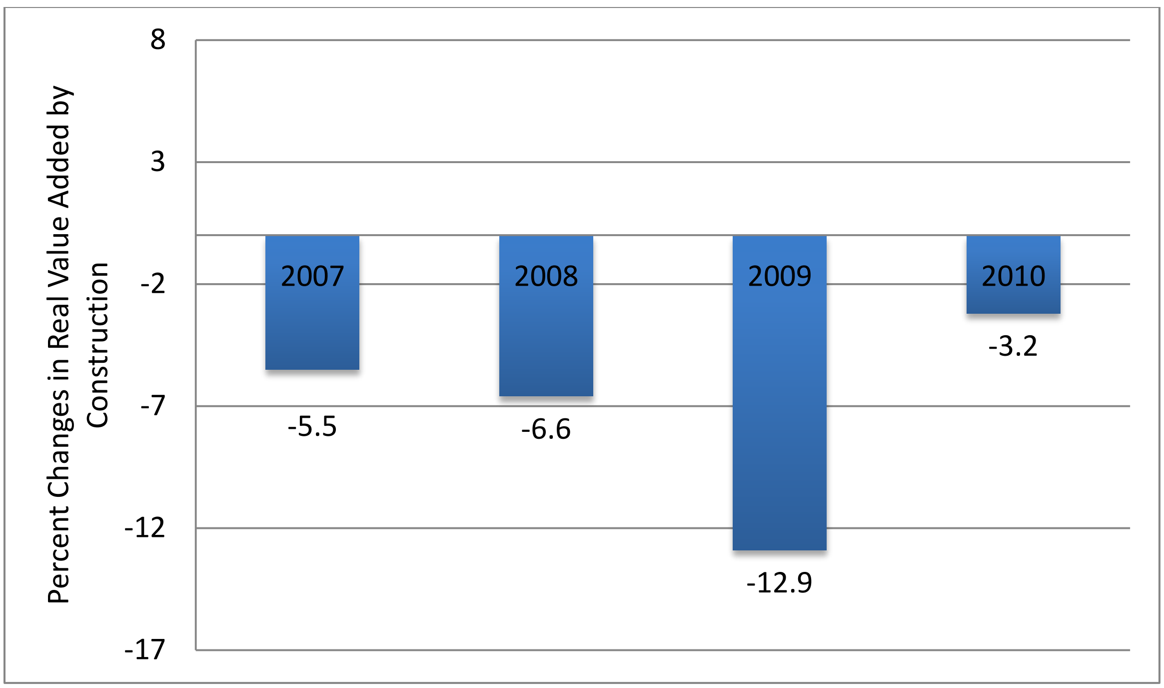


Figure 1.1: Percent changes in real value added by construction (For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this thesis.)

Unlike other industries such as manufacturing which have seen a steady increase in the value added to the U.S. Gross Domestic Product (GDP), construction industry has gone under a substantial decline over the past decade (U.S. Bureau of Economic Analysis). This decline in the value added by construction industry could be attributed to a lot of reasons and it would not be an exaggeration to say that the ever increasing size, scope and complex nature of the construction projects have played a major role towards this decline. However, the construction industry has displayed great difficulty in coping with the increasing complexity of major construction projects (Stocks and Male, 1984). Also, as the construction projects are becoming increasingly complex; that traditional project management methods are proving inadequate (Williams, 1999). Further, Dalchar, 1993 claims that ``Contemporary project management practice is characterized by: late delivery, exceeded budgets, reduced functionality and questioned quality. As the complexity and scale of attempted projects increases, the ability to bring these projects to a successful completion dramatically decreases".

Conventional construction management has focused for many years on overcoming the complexity and improving project performance by primarily focusing on project management techniques that rely on an outmoded time-cost-quality tradeoff paradigm. The failure and inability of the conceptual models of construction management to deliver on the mantra of ‘on-time, at budget, and at desired quality’ is discussed at length in Koskela’s seminal 1992 report and in Koskela (1999, 2000). Another paradigm-breaking anomaly was that observed by Ballard (1994), Ballard and Howell (1994a and 1994b), Howell and Ballard (1994a and 1994b) and Howell (1998). Analysis of project plan failures indicated that about 50% of weekly tasks were not completed (Ballard and Howell 2003). The preceding observations have led to the birth of Lean Construction as a discipline that subsumes the transformation-dominated contemporary construction management (Abdelhamid 2004).

According to Howell and Ballard (1999), the design of work methods under a Lean Construction paradigm happens in two phases; the first involves structuring of work during the product design stage before the start of construction operations; and the second phase carries forward from master scheduling to weekly work.

Examples of techniques used for production system design during the design stage include first run studies, computer simulation, and recently BIM. These techniques are used to minimize waste and improve system throughput. However, the design of crews has received less attention, and is typically considered adequate if the available resources are provisioned (Nerwal and Abdelhamid 2010).

The production process on construction jobsites may be considered the most complex undertaking in any industry (Bennett, 1991, El-Gafy and Abdelhamid 2008). These processes consist of multitude of interdependent, uncertain and variable flow of resources. These resource flows may produce varied outcome of operations in terms of cost, time and other performance indicators, with no clear understanding yet of underlying casual relations.

According to Halpin, (1973) the flow of resources are present in the operations at the micro and macro level of construction and may be classified depending on the resource type being considered. The flows at the macro level are of more strategic importance than the micro level flows which are present at the operational level.

Due to the complex interaction among units on the construction job site and in the construction environment, mathematical models (e.g. queuing systems) can be applied to only a limited number of special cases (Zayed and Halpin, 2000). But with advances in computer technologies, simulation models have been used and developed for decades to help analyze complex operations. Simulation is one of the most widely used operations research and management-science techniques (Law and Kelton 2000). The use of simulation for studying construction operations was first proposed and developed by Halpin in the 1970s (Halpin 1973).

Simulation modeling has traditionally been carried out using discrete event simulation (DES). And it has proved successful in providing detailed analysis of systems involving linear processes and modeling discrete changes in the system behavior over the last three decades. But DES has its limitation of modeling only at the operation level where the entities are passive objects present at a low level of abstraction. When the systems get more complex and integrated, discrete event simulation faces serious challenges to keep up with the high level of abstraction present at the macro level and at times modeling a system at the strategic level keeping the operational level details and analysis seems impractical (Nerwal and Abdelhamid 2010).

In discrete event simulation, it is also difficult to model the "softer" aspects of projects such as learning, pride or morale, and incorporate managerial actions which are important in determining the project behavior (Williams 2002, El-Gafy and Abdelhamid 2009). Moreover, along with modeling the softer aspects of projects, the various nonlinear cause-and-effect relationships, feedback loops, and time delays existing in the complex construction processes could be analyzed more effectively using the methods of systems thinking.

Systems thinking methods have been used for over thirty years (Forrester 1961) and are now well established. However, these approaches require that we move away from looking at isolated events and their causes and start to look at the organization as a system made up of interacting parts (Kirkwood, 1998).

System Dynamics (SD) is a system thinking approach that follows an integrative perspective in modeling systems while recognizing the information feedback characteristics so as to show how organizational structure (in policies), and time delays (in decisions and actions) interact to influence the behavior of the system (Forrester, 1965). It is an appropriate modeling approach to simulate complex construction systems by capturing the cause-and-effect relationships of the various factors affecting the behavior of the system in a casual loop diagram.

1.2 Need Statement

A problem facing estimating and scheduling teams working on early stages of a construction project is the need to determine a reasonable number and composition of crews that can be effectively used in the construction process (Hassanein 1997).

Can we choreographically design construction work crews, and how? This is the question that this research takes on. This will be referred to as Lean-based Crew Design (LbCD).

In an effort to have a better crew design as an integral part of a production system, two main systems-based theories are used in this research, namely, Lean Construction and Socio-Technical systems theory. These two theories along with other existing production management theories are used to develop guidelines for Lean-based Crew Design.

There are numerous factors which affect the crew executing the various interconnected tasks involved in any operation. How to form or design a crew to carry out an operation in a dynamically changing construction environment is a complex task and should be approached with formal methods rather than as assumptions that rarely materialize. There is a need to have a unified model based on the existing production theories that allows experimenting with different crew interactions and interrelations, and not only sizes with the help of using simulation models between discrete event simulation and system dynamics modeling.

In this research, discrete event simulation and system dynamics models are used to demonstrate an example of the use of proposed lean crew design guidelines for construction processes.

1.3 Research Questions

Traditionally, production systems have been designed as transformation of inputs into outputs neglecting the flow and value generation in the construction. There is modest number of research efforts in which production system are designed based on the transformation-flow-value theory leading to maximum value and minimum waste in construction. While crew design has a major impact on any production system model, there is no existing production system model which supports Lean Crew Design.

This research will primarily address the following central questions:

1. What are the important soft and hard factors affecting production system, crew and work design?
2. What improvements could be made to existing crew and work design models to develop a lean crew design?
3. What are the primary Lean-based Crew Design guidelines for construction operations?
4. How can different dynamic simulation methods be integrated to develop a have a better lean crew design model?

1.4 Research Goals and Objectives

The overall goal of this research is to develop crew design guidelines for construction operations. The goal will be achieved by fulfilling the following objectives:

1. Synthesizing Lean Construction and Socio-Technical production system theories, supplemented by other existing production system theories, into crew design guidelines. Objective 1 will be achieved by performing the following tasks:
    a. Conduct literature review of existing construction models, production system theories, and crew & work design models.
    b. Identifying the limitations of existing production system, crew and work design models in the construction industry.
    c. Identifying the important soft and hard factors affecting the production, crew and work design models in the construction industry.
2. Develop crew design guidelines based on literature review and hypothesized inferences.
3. Demonstrating an example of the use of proposed guidelines using simulation models between discrete event simulation and system dynamics.

1.5 Research Hypothesis

In this research, it is hypothesized that lean-based crew design guidelines will give rise to better overall crew performance. Hence, using the developed guidelines for crew design, the following will be achieved, or at least approached:

1. Executing the construction operations in the most efficient way.
2. Minimizing waste in the construction operations.
3. Maximizing value generation in the construction operations.

1.6 Research Scope

The scope of this research would mainly be limited to the design of crews executing operations on site. The study will contrast operations performance using a Lean-based Crew design versus a conventional (non-Lean) Crew design. Lean-based crew design guidelines will be developed based on analysis of performance obtained using the simulation models between discrete event simulation and system dynamics modeling. For the scope of this research, sensitivity analysis is not conducted. However, it would be next step for future research to conduct sensitivity analysis and is acknowledged as one of the limitation of this research.

1.7 Research Method

To complete this research, five phases were followed (Figure 1.2). In the first phase, literature review on the existing construction models, production system theories, and crew & work design models was examined (Chapter 2 and 3). The second phase involved synthesizing the existing production system theories, crew and work design models into crew design characteristics and development of crew design guidelines (Chapter 4).

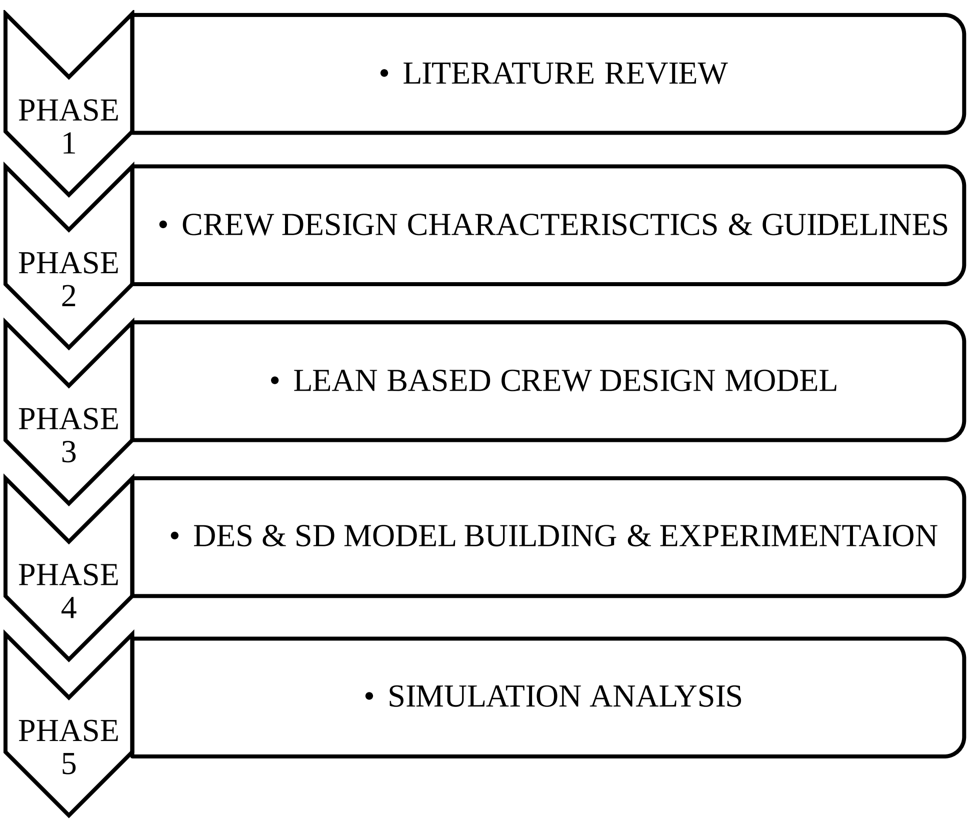


Figure 1.2: Representation of research method phases.

The third phase involved creating a Lean-based Crew Design (LbCD) Model (Chapter 4). The fourth phase involved development of DES and SD computer simulation models with experimentation about crew interaction/design attributes (Chapter 5). In the fifth phase, analysis of the simulation results took place to finalize the impact of the different crew design guidelines (Chapter 5).

In the *1st phase*, an extensive review of the concepts related to this research was conducted. Existing construction models present in the construction industry were reviewed. Next, existing crew and work analysis methods followed by production theories such as Lean Production, Lean Construction and Socio-Technical System theories were reviewed to identify the important soft and hard factors or characteristics affecting the construction crew design.

Literature on crew design or crew formation mainly revolved around how to increase the productivity of workers of the crew involved in the construction operations. Literature reviewed on crew design or crew processes defined input-output or control methods for improving crew performance and optimizing crew on the site. Further, simulation approaches such as Discrete Event Simulation and System Dynamics modeling were reviewed in detail along with discussing the applications, advantages and limitations of each of the modeling techniques in order to gain better understanding of the process of building simulation models.

This research aims to develop a Lean-based Crew Design model that integrates both the existing *crew design* and *work design* research; hence, in the *2nd phase* research studies on "work design/team design" that have well developed theoretical and empirical foundations in *lean production*, *lean construction*, *socio-technical system theory*, *social and organizational psychology* were synthesized into lean crew design characteristics (Figure 1.3).

The lean crew design characteristics are comprised of “primary crew design characteristics”, “intermediate crew design characteristics and outcomes” and “final crew performance outcomes”. The primary crew design characteristics are divided into two groups: (1) work characteristics and (2) flow characteristics that are again divided into waste, task, social and crew characteristics. The crew design characteristics are based on the TFV (transformation-flow-value) concept outlining important design characteristics and performance outcomes that should be considered while designing a crew.

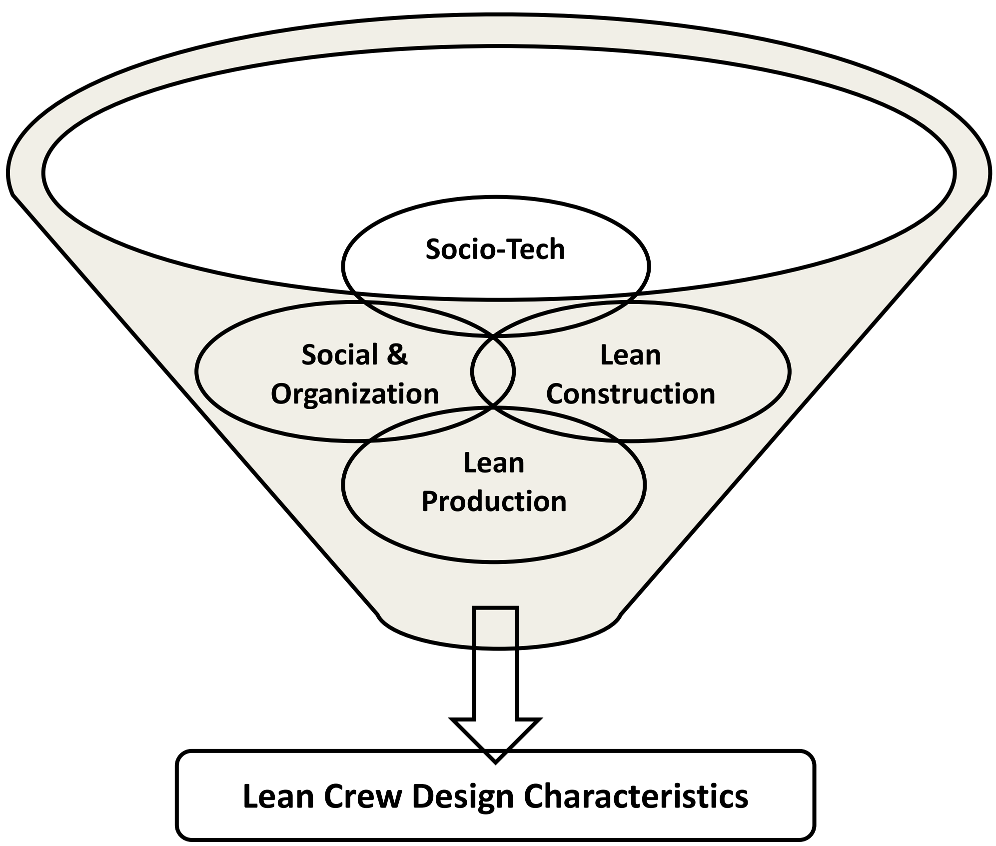


Figure 1.3: Synthesis of existing crew and work design approaches to develop lean crew design characteristics.

After, synthesizing the existing *crew design* and *work design* research into lean crew design characteristics, lean-based crew design guidelines are proposed to guide the crew design. The proposed guidelines lead to the joint optimization of both the *crew* and the *work* performed, resulting in better overall *crew performance* by optimizing the following crew performance outcomes: (1) *duration* of work performed; (2) *cost* of work performed; (3) *productivity*; (4) *quality* of work performed; (5) worker *satisfaction*; (6) worker *learning*; (7) worker *motivation*; (8) *pride* in work performed.

The *3rd phase* involved creating a Lean-based Crew Design (LbCD) Model. The structure of the Lean-based Crew Design (LBCD) model (Figure 1.4) is patterned after a transformation process structure where inputs are converted to outputs by means of a conversion process. The model input consists of the lean crew design characteristics, developed based on existing crew and work design approaches. The transformation process is comprised of three main phases: (1) formation, (2) execution, and (3) refining.

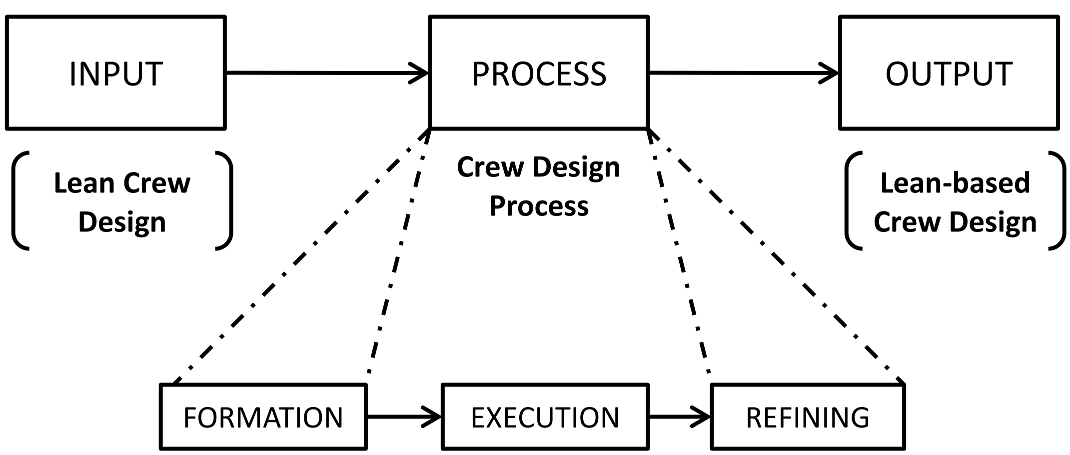


Figure 1.4: Lean-based Crew Design (LbCD) Model

The three phases are proposed to guide the crew design process in a production setting involving initial formation of the crew, structuring of the work, execution of work/implementation (actual work/simulation model execution) where data collection of primary and intermediate crew design indicators is conducted. Finally, the design indicators/characteristics are analyzed in the third phase to refine the initial crew design and maximize the crew performance based on the lean crew design guidelines to produce output of the process as the lean crew design.

The *4th phase* involved development of DES and SD computer simulation models with experimentation about crew interaction/design attributes in order to demonstrate how the crew design characteristics affect the performance of the crew. For the purpose of modeling and simulation, a case study involving a well-documented construction operation from a prior research work conducted by Howell et al (1993) was selected. The case study consists of a real time construction operation focusing on the installation of light fixtures by a construction crew.

To develop a simulation model that can effectively identify and demonstrate both the hard and soft crew design characteristics, a combination of Discrete Event Simulation (DES) and System Dynamics (SD) is used. The simulation models are developed first using Discrete Event Simulation (DES) and then moving to System Dynamics (SD) providing the qualitative and quantitative crew design models.

In the *5th phase*, analysis of the simulation results took place to finalize the impact of the different crew design guidelines.

1.8 Research Benefits and Contribution

This research is expected to contribute in developing a set of guidelines to design construction crews to achieve Lean Construction ideals. The introduction of the use of simulation models between discrete event simulation and system dynamics in this study will also be an addition to existing literature on simulation, which typically uses discrete event simulation only.

It is expected that a crew designed based on the developed guidelines would achieve higher performance levels on the short and long term. This research would benefit the construction industry by providing basis for designing crew interaction and roles during performing a construction operation.

1.9 Chapter Summary

This chapter provided an overview and scope of this research. It outlined and explained the need to develop Lean-based Crew Design guidelines for construction operations. Further, it briefly proposed a five phased research method to conduct this research.

2 LITERATURE REVIEW

2.1 Introduction

This chapter presents and discusses the concepts related to this research. The review starts with discussing the dynamic and complex construction environment. This is followed by a brief review of the existing crew design and construction models present in the construction industry. Next, existing crew and work analysis methods are reviewed. Finally, production theories such as Lean Production, Lean Construction and Socio-technical theories are reviewed.

Literature on crew design or crew formation mainly revolves around how to increase the productivity of workers of the crew involved in the construction operations. Literature reviewed on crew design or crew processes defined input-output or control methods for improving crew performance and optimizing crews on the site. Production theories reviewed such as Socio-technical, Lean Production, and Lean Construction theories formed the basis for developing the guidelines for lean crew design. Also, simulation approaches such as discrete event simulation and system dynamics modeling are presented in more detail together with discussing the applications, advantages and limitations of each of the modeling techniques.

2.2 Construction as a Complex System

The real world is a world full of complexity, chaos, uncertainty, change, flow and processes and cannot be pinned down to the simple, solid, certain, uniform or unchanging objects (Merry, 1995). And construction industry is considered to be one of the most complex systems existing in the real world environment. It has been shown that construction system and the processes involved in construction projects are highly complex and dynamic in nature (Wood and Gidado

2008; Bertelsen 2003a, 2003b; Antoniadis 2008; Baccarini 1996). In fact, the construction process may be considered the most complex undertaking in any industry (Bennett, 1991) which is also supplemented by Mills (2001) who describes the construction industry as one of the most dynamic, risky and challenging businesses.

In order to deal with complex construction systems, it is first important to comprehend what complexity actually means. At times complexity in general usage is confused for the term complicated, for example, The Collins English Dictionary (2006) defines complexity as “the state or quality of being intricate or complex”, or “something complicated” and the term complex here is defined as “intricate or complicated”. But it is to be noted that complexity and complicated do not mean the same, as complicated means something physical or social which is difficult to understand, analyze or manage for one person which may not be true for another person.

The study of complexity and complex systems holds much scope for modern problems where traditional practices have struggled. However, the study of complexity is still relatively recent and it is difficult to reach a standard definition of complexity (Wood and Gidado, 2008). Kauffman (1995) has stated: The efforts are still so new that there is not yet even a generally accepted, comprehensive definition of complexity. Williams (1999) states: While many project managers use the term complex project, there is no clear definition about what is meant – beyond the general acceptance that it is something more than simply a ‘big’ project.

However, a generally accepted definition of complex systems can be presented as systems which are composed of interconnected parts that exhibit one or more properties or behaviors may not be obvious from the individual parts.

Williams (1999) proposed that the overall project complexity can be characterized by two types of uncertainty such as “structural uncertainty” in terms of the number of elements involved and interdependence of these elements and “general uncertainty” which could exist in the form of uncertainty in goals and uncertainty in methods adopted. Williams (1999) classification was very similar to the one given by Jones and Deckro (1993) who defined technical complexity in projects in terms of variety of tasks, the degree of interdependencies within these tasks, and “the instability of the assumptions upon which the tasks are based”.

Baccarini (1996) proposes a definition of project complexity as “consisting of many varied interrelated parts and can be operationalized in terms of differentiation and interdependency.” The terms differentiation and interdependency are related to the number of varied elements present and the degree of interrelatedness between these elements. He discusses these concepts in terms of two types of project complexity such as organizational complexity and technical complexity. Differentiation in an organizational complexity would mean the number of levels in the organizational hierarchal structure, number of formal organizational units, division of tasks, number of specializations, etc, whereas in technical complexity it would mean variety or diversity of some aspect of a task, such as number and diversity of inputs and/or outputs, number of separate and different actions or tasks to produce the end product of a project, and number of specialties (subs or trades) involved on a project.

Gidado (1996) conducted a structured interview with selected experts in building industry to determine what they consider as project complexity and their views and opinions have been presented below:

1. That having a large number of different systems that need to be put together and/or that with a large number of interfaces between elements;

2. When a project involves construction work on a confined site with access difficulty and requiring many trades to work in close proximity and at the same time;
3. That with a great deal of intricacy which is difficult to specify clearly how to achieve a desired goal or how long it would take;
4. That which requires a lot of details about how it should be executed;
5. That which requires efficient coordinating, control and monitoring from start to finish;
6. That which requires a logical link because a complex project usually encounters a series of revisions during construction and without interrelationships between activities it becomes very difficult to successfully update the program in the most efficient manner.

Form the above definitions, complexity as defined by Gidado (1996) was divided into two perspectives of project complexity: (1) The managerial perspective, which involves the planning of bringing together numerous parts of work to form work flow and; (2) The operative and technological perspective, which involves the technical intricacies or difficulties of executing individual pieces of work.

Also, from the structured interviews conducted, Gidado (1996) determined that complexity factors that affect managerial actions in construction originate from a number of sources which can be categorized into two types: (1) Category A, which deals with the components that are inherent in the operation of individual tasks and originate from the resources employed or the environment and; (2) Category B, which deals with those that originate from bringing different parts together to form a work flow. Grouping the sources of complexity factors affecting managerial actions forms a clear distinction between the various originating sources such as employed resources, the environment, number and interaction of different parts in the work flow etc, which makes it much easier to manage, control or reduce complexity, once we know from where it is originating.

Gidado (2004) also deduced that the project complexity can be divided into six main components, each of which is made up of various intersecting factors. The six main components to project complexity are: (1) Inherent complexity; (2) Uncertainty; (3) Number of technologies; (4) Rigidity of sequence; (5) Overlap of phases or concurrency; (6) Organizational complexity

Also, Sven Bertelsen (2003) discussed how the three group of characteristics of complexity such as autonomous agents, undefined values and non-linearity may be directly related to the three different perspective of construction process such as transformation, value generation and flow provided by Koskela (2000).

According to conventional production theory, production is simply considered as the transformation of inputs to outputs, which ignores the flow and value generation concept. However, according to Koskela (2000), three different conceptualizations should be simultaneously used: production as transformation, flow and value generation. By using this conceptualization, the transformation model is in an auxiliary position, and the other two flow and value generation models are successfully able to address both the time-dependent and the time-independent complexity (Pennanen and Koskela 2005).

The proceeding literature seems to suggest how the construction industry and the processes involved are considered to be quite complex. The construction environment is affected by many dynamic and uncertain variables, such as weather, space congestion, crew absenteeism, regulatory requirements, and design changes and reworks (Ahuja and Nandakumar, 1985). These factors along with others such as project size, technical tasks involved, interactions among the resources (equipment, labor and material), team structure, work structure etc lead to even more complexity in construction. This high complexity may lead to difficulty in comprehending the interaction between the various processes involved in construction.

2.3 Existing Production Planning Models

The successful planning of the production process is critical to the success of any construction project; it has to address strategies for site and crew set-up, and a whole host of policies, methods, and procedures (Gidado, 1996). While project management focuses on macro level, strategic issues (Lee et. al. 2006; Pena-Mora et al. 2008), production (or operation) management focuses on the micro level.

Project management can simply be defined as the "process that takes into account a company's way of doing business, allowing for the possibility of a significant payoff with fewer risks" (Callahan & Brooks, 2004) whereas, production management can be defined as the management actions incorporated to meet a project's target by adjusting time, cost, and resources (Lee et. al. 2006). The basic difference between the two is that project management is the use of skills, tools, and management techniques incorporated together to meet company's goals and objectives while production management deals with the skills, tools and actions employed to deliver the project objectives.

Since the early 1970's, researchers and practitioners have developed various construction models to deal with both project and production issues in construction. Kartam et al. (1997) suggested that the existing models could be divided into types of construction models such as system models and process models depending on whether the models emphasize whole system or the on-site construction process. Kartam et al. (1997) differentiated between process models and system models as:

"A process is defined as a set of consecutive steps or activities with an end product or service being delivered … On the other hand, a system model neglects the steps that constitute the process; instead it focuses on the process environment. Portraying the process with its inputs, outputs, directives, feedback loops, and interactions with other processes is a major objective of system modeling. Thus, a process model gives a different perspective and accordingly serves a different purpose than does a system model".

In the following section, the existing process and system models present in the construction literature are discussed in more detail. We discuss how these models correlate with the crew design process and operations design.

2.3.1 Entity Interdependence Model

Entity Interdependence Model was proposed by Thompson (1967), which is part of one of the best known work on organization theory containing the most widely accepted typologies of technology in management. The term technology as used by Thompson refers to the work flows or the transformation processes. In this model, the interdependencies existing between the various entities were explicitly explained. His classifications are based on flow of work or how the work is to be divided between individual members of the work group. Thompson identified three types of interdependencies such as: 1) pooled (no coordination), 2) sequential (simple coordination), and 3) reciprocal (complex coordination).

These three types of interdependence existing between the entities are shown in Figure 2.1. Pooled interdependence requires little to no coordination between the entities. Pooled interdependence means that an entity A or B or Z would make a discrete contribution to the whole; each entity would be involved in accomplishing individual tasks, and the collective output of these entities is what constitutes production for the unit/project. Sequential interdependence is a one way directional interdependence with simple coordination, which means each entity has to accomplish their individual tasks before the next or any other entity in the work unit could start their task/work. This means that output of an entity C becomes the input for the next entity D and the first entity C must finish before the next entity D could start. Reciprocal interdependence is a two way directional interdependency requiring complex coordination, which means two entities such as E & F could be dependent on each other; the output of each of the entity could be the starting point for the other, meaning that both the entities are dependent on each other to finish. The knowledge of these interdependencies is very important for the purpose of coordinating the work units/crews working on the construction site.

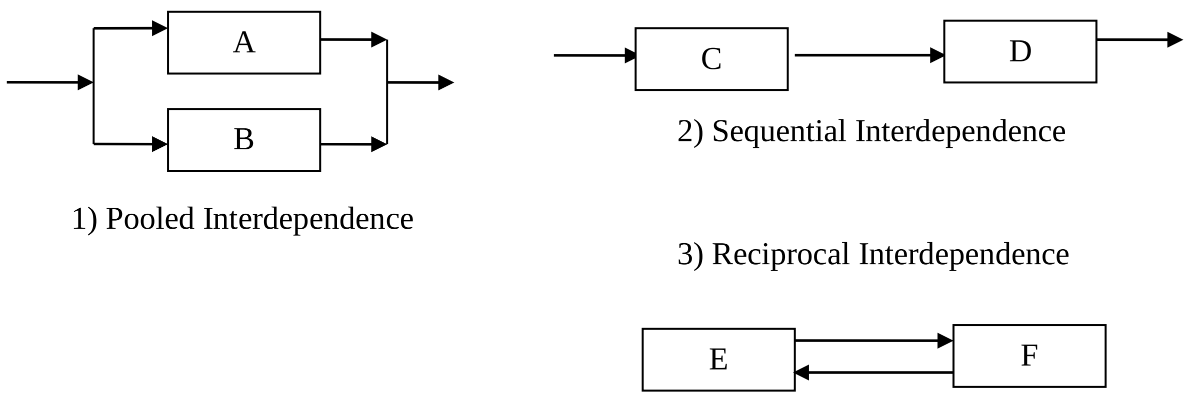


Figure 2.1: Entity Interdependence Model, Thompson (1967).

2.3.2 Conversion Model

One of the focuses of the past research in traditional project management has been to follow the transformation theory converting the inputs into outputs. The dynamic system model (Figure 2.2) defined by Alexander (1974) best describes this conversion process where he showed that the inputs are converted into output by going through a process and this process is regulated by a controller, which establishes the operating characteristics of the process.

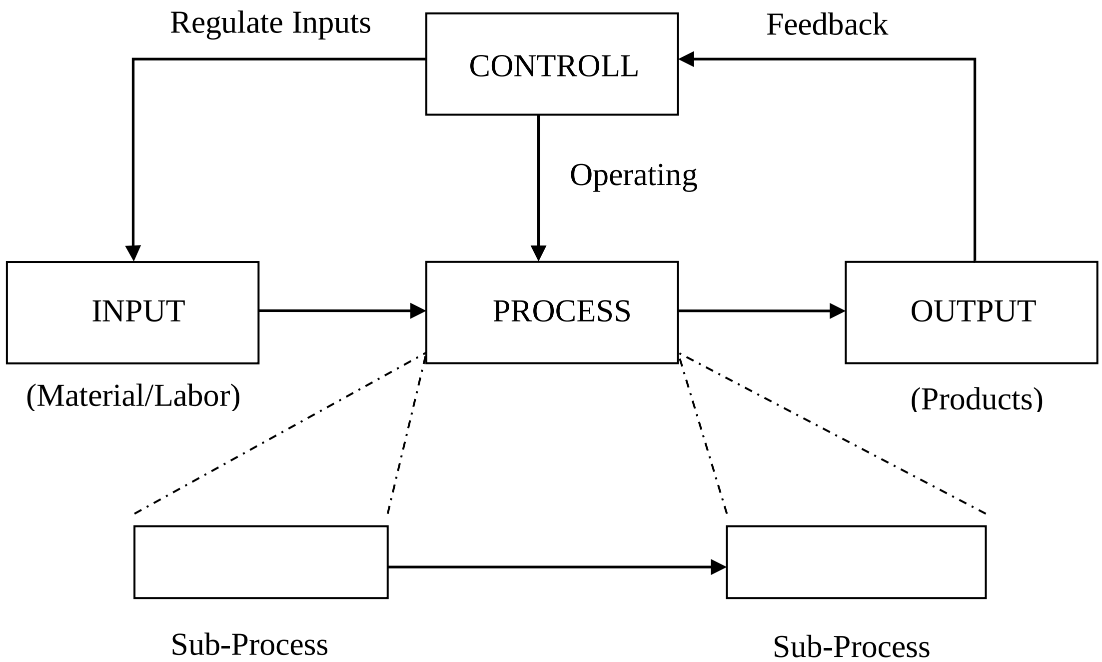


Figure 2.2: Conversion Model adapted from Alexander (1974), Koskela (1992).

According to Kartam (1995), Alexander's conversion model is more appropriate to describe the construction process than other static models such as bar charts, PERT diagrams or decision trees. This model was mostly dominant in the manufacturing setting; and was extended by Koskela (1992), where he stated that production process was aimed at maximizing the conversion of inputs such as material and labor into outputs such as completed units of work; where the work was further divided into sub tasks and activities; again seen as a conversion process. In the conversion model, it was assumed that the cost of any process could be minimized by minimizing the cost associated with respective sub-processes.

Walker (1985) extended the conversion model provided by Alexander (1974) and applied it to the construction process. He divided the transformation process in two groups, namely the construction process and client process; where each of them, while converting inputs to outputs, is affected by various factors from the environment. The model was sufficient and seemed acceptable to show the construction process but only in terms of transformation of processes. It neglected the flow of material and information and value generation components associated in a construction process, which Koskela advocated in his work (Koskela 1992). Further, it did not explain how the construction processes are interdependent with considerable performance variation. The conversion model developed by Walker (1985) is shown below in Figure 2.3:

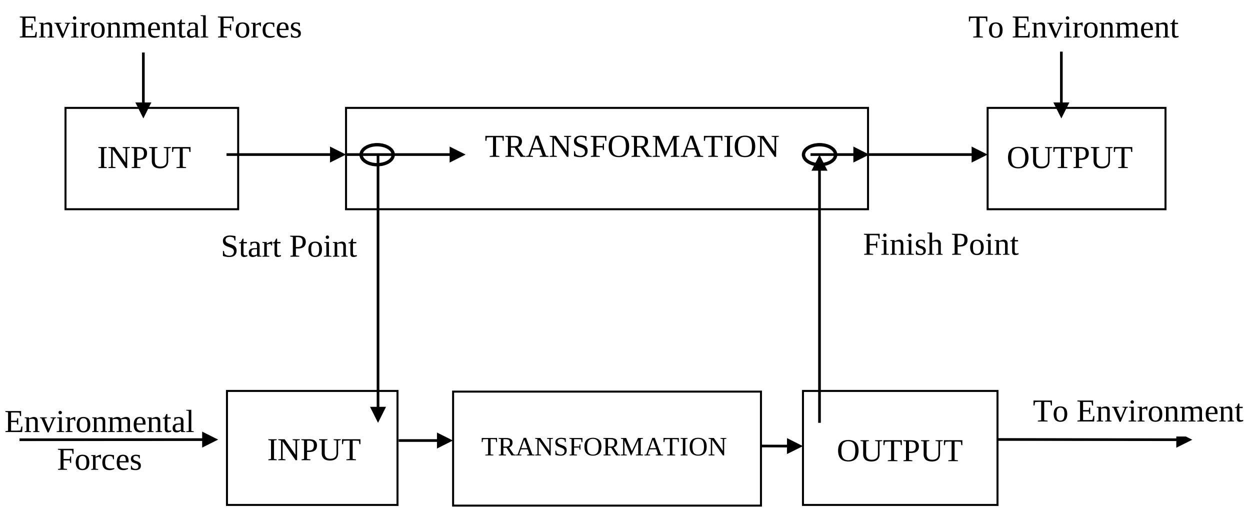


Figure 2.3: Conversion model, Walker (1985)

2.3.3 Method Productivity Delay Model (MPDM)

Adrian and Boyer (1976) introduced the method productivity delay model (MPDM). This model was developed for application by a small to mid-size construction firm that cannot afford professional services. Simple statistical methods were used in this model to make it accessible to construction personnel. It was developed to measure, predict and improve the productivity of the construction operations. For this purpose, this model incorporated elements of other techniques such as work sampling, production function analysis, statistical analysis, time study, and balancing models (Halpin and Riggs 1992).

The MPDM measures, predicts and improve the productivity of the construction operations in four stages, namely, data collection, data processing, model structuring, and finally model implementation. The construction delays were classified into five major types: environmental, equipment, labor, material, and management. By collecting the data on these delay types occurring in the construction operation, efficiency of construction operations is measured by identifying the problematic areas lowering the productivity. MPDM does not consider the other interactions and interdependencies occurring between crews on the site, which may lead to optimizing processes but not the whole system.

2.3.4 Control Model

To address the limitations in the conversion model given by Alexander (1974), Sanvido (1984) suggested a control model that addresses the dynamic construction environment and identifies eight major activities that constitute on-site construction. This model described the various important functions of the construction process and how to regulate or control them (Figure 2.4).

The main focus of this model was to take corrective actions once mistakes or inefficiencies are encountered rather than taking preventive actions before their occurrences (Kartam 1995). This model was significant as it established a hierarchical way to address and control the construction process by highlighting the interdependence between the important on-site construction activities and allowing the management to address the dynamic construction process in a much better way.

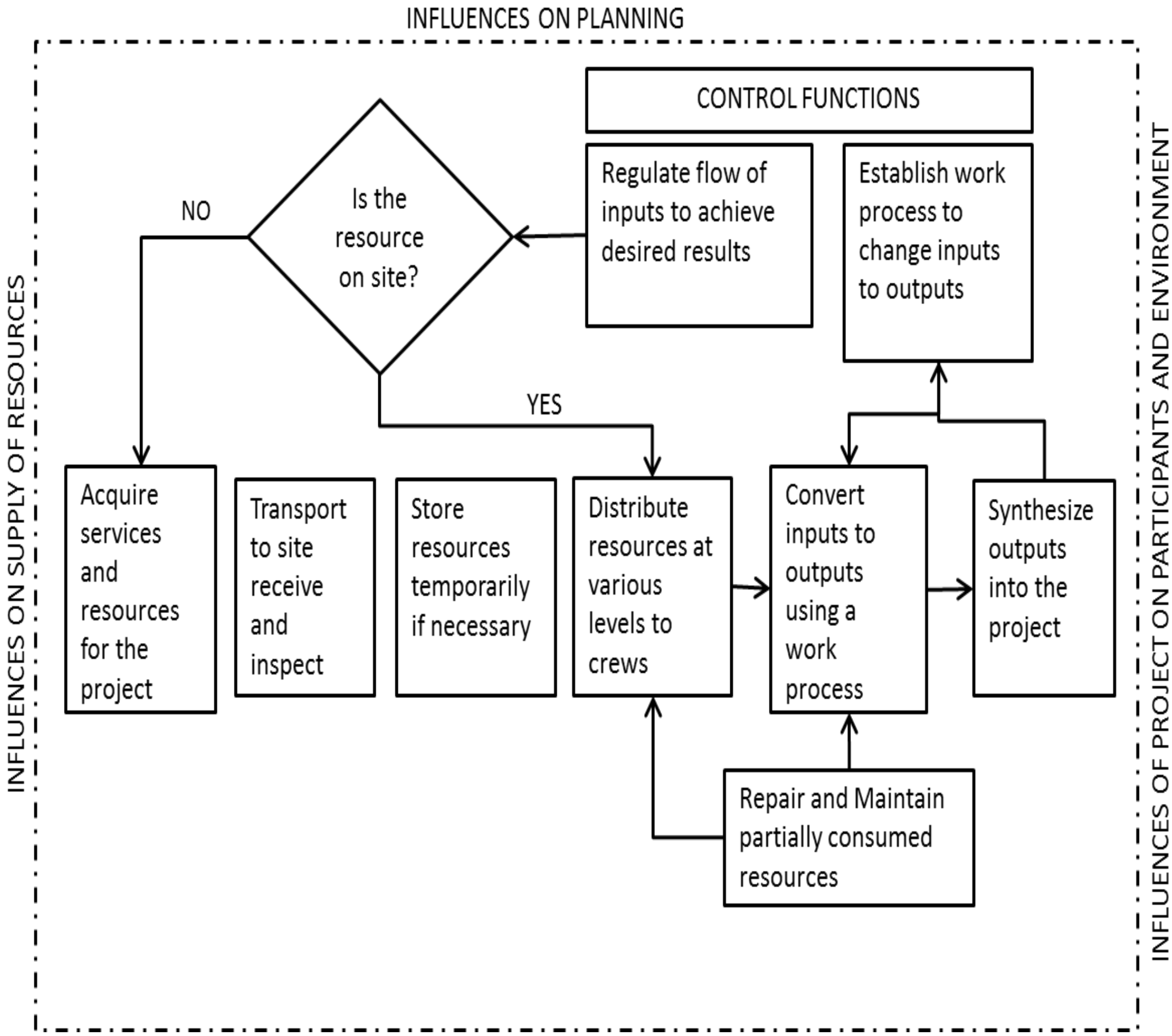


Figure 2.4: Control Model Sanvido (1984).

2.3.5 Factor Model

Crew productivity has been an important factor in determining crew effectiveness and construction operations performance, and in turn the overall project performance in achieving intended aims (typically time, cost, and quality). A lot of factors act together which may affect the productivity and hence the performance of construction operations. Thomas and Yiakounis (1987) developed a factor model to capture this multi-factor influence. This model was developed for labor-intensive construction activities based on the fact that work executed by a crew is affected by a number of factors which may lead to incidental disturbances, leading to low crew performance.

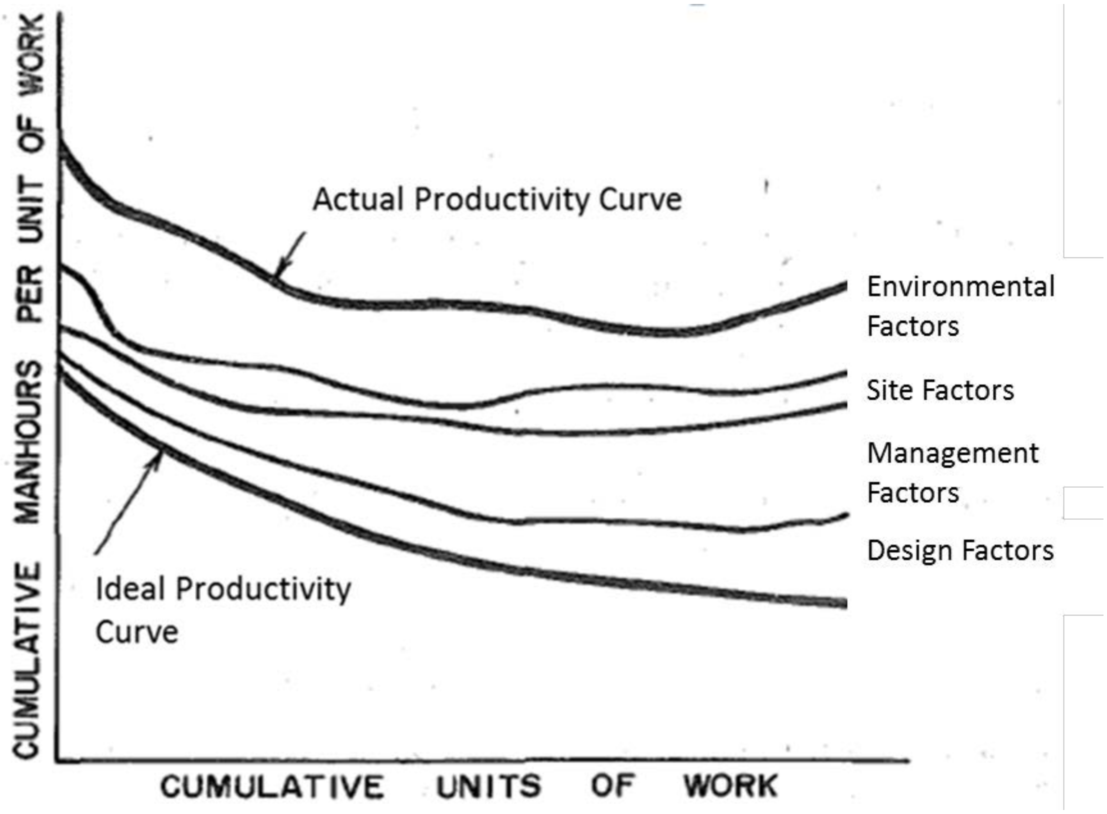


Figure 2.5: Actual productivity vs. ideal productivity curve, Thomas et al (1987).

According to Thomas et al (1987) these disturbances could be due to the following factors: environmental factors, site factors, management factors, and design factors which may add up to give an actual productivity curve that may be irregularly shaped and difficult to interpret. They argued that if these disturbances can be mathematically discounted from the actual productivity curve, one is left with an ideal productivity curve (Figure 2.5). Based upon design requirements and construction practices, it is theorized that this ideal productivity curve can be predicted before the start of work.

Further, based on U.N. Report ("Effect" 1965), Thomas et al (1990) extended the factor mode to divide the factors affecting the labor productivity into two groups such as 1) Work environment and 2) Work to be done. The work to be done and work-environment categories are analogous to catalysts in the form of resources and conditions needed to efficiently convert inputs (work-hours) to outputs (quantities) (Thomas et al 1990). The detailed representation of the factor model is shown in Figure 2.6.

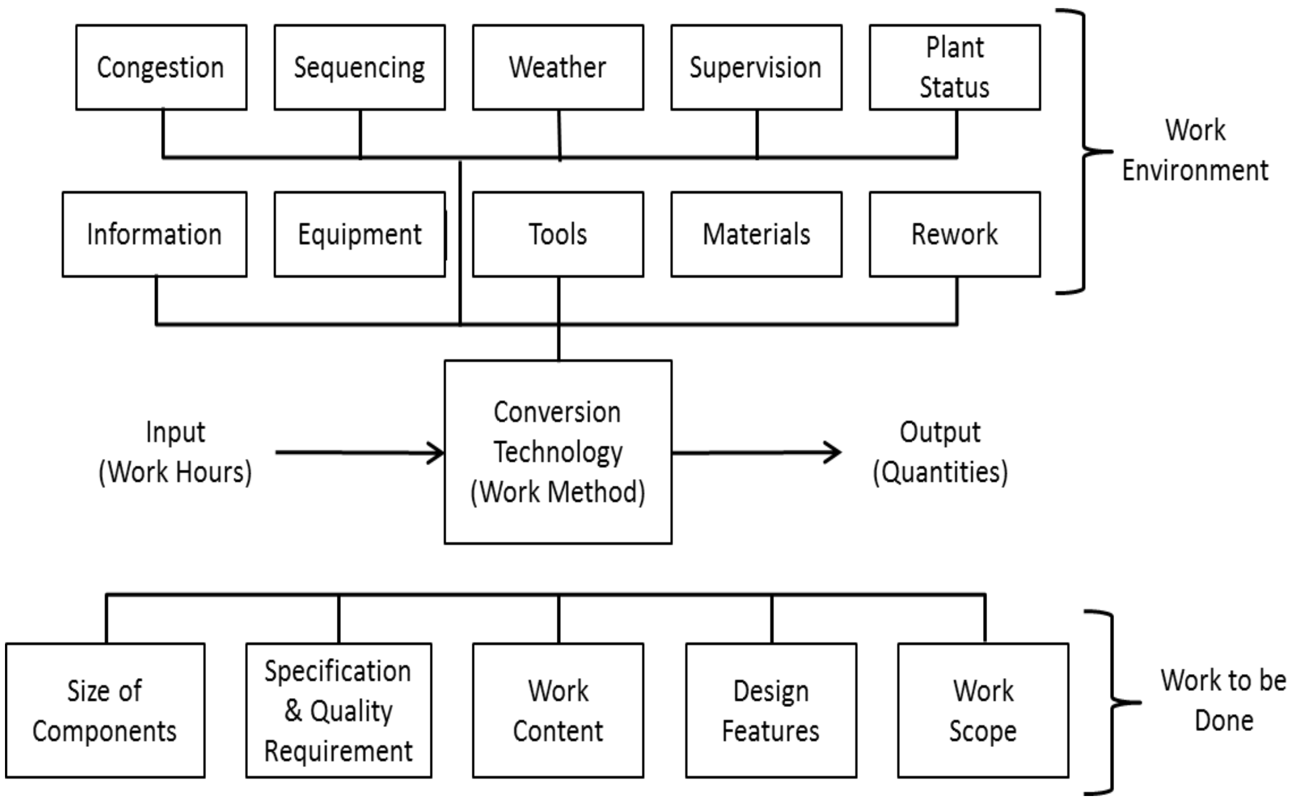


Figure 2.6: Factor Model, Thomas et al (1990).

This model is different from previous models as it focuses on productivity at the crew level and mathematically calculates the actual productivity considering the most common factors affecting the crew productivity. It is similar to the method productivity delay model where both attempt to account for the factors which affect the productivity and then predict the actual productivity. Both models attempt to improve the performance of crews by focusing on the crew productivity but lacked the consideration of interdependencies existing among crews or the variation in the flow of work within the crew.

2.3.6 Conceptual Construction Process Model

To overcome the limitations of the previous models, Sanvido (1988) extended the control model (Sanvido, 1984) focusing on the functions that a crew must perform and the management support needed to perform that particular work. The CCPM (Sanvido, 1988), shown in Figure 2.7, introduced the following features to improve the productivity and performance of site construction operations: (1) definition of the basic tasks of the crew and the input resources required by them; (2) identification of interrelationships between different functions involved in supporting the field construction process and specification of rules to govern their performance; (3) definition of the scope and boundaries of the on-site construction process; and (4) categorization of external influences on the construction process that are beyond the control of the site personnel. One of the other features where this model differs from the Alexander's (1974) model is that here the control function is performed by the crew and supervisors and not by some automatic controller. In the CCPM, the craftsman/crew worker has control over the process of taking the inputs and converting them to outputs. The transformation of inputs into outputs by the craftsman/crew worker is restricted by three main functions (Figure 2.7) such as (1) Influences on the supply of resources, (2) Influences on planning, (3) Influences of project on participants and environment.

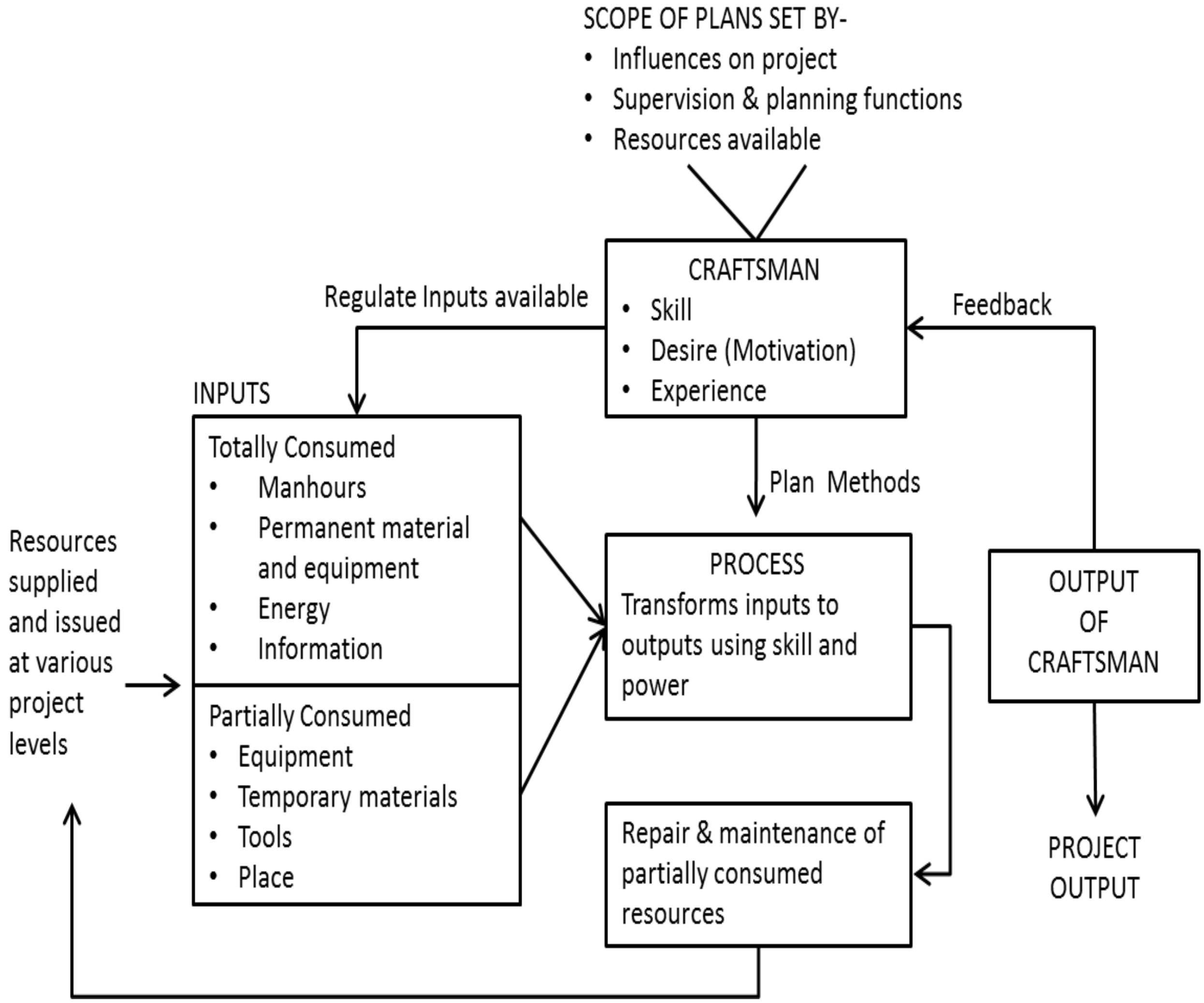


Figure 2.7: Conceptual Construction Process Model, Sanvido (1988)

The CCPM presented the structure of functions that should be performed on a project. The research showed that projects that better matched to the ideal case specified by the CCPM perform better in terms of schedule, cost, and quality than those who did not (Sanvido 1988). However, the research did not define the flow of resources for the operations, how these resources would be shared among the crew.

2.3.7 Integrated Building Process Model

Sanvido et al (1990) developed a hierarchical model known as Integrated Building Process Model (IBPM) to provide a generic representation of the building construction process from initial conception stage to the operations stage. This model is based on the Structure Analysis and Design Technique (SADT) which is a graphical language consisting of a set of boxes, each of which represents a conversion process (Kartam et al. 1997). This model provides the primary function "Provide Facility" which is divided into five main sub-processes such as Plan Facility, Design Facility, Construct Facility, Operate Facility and Manage Facility defining the initial hierarchical structure of this model. Each of the process consists of four main elements such as input, control, mechanism and output representing the conversion process associated with that process (Figure 2.8).

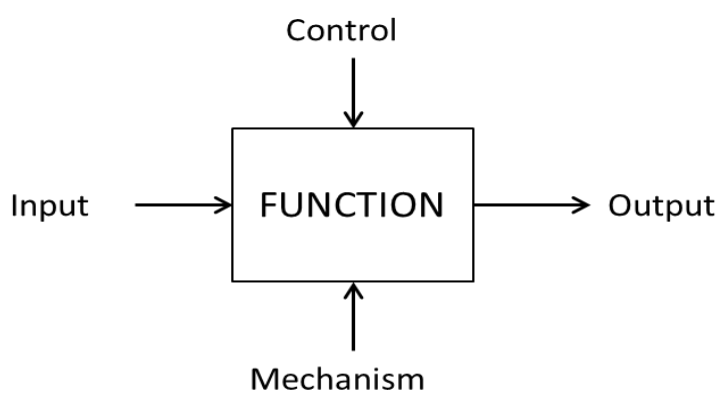


Figure 2.8: Schematic representation of the Function Box, Chung (1989)

The IBPM has its advantages over the other models such as conversion model (Alexander 1974, Walker 1985) and the control model (Sanvido 1984) in terms that it covers the building construction process from initial conception stage to the operations stage in detail and also by including control and mechanism elements apart from just the input/output elements. However it provides a broad overview of the construction process and lacks the consideration for the sub-processes at the operational, activity or task level. Also, consideration for formation and operational processes of the crew is not defined.

2.3.8 Flow Process Model

Koskela (1992) developed the Flow Process Model (Figure 2.9) where construction operations were considered not just as a conversion of inputs into outputs but as flow of resources such as material and/or information from the starting to the end product. The model was proposed to cover all the important features of the production process and overcome the limitations of the conversion model.

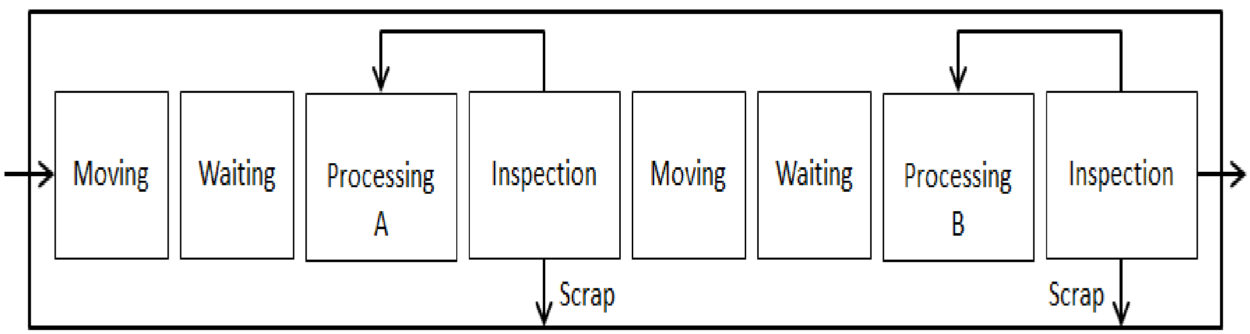


Figure 2.9: Flow process model, Koskela (1992)

According to Koskela (1992), in the production process, material and/or information goes through a number of other functions/activities such as waiting, inspection, or movement apart from the traditional view of being just processed (i.e. conversion or transformation); however these functions/activities are inherently different and have not been addressed in the earlier construction models. The processing activities fall under the conversion aspect of production whereas inspecting, moving and waiting fall under the flow aspect of production. In the flow process model, any activities other than processing, such as moving, waiting, inspection etc. are considered as waste not adding any value to the project. The flow process model is a good model for the representing the production process, however, it does not take into account the system concept and lacks the feedback and interdependencies existing in the production process. Also, it focuses more on the flow of resources such as material and/or information being processed but the reasons for the variation in the performance of the crews and the reasons for the inherent waste in the crews executing these activities hasn't been discussed.

2.3.9 The Last Planner® System

The Last Planner® System was introduced by Ballard and Howell (1997) to overcome the limitations of the conversion process models and traditional project management practices to coordinate and control the field production process (Figure 2.10).

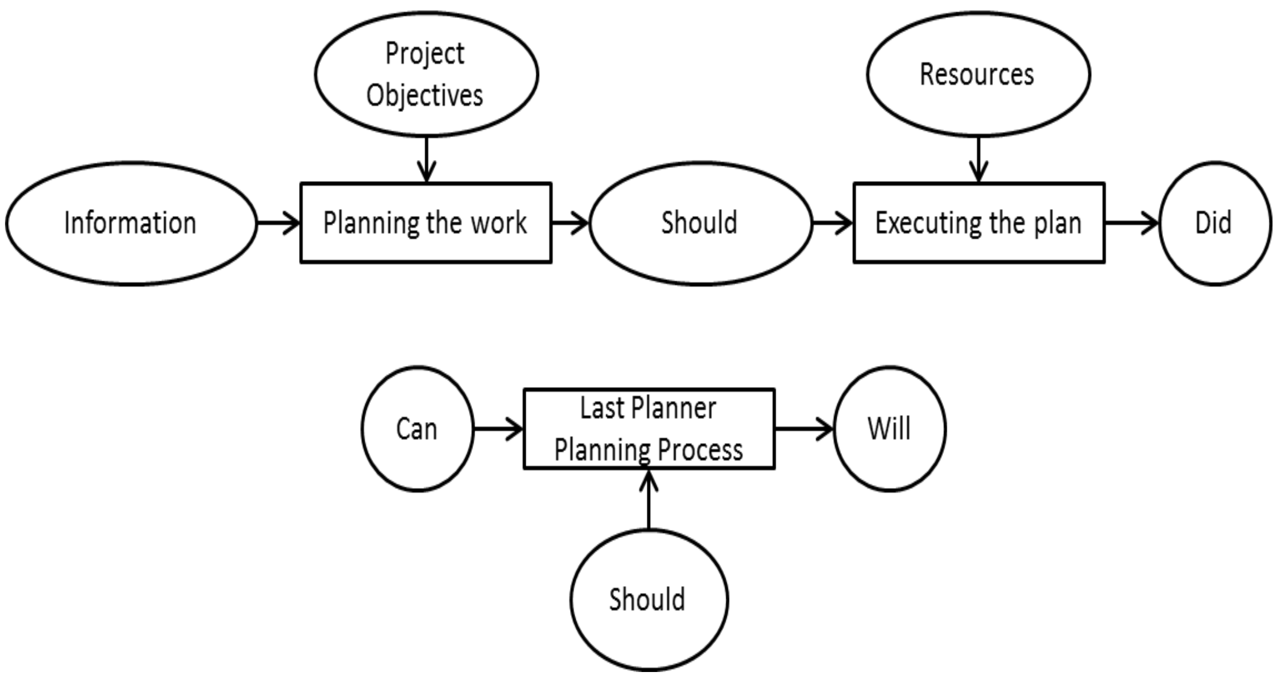


Figure 2.10: Traditional PM Vs. Last Planner system, Ballard and Howell (1997)

This system was implemented to stabilize the production work environment by reducing the upstream variation and management uncertainty. Due to the huge gap, almost 50%, between the number of planned activities that SHOULD be done to those which are actually DONE, Ballard and Howell (1997) suggested that the traditional project management practice of planning & controlling the work should be modified from “Should-Did” to “Should-Can-Will”. They argued that differentiating between what SHOULD be done and what CAN be done is of importance in order to improve the reliability of plans.

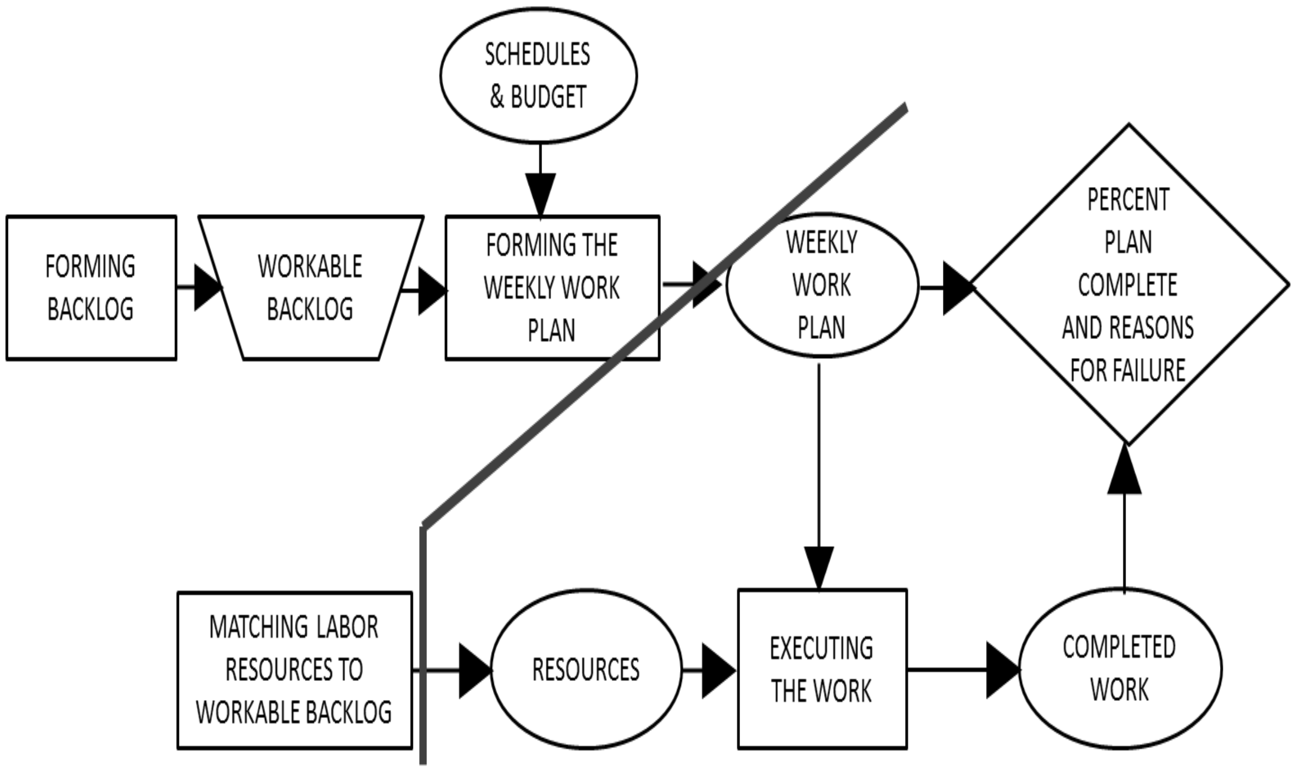


Figure 2.11: Last Planner® System, Ballard and Howell (1997)

Moreover, allowing the task performers, last planners, to commit to work that can be done, i.e., going from CAN to WILL, the opportunity to reflect the most up-to-date information about the project at the production level instead of over committing to work that will not be completed yet expected by downstream trades. In the Last Planner® System , Make-Ready (look ahead) schedules are developed for the upcoming 5-6 weeks by selecting assignments/work packages from the master/phase schedule that was prepared jointly by the construction manager and the involved trade partners. The assignments from the make-ready schedule which are cleared with respect to resources, directives and pre-requisite work constraints are then selected to be included in the weekly work plans. The rest of the assignments, enter a workable backlog to be considered for next week work plans. At the end of each week once the work is executed, the weekly work plan is then compared with the actual work completed to determine any reasons for a low percent plan complete (PPC). PPC is defined as the ratio of the number of activities completed to the total number of activities on the weekly work plan. This model has gained a lot of acceptance due to its simple conception and successful implementations. It is a preferred system to coordinate and control the field production process by stabilizing the work flow. However, it still lacks the consideration for how the crews should be designed and the work flow variation which could exist due to interactions existing within the crews.

2.3.10 Construction Process Analysis model (CPA)

This CPA model was proposed by Lee et al (1999) to identify and quantify waste in the construction operations by analyzing the work processes. It implements process charts and top-view flow diagrams common among process analysis techniques (Parker and Oglesby 1972).

The simple charts and diagrams used in this model are based on the standardized symbols under Japanese Industrial Standards JIS Z 8206, effectively describing the flow of processes in order to quickly determine the existing problem areas in the process Lee et al (1999). The basic symbols used in the CPA model include Operation, Transportation, Storage, Delay, Volume Inspection, and Quality. The process charts are used to record the steps of the construction operation and the flow occurring within each unit, section etc. And flow diagrams are used to supplement the process flow charts by observing the layout diagrams of the area in which that process flows.

2.4 Existing Crew and Work Analysis

A significant amount of the research on crew and work analysis has been focused on productivity studies and time and motion studies (work-study), work observation and activity sampling. The focus of these studies has been to improve the performance of crews and optimize construction operations. These studies determine the factors affecting the crew performance and then suggest implementing corrective measures.

Productivity has been widely perceived to play a major role in affecting the performance of crews. Higher productivity levels are considered to increase the performance of the crews and hence productivity studies have been used to improve the low productivity within a crew. Extensive amount of research (Adrian and Boyer 1976; Maloney 1983; Oglesby et al. 1989; Thomas and Yiakoumis 1987; Diekmann and Heinz 2001; Dai et al 2009) has been conducted to determine the factors affecting labor productivity. Listing these factors would easily run into 100 plus factors.

Adrian and Boyer (1976) classified construction productivity factors into five major types: environmental, equipment, labor, material, and management. According to Maloney (1983), labor motivation and performance factors have a significant influence on construction productivity. He discussed how driving, induced, and restraining forces act on the construction workers to affect their level of productivity. Maloney (1983) presented four major labor factors influencing the productivity: (1) The intensity of the individual worker's effort; (2) the duration of that effort; (3) the effectiveness with which the worker's effort is combined with technology and other resources; and (4) the overall efficiency with which these inputs are translated into usable outputs of acceptable quality.

Thomas and Yiakoumis (1987) developed a factor model to forecast the crew performance by determining factors disturbing the crew performance. The factors affecting productivity were divided into four groups: (1) Environmental factors; (2) Site factors; (3) Management factors; (4) Design factors. The model was developed to improve productivity for repetitive construction operations. The factor model recognizes that the labor productivity is not constant and varies over time in a unique way but assumes it can be predicted because it takes different amount of resources to complete different activities. Thomas and Sakarcan (1994) classified the factors affecting construction productivity into two main groups: (1) Work to be done factors such as work scope, work content, design features etc. and (2) Environmental factors such as congestion, sequencing, equipment, material etc.

To estimate productivity rates with a higher degree of accuracy, Herbsman and Ellis (1990) developed a statistical model to better illustrate the quantitative relationships existing between the influencing factors and productivity rates. Productivity factors were divided into two main groups such as technological factors and administrative factors based on the interviews with the industry.

Liberda et al (2003) made a broad classification of factors in terms of human, external and management issues that affect construction productivity and presented 51 major productivity influencing factors. The factors presented were prioritized along with identifying measurement criteria to improve future construction projects. Based on industry interviews, Liberda et al (2003) identified management as the most influential factor affecting labor productivity. Dai et al (2009) also developed factors affecting productivity from the construction craft workers perspective by conducting a nationwide survey. The survey quantified the relative impact of 83 productivity factors showing that the factors involving tools and consumables, materials, engineering drawing management and construction equipment have the greatest impact on productivity. Latent factors representing the underlying structure of these 83 productivity factors were identified in this study. The results were further compared to similar previous efforts identifying significant differences that may impact future productivity improvement strategies.

Among other productivity studies, the effects of scheduled overtime on labor productivity have been examined in the past (Oglesby et al. 1989; Thomas 1992; Thomas and Raynar 1997). These studies described how the productivity data were collected, processed, and analyzed. It was shown that as the number of hours of overtime increased to 50-60 hour weeks, there was a 10-15% loss in the efficiency which was comparable to other published data including Business Roundtable (BRT) curves. Also, it was concluded that the losses of efficiency are caused by the inability to provide materials, tools, equipment, and information at an accelerated rate.

Thomas and Napolitan (1995) and Hanna et al. (1999) documented the effect of changes in construction on labor efficiency. It was found from these studies that lower labor efficiency is strongly related to the presence of change work, disruptions and rework and on an average 30% loss of efficiency occurs when change orders happen in the construction. Among the few disruptions quantified such as sequencing, information availability, material availability, equipment availability, and tool availability, lack of material availability was found to be the most serious disruptions of all.

Thomas et al (1990) defined work study as the systematic study of work systems for the purposes of finding and standardizing the least-cost method, determining standard times, and assisting in training in the preferred method. Work study could also be called time-and-motion study (Barnes 1980). A work study is composed of 2 main interrelated methods such as (1) a work-methods study (also known as motion study) and (2) a work-measurement study (also known as time study). The relationship between the two methods has been shown in the Figure 2.12.

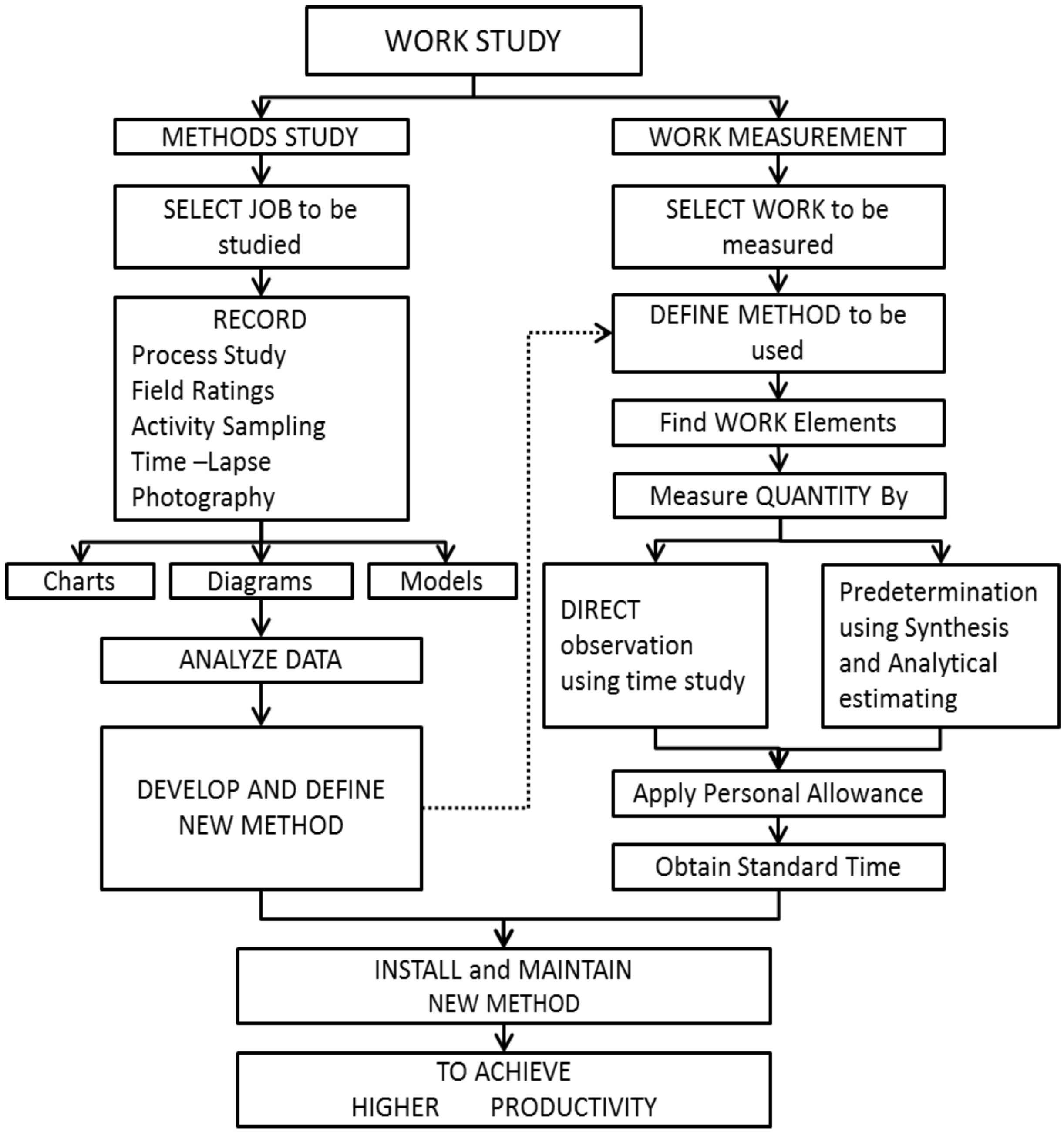


Figure 2.12: Work Study Process, Drewin (1985)

The work-methods study or motion study is used to determine the best method of doing a work/task whereas work-measurement study or time study involves determining the standard time to perform a certain work/task. Both methods originate from industrial engineering and involve in-depth examination of the production process (Thomas et al 1990). Thomas et al. (1990) proposed three labor productivity models based on the work-study concepts to be implemented at crew-level operations. These models were classified as delay model, activity model, and task model. And to implement these models as labor productivity models, three fundamental assumptions must be met (Thomas et al 1990): (1) productive time and delay times are related and hence reducing delays will increase productive time; (2) productive time is related to output and productivity and hence knowing productive time, production output can be calculated; (3) waiting time is related to productivity and hence productivity is improved as waiting time is reduced. The three labor productivity models proposed by Thomas et al (1990) are discussed below:

1. Delay Model

The delay model is a very simple model. To quantify productive time and delays happening on the site, a work day in this model is divided into three parts to record instances of delays. Graphical representation of the delay model is shown in Figure 2.13.

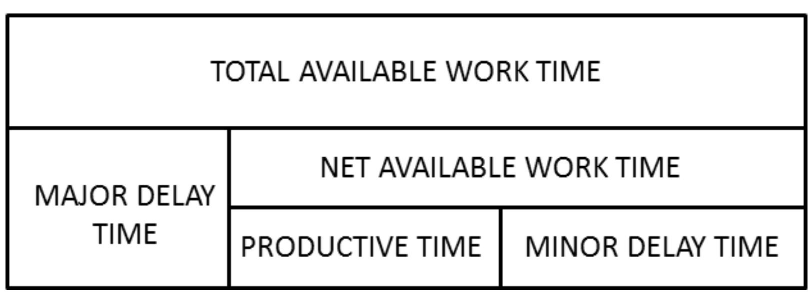


Figure 2.13: Graphical representation of Delay Model (Bernard et al. 1973)

Thomas et al (1990) suggested that application of this model to most labor-intensive processes is not feasible or difficult as the output-productive time relationship, even for simple operations, is very complex.

2. Activity Model

To measure the time spent on various activities, work measurement technique such as work observation, activity sampling or work sampling are employed. The activity model (Figure 2.14) is a simple model based on these work measurement techniques (Thomas and Daily 1983; Thomas et al. 1984; Liou and Borcherding 1986). This method can be applied to labor-intensive activities to measure the time utilizations of the labor but it is only an indirect measure of the actual productivity, since there is no measure of the output (Thomas 1981).

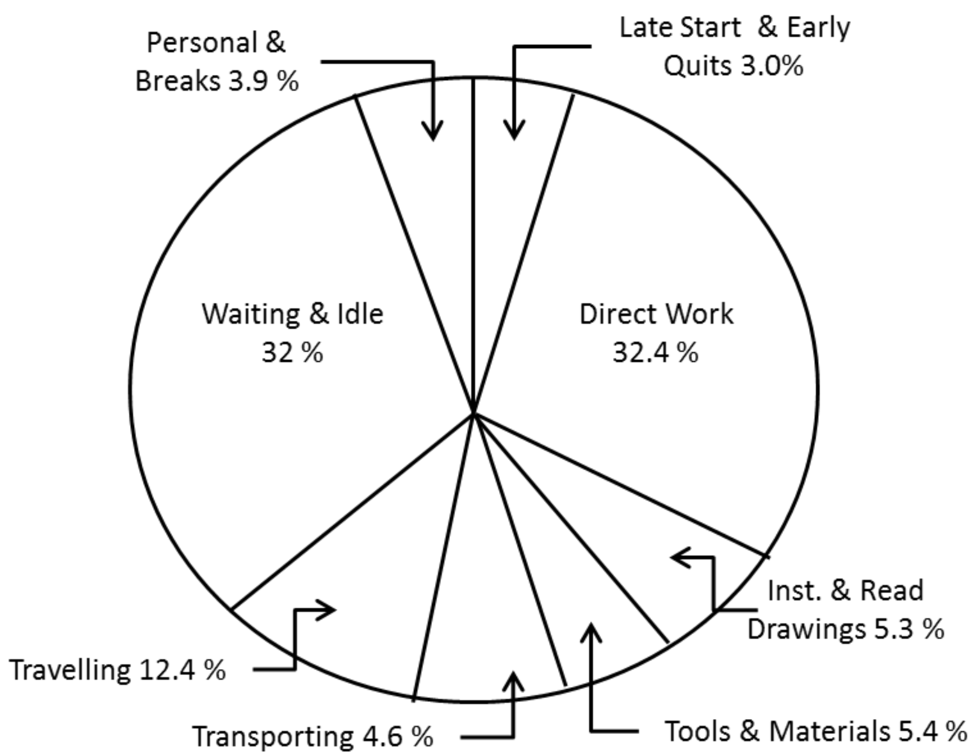


Figure 2.14: Graphical representation of Activity Model (Thomas et al. 1983)

Also, various studies have shown that activity model cannot be considered as a valid productivity model, as the direct work time and output are unrelated to each other (Thomas 1981; Thomas et al 1983). This was also supplemented by Rogge et al (1982) who presented data showing that productivity and waiting time are only somewhat related. As work sampling focuses more on the measurement of time utilizations for individual worker rather than a crew; direct work can be considered as a measure of individual worker activity, and not the productivity itself (Thomas et al 1983).

3. Task Model

The Task Model extends from the previous delay and activity models and was developed by researchers at Loughborough University, England. This model introduced the concept of dividing the work/tasks according to their importance or necessity; certain activities are considered as basic or necessary, others are additional but necessary, and a third group are unnecessary (Thomas et al. 1983).

A number of analysis methods have been implemented in construction for crew and work analysis. Job analysis is an important aspect of any design or redesign process. Morgeson and Campion (1997) defined job analysis as the number of systematic techniques for collecting and making judgments about the job information. Information derived from job analysis can be used to make informed decisions about the design process; can be used to make selection decisions, determine training and development needs develop performance appraisal systems, as well as to analyze various tasks and jobs (Morgeson et al 2006). According to Morgeson et al (2006), job analysis may also focus on tasks, worker characteristics, worker functions, work fields, working conditions, tools and methods, products and services etc. Some of the common methods for job analysis presented by Morgeson (2006) are briefly discussed below:

1. Interviews
2. Questionnaire
3. Checklists
4. Critical Incidents Reporting

5. Work Observation & Activity Sampling
6. Variance Analysis
7. Time & Motion Studies
    - Process Charts
    - Flow Diagrams
    - Possibility Guides
    - Network Diagrams
8. Linkage Analysis

Interviews with job experts such as the field personnel involving the supervisors and workers are often the first step towards a better crew design. During such meetings, important information such as duties, tasks, skills, knowledge is collected and used for optimizing the field operations. The questionnaire format is adopted where information needs to be collected from a large number of people. Questionnaire are constructed and used to collect judgments about the way the work is being done and how could it be improved. Checklists are a quicker method of getting job information from the field personnel.

Critical incidents method focuses on incidents which happen or might happen on the job site affecting the construction operation performance. They emphasize on the worker behavior that are ineffective or effective in the outcome of the operations. Work Observation & Activity Sampling are important form of observation methods which at times needs to be implemented where job analysis demands actual observation of the work performed. More sophisticated methods involve statistical sampling of work activities. Variance analysis is a tool of socio-technical design used to identify areas of uncertainty in a production process. The variance concept is applied to technical systems and involves five steps (Davis and Wacker, 1982):

1. List variances that could impede the production or service process.
2. Identify causals relationship among variables.
3. Identify and focus on key variances whose control is most critical to successful outcomes.
4. Construct a table of key variance control that contains a brief description of variances.
5. Construct a table of skills, knowledge, information and authority needed so that workers can control key variances.

Time and motion studies include tools such as Process Charts, Flow Diagrams, Possibility Guides, and Network Diagrams help the design engineers visualize operations in the study or design of job in order to improve efficiency. Process charts graphically represent separate steps or event that occurs during performance of a task. Flow diagrams differ from process charts because they utilize drawings in which an activity takes place. Lines between the symbols help to show the path of travel. Possibility guides help in examining consequences of suggestions to aid in selecting the most feasible changes. Network Diagrams are used where there are a lot of complexities such as (a) dependencies are tangled, (b) output has many components, (c) process is too complex. Finally, linkage analysis is used to determine the various linkages present among the components in an operation/process. Links can be classified into three types such (a) communication links, (b) control links, (c) movement links.

The brief review of the previous research on productivity studies is not meant to be exhaustive here; rather the review aim is to demonstrate the state of productivity research conducted to optimize crew performance. Productivity studies are appropriate to improve low productivity issues in construction and they also contribute in the knowledge of the various factors affecting the labor productivity or low labor efficiency. However, the current productivity models are implemented in isolation of each other, and at times only considering a few or single productivity factors. In addition, these studies do not model the crew or provide knowledge about how a crew should be choreographed in terms of crew structure, crew size, crew multi-skilling, how the work-flow is to be designed within a crew.

Formation of a crew is a consequential process, and it should not be designed based on ad-hoc basis. A crew design model or guidelines based on lean principles such as pride in final product, waste reduction, learning, labor utilizations, and pull systems should be explored.

2.5 Existing Production System Theories

2.5.1 Theory of constraints

Theory of constraints is an approach developed for the manufacturing industry for improving manufacturing operations. It focuses on managing a process or a series of manufacturing or production steps required to create a product. The Theory of Constraints (or TOC for short) also evaluates how projects are managed as well as provide estimates of completion, amount of safety stock included and where buffers should be located. The five basic TOC are (Goldratt 1997):

1. IDENTIFY the system’s constraints.
2. EXPLOIT the system’s constraints.
3. SUBORDINATE everything else to the above decision.
4. ELEVATE the system’s constraints.
5. GOTO step one again.

By following these steps, bottlenecks could be identified in a process. This bottleneck could either be an activity or a resource (person or equipment). By identifying the bottleneck, the rest of the production process is managed to the capacity of the bottleneck or the bottleneck’s production capacity is increased thereby removing that bottleneck. The bottleneck activity's schedule is detailed to minimize any disruptions or impacts on downstream activities.

Using TOC results in less amounts of inventory pileup, and identification of where to focus efforts to increase production capacity, remove bottlenecks and thereby maximizing the performance operations. In the context of construction operations and the crews executing them, operations would not be optimized unless performance of all the workers in the crew is increased or at least limited to only a very small part of the crew. It is worth noting also that the workers which are working or executing sequential operations with interdependencies cannot finish the whole operation or work faster than the slowest worker in that crew. And if capital is spent on improving activities that are not bottlenecks, it will not optimize the system but only lead to waste.

2.5.2 Lean Production Theory

Lean Production is a production practice developed for manufacturing, primarily aimed at shortening the time from order to delivery by eliminating waste in the entire production system. Any expenditure of resources which does not add value for the customer is considered waste. Lean Production as presented by Womack et al. (1990) states that "Lean Production is 'lean' because it uses less of everything compared with mass production: half the human effort in the factory, half the manufacturing space, half the investments in tools, half the engineering hours to develop a new product in half the time". The principles of Lean thinking as presented by Womack and Jones (1996) are:

1. Specify value for the customer
2. Identify the value stream, and remove non-value added steps
3. Make the remaining value adding steps flow

4. Let the customer pull the product
5. Pursue perfection through standardization & continuous improvement

Lean production method has revolutionized operations not only for the manufacturing industry but also for other production and service industries such as construction, banking, insurance, and medical.

2.5.2.1 Toyota Production System

Lean production philosophy was derived mostly from the Toyota Production System (TPS) (Shingo 1989; Ohno 1988). The simple concept of elimination of unnecessary inventory and waste to simultaneously achieve high quality, low cost and deliver maximum value to the end customer is at the heart of TPS (Monden 1983; Shingo 1989; Ohno 1988).

According to Taiichi Ohno, the main focus of the TPS was "the absolute elimination of waste," where waste is anything that prevents the value-added flow of material from raw material to finished goods. Also, according to sensei Shigeo Shingo (1989) the significant principle and unique feature of the Toyota Production System lies in the following:

1. Eliminating unnecessary inventory.
2. Total elimination of waste
3. Relentless efforts made to cut man-power costs.

The TPS aims to reduce overburden (muri) and inconsistency (mura), and eliminate waste (muda) in the production system. The seven commonly defined wastes in the Toyota Production System (TPS) are:

1. Over-production;
2. Waiting;

3. Transport;
4. Over-processing;
5. Unnecessary inventory;
6. Unnecessary motion;
7. Defects.

Overproduction is considered to be the most serious and worst waste of all, as it leads to the disruption of continuous flow of products or material. Over-production encourages the push of products down the line, which results in extra in-process inventory and excessive work-in-progress. As a result, more pressure on the work rate generates leading to overburden (muri) and inconsistency (mura). In addition, overproduction may also lead to more number of defective products down the line.

Waiting takes place whenever products or material are not being processed or worked on. Also, the idle time spent by the workers waiting for the machine to complete an operation or waiting for the next batch of material to process is considered as a waste.

Transport, involves the movement of materials, labor or equipment over distances in a production process. Transportation does not add any actual value to the final product, and hence any unnecessary or excessive transport should be considered as a waste. Unnecessary transport adds extra time to the operations and therefore should be avoided.

Over-processing occurs when extra steps or processes are employed to carry out an operation than required to deliver value. In addition, it involves any complex solutions used where simple solutions would work. Any non-value added steps in an operation are considered as a waste.

Unnecessary Inventory involves any raw material or work-in-progress that is not being processed or has not been converted to a finished product providing value to the end customer. Excessive in-process inventory may lead to overburden among the workers and low quality. In addition, excess inventory requires more transportation and more storage space and may get damaged before being processed.

Unnecessary Motion involves any movement of labor, equipment or material which does not add value to the product directly. The movements of the workers to process a material or while using equipment should be simple and any complex movements which may lead to poor productivity or low quality of the product should be avoided.

Defects are the direct source of investing extra capital to re-do the work. They could occur due to various problems or due to the presence of other types of wastes in the system.

Further, apart from these seven common types of waste (non-value added waste) known as "muda", TPS also identified the negative impacts of "mura" and "muri". Mura results from inconsistency or unevenness in the system and "muri" occurs when there is overburden on the labor or equipment. Presence of inconsistency or unevenness in the system may also lead to the need of keeping extra buffers in the system to encourage continuous flow and avoiding any disruptions to the work. Also, as compared to the "muda" of idleness or waiting, "muri" creates the potential for safety or quality failures as people or machines are pushed beyond their limits (Lichtig et al 2005).

In TPS, "process" and "operation" have very specific meanings. Knowledge of how to improve a process or operation is of value in order to design a crew executing a job. In TPS, as defined by Shingo (1989):

> “a process is a flow of material in time and space; a transformation from raw material to semi-processed components to finished product whereas, operations are the work or actions performed to accomplish this transformation; the interaction and flow of equipment and operators in time and space”.

Process Improvement

To maximize production efficiency, TPS emphasizes analyzing and improving the “process” before improving the “operations”. Shingo (1989) defines four distinct types of “process” elements: (1) processing, (2) inspection, (3) transport, and (4) delay.

“Processing” improvement is achieved by first redesigning the product to reduce manufacturing costs while maintaining the required quality and then improving the manufacturing process of the product itself.

Three types of *“Inspections”* are defined in TPS in order to maintain quality, reduce defective products and save time and capital on rework. These are successive inspection, source inspection and enhanced inspection. Successive inspection involves workers inspecting the products passed to them from previous operation before processing them themselves; implementing successive inspection on average could reduce the number of defects by 80-90% Shingo (1989). Source inspections are also of value as they help in preventing the defects by controlling the conditions at their source. Finally, enhanced inspections are best at providing the fastest feedback; they involve the use of devices for automatically detecting the defects. These devices are also known as “poka-yoke” or "mistake-proofing" devices. The three types of “poka-yoke” control methods identified in the TPS (Shingo 1989) include:

1. Contact method - identify defects by whether or not contact is established between the device and some feature of the product's shape or dimension
2. Fixed value method - determines whether a given number of movements have been made
3. Motion step method - determines whether the established steps or motions of a procedure are followed

The above inspection methods identified in the TPS leads to up to 100% reductions in the number of defects occurring in an operation, faster feedback for the mistakes, reduction in the amount of rework required and hence saves both time and capital. Therefore, while designing a crew, consideration for incorporating these inspection methods should be made in order to improve a “process” and hence improving crew performance.

TPS identifies the need to reduce process element such as *“Transport”* as much as possible, as it does not add any real value to the finished product. Shingo (1989) discusses how improving the layout of the process accounts for real elimination of the transport function. He explains that “transport improvement” and “transport operation improvement” are two distinctly different problems and that unavoidable transport work should be improved through mechanization only after opportunities for layout improvement have been exhausted.

Finally, Shingo (1989) presents three storage types that lead to unnecessary *“Delays”* in the process. Process delays occur due to unprocessed items waiting to be processed and also due to the accumulated extra inventory that is waiting in line to be processed or delivered. To improve a “process” following accumulations between the processes should be reduced or eliminated:

1. E (engineering) storage – this results from the unbalanced flow between processes and can be eliminated by leveling the flow of items to match the output of all the processes.

Elimination of this storage would lead to continuous flow and reduction of any inventory piling up.

2. C (control) storage – this results from the need of buffer or cushion stocks to avoid any delay in the subsequent processes which may happen due to failure of machine or equipment and any rejects or major defects that may happen down the line. This storage can be reduced by employing better inspection processes to avoid any rejects or defective work.
3. S (safety) storage – this results from the presence of over-producing beyond what is needed for the control storage. Safety stock is useful to guard against any scheduling errors, delay in delivery, damage to raw materials etc.

Operations Improvement

In TPS, "operations" are defined as the work or actions performed to accomplish the transformation of raw material to semi-processed components to finished product. It involves the interaction and flow of equipment and operators in time and space (Shingo 1989). In TPS, the operations are improved by reducing or eliminating the waste present among the workers and the equipment.

For example, waste of overproduction could be due to over staffing of workers and producing more than required; this waste can be reduced by better managing the workers and designing a crew in a way not leading to this waste. Also, waste of over-processing among the workers and equipment can be reduced by eliminating any extra or complex steps that workers or the equipment might be doing while executing the operations. Further, reduction of unnecessary motion or transport would also lead to improving the operations. As the cost of workers waiting is generally more than the idle machine or equipment cost, TPS aims to reduce labor cost by improving worker motions, improving machine or equipment motions, and mechanizing worker motions and thereby improving the overall “operations”.

In addition to removing overburden (muri) and inconsistency (mura) and waste (muda) to improve the “operations”, Shingo (1989) mentions that the easiest way to improve the operations is to separate the workers from the machine; following the "one worker, many process" theory. TPS also emphasizes the concept of “multi-skilling” where one worker is not fixed to a single machine or process, but is attending or operating other machines also. This is also supported by the use of the “Nagara System” in TPS, where a worker performs more than one process at a time by automating a number of processes. This results in reducing the waiting time, increasing the productivity and reductions in labor cost. Hence “multi-skilling” is an important aspect for improving operations and should be considered while designing crews for operations.

Further, various research efforts (e.g. Ohno 1988, Shingo 1989; Koskela 1992; Howell 1999; Liker 2004) have defined and listed the lean production principles in different formats and level of detail. For the purpose of this research, the most recent and simple grouping of the lean production principles were considered and combined together to form crew design guidelines.

2.5.2.2 Application to Construction

2.5.2.2.1 Lean Construction

The application of above discussed production theories such as Theory of Constraints (Goldratt 1997) and Lean Production (Ohno 1988; Shingo 1989; Womack et al. 1990; Womack and Jones 1996) has demonstrated significant improvements in the performance and quality for the manufacturing industry. Lean production has caused a revolution in the manufacturing and when this production theory is applied to construction, it changes the way work is done throughout the delivery process (LCI 2007).

The term "Lean Construction" was coined in 1993 by the International Group for Lean Construction in its first meeting (Gleeson et al. 2007). According to Lean Construction Institute, “Lean Construction is a production management-based approach to project delivery -- a new way to design and build capital facilities”. Lean construction is a “way to design production systems to minimize waste of materials, time, and effort in order to generate the maximum possible amount of value” (Koskela et al. 2002).

Another definition by Abdelhamid (2004) states that “Lean Construction is holistic facility design and delivery philosophy with an overarching aim of maximizing value to all stakeholders through systematic, synergistic, and continuous improvements in the contractual arrangements, the product design, the construction process design and methods selection, the supply chain, and the workflow reliability of site operations”.

As noted by Abdelhamid (2008), “while Lean Construction is identical to Lean Production in spirit; it is different in how it was conceived as well how it is practiced”. Also, the inherent characteristics of the construction industry have been identified as a challenge to transfer all the concepts of lean production to construction (Tommelein 1998). However, both the lean production and lean construction conform to the Socio-Technical construct (Niepce and Molleman 1998) where both the human and technical elements work together to ensure higher performance outcomes (Moore 2002). Lean Construction is the result of combining the existing research in construction with an adaption of Lean Production principles and practices.

Despite the challenges to implement Lean Production to construction as a whole, certain parallels can be made between the two industries. Similarities can be found in the production process of manufacturing and construction. The conceptual basis for construction management is the same as that of manufacturing, i.e. it is conversion oriented (Koskela 1992). For example, in both settings, conversion of raw materials into finished products by expenditure of resources over certain period of time takes place.

As in manufacturing, the conversion process in construction also generates a lot of waste, making possible opportunities to apply the lean production principles to generate value by eliminating the inherent waste in the process. This is supplemented by two similar characteristics identified by Sanvido and Medeiros (1990): (1) they both produce engineered products that provide a service to the user; (2) they both may include processing of raw materials and assembly of many diverse pre-manufactured components in the final product.

The conventional theory of production and operations management both in manufacturing and construction has been based on conversion of inputs into outputs or the transformation view (Koskela 1992). However, in manufacturing since the adoption of the new production philosophy based on the transformation and flow perspective embodied in Lean Production (TPS), significant improvements in performance have been realized.

On the other hand, the construction industry is still facing an ongoing challenge of improving the performance of projects at the production level. Koskela’s seminal 1992 report argued that conventional Construction Management has focused for many years on improving project performance by primarily focusing on project management techniques that rely on transformation-based philosophy or the conversion model where the main focus is on transforming inputs to outputs with typically no management of the transformation process itself (Abdelhamid 2004).

Production based on the transformation-based philosophy or the conversion model can be defined as follows (Koskela 1992):

1. A production process is a conversion of an input to an output.
2. The conversion process can be divided into sub-processes, which are also conversion processes.
3. The cost of the total process can be minimized by minimizing the cost of each sub-process.
4. The value of the output of a process is associated with costs (or value) of inputs to that process.

However, Koskela (1992) states that “the conversion process model, as applied to analyze and manage productive operations, is misleading or even false.” This is supported by the arguments provided by Ohno (1988) and Shingo (1989) that the conversion model neglects the overall flow and value generation in a process. In the conversion model, physical flow between the conversions is not considered; even the non-value-adding activities such as waiting, moving and inspections, etc., are considered inseparable from the conversion process.

To overcome the limitations of the conversion model, Koskela (2000) presented the ‘TFV’ theory of production (Table 2.1) where the production was conceptualized in three complementary ways: (1) Transformation (T) of inputs into outputs; (2) Flow (F) of materials and information; (3) Value (V) generation for the customers. According to Koskela (2000), to improve productivity and optimize production, it is important to consider all aspects of production (transformation, flow and value).

Table 2.1: Integrated TFV view of production Koskela (2000)

	Transformation view	**Flow view**	**Value generation view**
Conceptualization of production	As a transformation of inputs into outputs	As a flow of material composed of transformation, inspection moving and waiting	As a process where value for the customer is created through fulfillment of his requirements
Main principles	Getting production realized efficiently	Elimination of waste (non value-adding activities)	Elimination of value loss (achieved value in relation to the best possible value)
Methods and practices (examples)	Work breakdown structure, MRP, Organizational Responsibility Chart	Continuous flow, pull production control, continuous improvement	Methods for requirements capture, Quality Function Deployment
Practical contribution	Taking care of what has to be done	Taking care that what is unnecessary is done as little as possible	Taking care that customer requirements are met in the best possible manner
Suggested name for the practical application of the view	Task management	Flow management	Value management

Further, conventional project management in construction is inadequate because it relies on the transformation theory or the conversion model rather than the TFV theoretical framework (Howell and Koskela 2000; Koskela and Howell 2001).

In the conventional scenario, a project is broken down into activities by using the work breakdown structure. Then, time and cost of each of these activities is calculated. Using critical-path network methods, the logical order of performing these activities is determined. In this scenario, all the activities are considered as value-adding activities which may not be true in practice. Activities are typically scheduled to start on the earliest possible start date and then project controls is applied to keep the schedule on track.

The practice as described completely ignores the flow of work within and between different activities and that controlling by tracking activity completion and accrued costs fails to assure reliable work flow (Howell and Ballard 1996; Koskela et al 2002). In addition, value is assumed to be delivered to the customer by delivering the project on time and within initial budget and providing the customer with the specified quality level. A notion of value delivery based on extending and expanding the construction client's needs is advocated in Lean Construction. According to Koskela et al (2002):

> "from the Lean Construction perspective, current practice rests on a defective model of the project, the work involved, and its control … it fails even in the attempt to manage activities and misses entirely the management of work flow, and creation and delivery of value".

The preceding observations have led to the birth of Lean Construction as a discipline that subsumes the transformation-dominated contemporary construction management and acknowledges the flow and value generation character of production (Abdelhamid 2004).

In Lean Construction, production system design serves the three main goals:

1. Produce a product in the most efficient way (Task management).
2. Eliminating waste (Flow management).
3. Maximizing value (Value management).

A main premise in achieving all three goals is the necessity of having reliable workflow. Arriving at high work flow reliability, a conceptual framework titled Lean Project Delivery System (LPDS™) was developed by the Lean Construction Institute (Ballard2000) to guide the implementation of Lean Construction on project-based production systems. Although all the parts of LPDS™ are crucial for success of a lean project, the heart of LPDS™ lies in Work Structuring and Production Control (Abdelhamid 2008).

Workflow is the movement of information and materials through the networks of production units (Ballard 1999; Ballard and Howell 1994). Koskela (1992 and 2000) provided some general principles for how a 'flow' process should be designed, controlled and improved in practice. Certain principles relevant to the crew design process are:

1 Reduce the share of non value-adding activities.

2 Reduce variability.

3 Reduce the cycle time.

4 Simplify by minimizing the number of steps, parts and linkages.

5 Increase output flexibility.

6 Increase process transparency.

7 Balance flow improvement with conversion improvement.

In Lean Construction, the concept of *work structuring* has been used to refer to the design of the production system; which is designed to "achieve the purposes of both their customers and those who 'deliver' the system" (Ballard, et al., 2001). Work structuring is the most fundamental level of process design, answering the questions (Ballard 1999):

1. In what chunks will work be assigned to specialist production units (PUs)?
2. How will work chunks be sequenced through various PUs?
3. In what chunks will work be released from one PU to the next?
4. Where will decoupling buffers be needed and how should they be sized?
5. When will the different chunks of work be done?

Work structuring encourages the design of the production process during the product design stage. Lean work structuring can be "accomplished using a myriad of tools such as BIM, Target Costing, set-based design, CPM, simulation, etc." (Abdelhamid 2008). Further, *work structuring* is a complex process and includes the following sub-processes (Ballard 1999) such as: (1) chunking; (2) sequencing; (3) releasing; (4) decoupling; (5) scheduling.

In the following section, lean principles and concepts aimed at the elimination of waste (muda), variability (mura), overburden (muri) and maximization of value in construction are reviewed.

2.5.2.2.2 Waste (Muda)

In a production process such as in construction, non-value-adding activities (waiting, moving, inspection etc.) have a considerable share and reducing them to improve the production process has been discussed at length in various studies (Koskela 1992; Koskela 2000; Ohno 1988; Shingo 1989; Womack and Jones 1996; Liker 2004). Further, Ballard et al (2001) extended the categorization of waste into *defective products, lack of flow, lost capacity, and avoidable cost* apart from the waste generated by *non-value adding activities* and the *activities other than processing*.

2.5.2.2.3 Variation (Mura)

Variation can be defined as the occurrence of output differences due to inconsistencies in the work methods. It typically exists when workflow is out of balance and workload is inconsistent. In simple terms, having zero variation would mean that the production process is completely reliable with a continuous flow of work whereas, high variation would lead to disruptions in the production process, creating unnecessary waste (Tommelein et al 1999, Abdelhamid and Everett 2002).

In the construction industry, lack of materials, late delivery, equipment breakdowns, tools malfunctions, defects, improper sizing & composition of the crew, improper crew utilization, schedule compression, etc., lead to variation and hence hampers the reliable work flow.

For example, the impact of work flow variation on the performance of construction trades has been successfully illustrated by "The Parade Game" (Tommelein and Howell 1999). It is a simulation of a construction process involving single line of processing stations where products output by one are input required by the next one.

The game shows that reduction of waste and shortening of project duration could be achieved by reducing the variation in work flow between trades. It was shown that variations leading to unreliable work flow results in two kinds of waste: (1) Production stations cannot realize their full production capacity due to starvation of resources; and (2) Intermediate buffers are larger when high variation prevails. Finally, it was also deduced that high variations in flow would result in reduction of throughput, delayed project completion, and increased waste.

It is generally accepted that variation in construction activity durations or production capacity may lead to increases in both the volume of non-value-adding activities and the cycle time (Koskela 1992). In addition, "*variation within a production process affects the performance and work flow reliability between the different processes* and in turn affecting the overall project performance," (Abdelhamid and Everett 2002). It is also worth noting that variation affects reliable workflow in any system that has processes and operations – whether it by a production system or a product design system.

A significant amount of research has been conducted on how to stabilize and improve work flow and the effects of flow variation in the production process (Howell and Ballard 1994; Ballard and Howell 1994; Ballard 1999; Ballard and Tommelein 1999; Tommelein and Howell 1999; Horman et al 2002; Liu and Ballard 2009). One of the essential features of these studies was how to ensure a continuous and reliable work flow. Improving work flow reliability is important for the productivity of linked production units, and consequently for project cost and duration (Liu and Ballard 2009). In a continuous flow process (CPF), work moves from one work station/production unit to another in a linear sequence. The main idea was to balance the processing rates of different work stations/production units to ensure a continuous and reliable work flow while only keeping a modest amount of work-in-process (WIP) in between production units. Continuous flow was achieved by reducing the resource idle time and WIP resulting in maximum overall throughput.

Ballard and Tommelein (1999) presented the following essential elements in balancing a production system to achieve continuous and reliable flow:

1. Adjust the crew sizes along with equipment and methods;
2. Redesign or restructure the operation;
3. Locate and size the in-line inventory buffers (output/in-process inventory)
4. Locate and size inventory buffers of delivered materials;
5. Locate and size capacity buffers.

Another study conducted by Zabelle and Ballard (1999) presented four simple tools to improve performance of fabricators serving the AEC industry through a flow driver process: (1) work mapping; (2) analysis; (3) compression and (4) prototyping. Steps to implement the compression tool are listed below:

1. Expand bottleneck capacities to increase system capacity.
2. Establish decoupling buffers before and after bottleneck processes to take best advantage of available system capacity
3. Implement pull techniques such as kanban or conwip to reduce work-in-process (WIP).
4. Reduce rework by implementing poka-yoke (mistake proofing) techniques.
5. Reduce transfer batch sizes.
6. Reduce process batch sizes where appropriate.
7. Organize production in cells using group technology and multi-skilled workers.

2.5.3 Sociotechnical System Theory

'Sociotechnical' (one word only) or 'Socio-Technical' (two words separated) is composed of two main words: (1) Socio (of people and society) and (2) technical (of machines and technology). Both variations mean the same; so should it be *Sociotechnical* System or *Socio-Technical System theory*? Walker et al (2008). Both terms either *Sociotechnical* (Cherns 1976; Emery 1978; Pasmore 1988; Niepcel and Molleman 1998; Clegg 2000) or *Socio-Technical* (Herbst 1974; Bostrom and Heinen 19777; Cummings 1979; Trist 1981) have been continuously used in organizational development literature and in practice can be been inferred as the same. But the precise meaning of each one of them and if there is a difference among the two remains unclear.

The term "Socio-Technical System" was created by researchers Eric Trist, Ken Bamforth and Fred Emery (Trist & K. Bamforth 1951; Trist 1960 and Emery) with a background in the behavioral sciences at the Tavistock Institute in London around the end of the 1950s. During the first decades of our century, a large amount of labor studies were conducted largely concerned with the adaptation of humans to the organizational and technical framework of production; however, there was a growing resistance of the workforce to the new technological systems.

The above researchers suggested that an organization was composed of two sub-systems namely social sub-system and technical sub-system; and that a proper fit of both the sub-systems was needed for achieving economic performance of the organization. When Socio-Technical system theory was first developed “it was seen by its creators as a means for optimizing the intelligence and skills of human beings and associating these with new technologies that would revolutionize the way we live and work” (Mumford 2006).

Sociotechnical refers to the interrelatedness of social sub-systems and technical sub-systems of an organization. The main goal of the socio-technical system theory is the “joint optimization” (Emery 1959), which states that for an organization to function optimally, both the social and the technical sub-systems of the organization should be designed to meet the demands of each other and the environment. The social sub-system of an organization is comprised of people and the relationships among them whereas the technical sub-system of an organization consists of tools, techniques, procedure, skills, knowledge and other devices used by the people of the social sub-system to achieve their goals (Trist & K. Bamforth 1951; Emery 1959; Pasmore 1978; Pasmore et al 1982; Cherns 1976).

One of the main concepts of Socio-Technical system is the notion of an “open system” perspective. This concept recognizes that for an organization to run and survive effectively over time it must thrive to interact with its surrounding environments and adapt to the changing environmental conditions. “The term *system* means that all parts of the organization are interrelated, so that the design of one necessarily effects the operation of another” (Pasmore et al 1982).

Sociotechnical theory is founded on two main principles: (1) the interaction of social and technical factors creates the conditions for successful (or unsuccessful) organizational performance; (2) optimization of each aspect alone, socio or technical tends to increase not only the quantity of unpredictable, ‘un-designed’ relationships, but those relationships that are injurious to the system’s performance.

In a Socio-Technical system, two types of interactions (linear and complex) between the two sub-systems is eminent, whenever these two sub-systems are put together to work in a system. The interactions could be of linear ‘cause and effect’ relationships that are normally ‘designed’ and partly from ‘non-linear’, complex, even unpredictable relationships that are often unexpected. The inevitable consequence of putting these two together results in growing complexity and interdependence; as the social subsystem (humans) do not behave in the same manner as the technical sub-systems (machines).

The features that scholars hypothesized for the two sub-systems are (Watson, 2004):

> “… the *technical sub-system* is much more than the sum of the equipment in the organization; it can be identified with the process responsible for the conversion of system inputs into system outputs” …. the *social sub-system*, on another hand, is much more than the set of technical control tasks to be performed by people. Technical tasks are combined with individual jobs and with responsibilities assigned to groups. Any analysis and redesign of the social sub-system implies a revision of the jobs and of the corresponding social roles, for the implications they have on the technical sub-system …”

Overall performance for an organization can only be achieved if the interaction and the interdependency among the two sub-systems are explicitly recognized. Any design or redesign must be done keeping in mind the critical impact each subsystem might have on the other and planning must ensure that both the sub-systems are in proper fit.

Crew design for construction operations has aspects of both the social subsystem (humans or workers) and the technical sub-systems (machines or equipment). In construction operations, there are number of both linear and complex interactions & interdependencies between the workers and the machines/equipment. And optimization of only one sub-system cannot lead to overall system performance for construction operations. Hence, a crew design derived from the principles of Socio-Technical system theory ensuring the joint optimization of both the social subsystem (humans or workers) and the technical sub-systems (machines or equipment) is of value.

Socio-Technical principles have been developed to enhance the levels of organizational performance by including operational measures such as effectiveness and productivity, along with psychological indicators of human well-being and attitudes (Clegg 2000). Albert Cherns (1976), an associate of Tavistock Institute presented nine principles of Scio-Technical system design. The following principles represent a distillation of real-world experience and a synthesis of writings by socio-technical icons such as Emery and Trist (1972) and Herbst (1974):

Principle 1: Compatibility

The process of design must be compatible with its objectives. "This means that if the aim is to create democratic work structures then democratic processes must be used to create these" (Mumford 2006). Cherns (1976) explained that if the design objective is to create an adaptive system which is capable of self-modification then, a constructively participating organization is required. For this to happen, people must be given an opportunity to participate in the design process of the work they are required to perform.

Principle 2: Minimal Critical Specification

This principle has two parts (minimum & critical) with one being a negative aspect and the other a positive one. The negative aspect states that no more should be specified than is absolutely essential. And the positive aspect requires identifying what is essential. Cherns (1976) discusses that specifying a lot arises out of the desire to reduce uncertainty in the job but it may results in closing the options which might arise in the future due to the changing environment. This often involves giving workers or group clear objectives but letting them decide how to achieve them.

Principle 3: The Socio-technical Criterion

This principle states that any variances or deviations should be eliminated. And if they cannot be eliminated, they must be controlled as close to their point of origin (source) as possible. Cherns (1976) defined variance as "any un-programmed event which critically affects the outcome." Variance could be present in the form of defects or deviations in the quality of raw material, machine breakdowns, failure to take action at a critical time, etc. Also any variances occurring should be eliminated or controlled by the group experiencing them and not by another supporting group.

Principle 4: The Multi-functionality Principle

Work in organizations needs to constantly adapt to their changing environment. The work groups have to be flexible in order to adapt to the changing environment. This can be achieved by adding new roles, modifying old ones or adding a variety of skills.

Principle 5: Boundary Location

Boundaries should facilitate the sharing of knowledge, experience, information and learning. They should occur where there is a need to group people and activities on the basis of – time, technology change, etc. – in the work process. Need for Boundaries occurs when work from one worker/group of workers passes on to another one and new set of skills or activities are required to perform that work. For a favorable socio-technical system design, working groups should learn to manage their own boundaries without hampering the coordination or communication needed among the groups.

Principle 6: Information Flow

This principle states that information must be provided to all those who require it and whenever they require it. Cherns(1987) suggested that information in the organization has three uses: for control, for record keeping and for action. Information provided at the right moment may also help in controlling the variances and improve the performance of the work groups.

Principle 7: Support Congruence

This principle states that systems of social support must be designed to reinforce the desired social behavior and that management's actions should be consistent with the expressed philosophy (Cherns 1976). He suggested that systems such as conflict resolution, work measurement, performance assessment, training, promotion etc. can all contradict or reinforce the behaviors which are desired.

Principle 8: Design and Human Values

This principle states that an objective of design should be to provide high quality work. Cherns (1976) suggested that quality is a subjective phenomenon involving responsibility, variety, growth etc. and the broad objective should be to provide these to only those who want them without subjecting others to peer control. Thorsrud (1972) identified six characteristics of a good job or high quality of work: (1) jobs to be reasonably demanding; (2) opportunity to learn; (3) an area of decision-making; (4) social support; (5) the opportunity to relate work to social life; and (6) a job that leads to a desirable future.

Principle 9: Incompletion.

This principle identifies that the design is a re-iterative process and that it never stops. Every design once implemented, because of the changing and uncertain environment will have consequences indicating the need for redesign. Multifunctional, multi-level, multidisciplinary team required for design is needed for its evaluation and review" (Cherns 1976).

The proceeding review of the existing Socio-Technical literature provides conceptual foundations for developing construction –specific crew design (formation and composition) criteria

2.6 Crew and Work Design

While designing "a team for work" or "work for a team" appear to be two different problems, both involve the integrated design of "*group of workers/people*" and the "*work/job*" that needs to be executed by them. The "*group of workers/people*" can be defined as a "team", "group" or "crew" and a *work/job* can be defined as a set of "activities" or "tasks" that are performed by the workers/people.

Also, a *job* can be defined as "an aggregation of tasks assigned to a worker" (U.S. Department of Labor 1972) whereas a *task* is a "set of actions performed by a worker who transforms inputs into outputs through the use of tools, equipment, or work aids," Medsker and Campion (2007). And *Job Design* is the "content and structure of jobs that employees perform" (Oldham, 1996, p. 33). In the literature, Job Design has been known by different names such as "Work Design" or "Team Design", but all are mean the same when generalized.

When work is executed by a "*group of workers/people*" known as a "team", "group" or "crew", then the performance of the team/crew affects the performance of the overall work or the operation. In addition there are numerous decisions to be made regarding:

- How the work is to be executed;
- How many workers need to be in a crew/team;
- What should be the composition of workers in a crew, sequencing of tasks; and
- How the work should flow among the workers in a crew.

For example in construction, one of the main problems facing estimating and scheduling teams working on early stages of a construction project is the need to determine a reasonable production rate for a crew based on their composition, experience, time working together, etc (Hassanein 1997). In the present scenario, this complex job/work/team design (involving both crew and work performed) is typically performed in an ad-hoc, random manner by the managers or supervisors, which, at best, is equally likely to produce low or high performance outcomes.

Crew design is not a luxury but a necessity and an integral part involved in the process of executing any job/work/operation. However, the design of either work/job/teams/crews hasn't received much attention in construction literature. As stated by Medsker and Campion (2007), "Job design is one of those aspects of managing organizations that is so commonplace that it often goes unnoticed".

Different scientific disciplines such as industrial engineering, organizational psychology, social psychology and socio-technical system theory, etc, have all developed approaches for "work design" (Gladstein 1984; Hackman 1980, 1987; Hackman and Oldham 1980; Guzzo and Shea 1992; Niepcel and Molleman 1998; Morgeson and Campion 2003; Morgeson et al 2006;

Campion et al 1993, 2005) but the studies conducted have been relatively independent of each other. These studies provide a framework for “work/job/team/crew design” focusing on work/team characteristics or indicators.

Campion et al (1993) suggested that psychological approaches to work design have been consistent in achieving increased satisfaction for the teams/groups; however, this approach to work design has always been in conflict with the traditional engineering approaches to work design (Campion, 1988; Campion & McClelland, 1991; Campion & Thayer, 1985). So what is the best way of designing work or a team? In the previous sections of this chapter, engineering approaches such as of Lean Production and Lean Construction have been discussed.

In the following discussion, we investigate the concept of “crews” as “production work teams” and provide a brief discussion of the distinctions among different types of “work teams” that have emerged in the theoretical literature.

A team can be defined as (a) two or more individuals who (b) socially interact (face-to-face or, increasingly, virtually); (c) possess one or more common goals; (d) are brought together to perform organizationally relevant tasks; (e) exhibit interdependencies with respect to workflow, goals, and outcomes; (f) have different roles and responsibilities; and (g) are together embedded in an encompassing organizational system, with boundaries and linkages to the broader system context and task environment (Alderfer, 1977; Argote & McGrath, 1993; Hackman, 1992).

Many classification schemes are present in the literature on how to define groups. Focusing on what groups do, Carter et al. (1950) identified six primary group task types: (a) clerical, (b) discussion, (c) intellectual construction, (d) reasoning, (e) mechanical assembly, and (f) motor coordination. In the sixties, McGrath and Altman (1966) extended these ideas by identifying four ways that small groups could be classified according to the (a) behaviors enacted by group members, (b) behaviors required of group members for effective performance, (c) abilities required of group members, and (d) characteristics of the group's task per se.

Later, McGrath (1984) consolidated several features of existing classifications to produce an eightfold typology of group tasks based on three dichotomized dimensions (i.e., conflict–cooperation, conceptual–behavioral, and choose execute): (a) generating plans, (b) generating ideas, (c) solving problems with correct answers, (d) deciding issues with no correct answers, (e) resolving conflicts of viewpoints, (f) resolving conflicts of interest, (g) resolving conflicts of power, and (h) executing performance tasks.

At about the same time, Hackman (1990) offered another influential classification of seven work group types in the preface to an edited volume featuring case studies of team effectiveness; he divided the teams into (a) top management groups, (b) task forces, (c) professional support, (d) performing groups, (e) human service teams, (f) customer service teams, and finally (g) production teams.

Present literature offers a conceptual distinction between "teams" and other types of "groups". McGrath (1984) concluded that in terms of small groups there are three attributes of interest: (1) two or more individuals, (2) regular interaction among group members, and (3) interdependence among them in some way. This was similar to the definition provided by Dyer (1984) who suggested that teams "consisted of two or more people who have a common goal, specific role assignment, and interdependence".

This was further supported by Morgan et al (1986) who defined teams as "distinguishable sets of more than two individuals who interact interdependently and adaptively to achieve specified, shared, and valued objectives". Further McGrath and colleagues suggest that "crews are formed when an organization has developed the technology to carry out a class of projects (tasks) and then select personnel to staff the project".

Guzzo and Dickson (1996) suggested that the use of term "group" has been largely replaced by term "team" in the discipline of organizational psychology and that many labels are used for "team" such as empowered teams, autonomous work groups, semi-autonomous work groups, self-managing teams, self-determining teams, self-designing teams, crews, cross-functional teams, quality circles, project teams, task forces, emergency response teams etc.

Further, a number of different types of work teams have been classified based on the team autonomy. The classification provided by Banker et al (1996) has been shown in Figure 2.15.

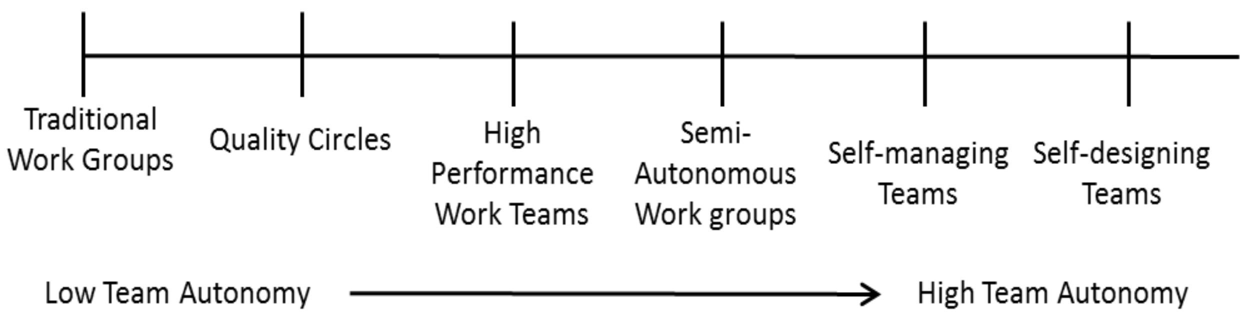


Figure 2.15: Graphical representation of Work Team Autonomy (Banker et al 1996)

Traditional work groups perform core production activities and have no management responsibility or control. Support activities such as quality control, inspection, maintenance, etc. are the responsibility of other groups. In Quality circles, the work group has the responsibility for making suggestions but do not have any decision making authority.

Along with execution, semi-autonomous work groups have the responsibility to also manage the production activities. The difference between the autonomous and semi-autonomous work groups is that "the scope of the production tasks managed and executed by autonomous groups is narrower than that of the semi-autonomous groups"; these autonomous groups can self-regulate their work and have complete control over the management (planning, execution and control) of their tasks. Further, "self-designing teams" are similar to the self-managing or autonomous groups along with a control over design of the team and the tasks involved.

Sundstrom et al. (1990) provided the following classification of work teams: advice/involvement, production/service, project/development, and action/negotiation. Sundstrom (1999) consolidated this classification where he distinguished six types of organizational teams: (a) production teams, (b) service teams, (c) management teams, (d) project teams, (e) action/performance teams and (f) parallel teams. Further, in a review of the research on work groups published in 1990's, Cohen and Bailey (1997) distinguished four team types: (a) work teams, (b) parallel teams, (c) project teams, and (d) management teams.

"A *work team* is a structured set of employees who require coordinated interactions to pursue collective performance objectives within the larger organizational system and successfully accomplish relevant tasks; such employees possess complementary skills" Ogungbamila et al (2010). Sundstrom et al. (1990) suggested that *work teams* have been extensively used to generate products or services, such as in manufacturing, maintenance, construction, mining, and commercial airlines, and they "usually consist of first-line employees working together full-time, sometimes over protracted periods, with freedom to decide their division of labor".

Work teams have been common both in manufacturing and service industry. Optimizing the performance of crews (production work teams) is a very essential element as "work teams are considered to be an integral tool aiding continuous improvement in work operations" (Cutcher-Gershenfeld and Associates 1994).

For this research, the classification by Cohen and Bailey (1997) and Sundstrom (1990, 1999) where work teams are defined as "continuing work units responsible for producing goods and providing service" fits very well with our description of a "crew" for a production setting in construction.

Work teams that exhibit the following characteristics could be "classified as crews: (1) membership of expert specialists, (2) perform events that are closely synchronized with counterparts and support units inside the organization (e.g., fire fighter crews), and (3) have brief performance events repeated under new conditions" (Sundstrom et al. 1990). Also, a crew can be defined as a "group of expert specialists each of whom have specific role positions, perform brief events that are closely synchronized with each other, and repeat these events across different environmental conditions" (Klimoski & Jones, 1995; Sundstrom et al., 1990).

Further, this study examines the several design indicators or characteristics of "work design/team design" and how they relate to different performance outcomes based on approaches other than engineering which has already been discussed in the previous section of this literature review. This is accomplished by primarily reviewing research studies on "work design/team design" that have well developed theoretical and empirical foundations in socio-technical system theory, social and organizational psychology. This is conducted, to ensure that the proposed crew design framework and guidelines in this study are strongly supported.

Work design or team design from a number of significant studies (Gladstein 1984; Hackman 1980, 1987; Guzzo and Shea 1992; Morgeson and Campion 2003; Morgeson et al 2005, 2006; Morgeson and Humphrey 2008; Campion et al 1993, 2005; Medsker and Campion 2007; Humphrey et al 2007; Kozlowski and Ilgen 2006; Sundstrom et al 1990) is reviewed to determine the relevant design indicators or characteristics and the impact of these indicators on various performance outcomes.

In the reviewed literature, as stated earlier, team/crew/group effectiveness has been defined in a number of ways. Guzzo and Dickson (1998) defined performance effectiveness consistent with Hackman (1987) and Sundstrom (1990) that “effectiveness in groups is indicated by (a) group produced outputs (quantity or quality, speed, customer satisfaction, and so on), (b) the consequences a group has for its members, or (c) the enhancement of a team’s capability to perform effectively in the future”. Shea and Guzzo (1987) defined group effectiveness as "production of designated products or services per specification".

Hackman and Morris (1975) suggested that effectiveness has three main components: group performance, satisfaction of group-member needs, and the ability of the group to exist over time. Campion et al (1993) defined work group effectiveness in terms of productivity, satisfaction, and manager judgments. Medsker and Campion (2007) extended Campion et al (1993) measures of performance outcomes into “productivity: productivity, efficiency, quality, reduced costs” and “satisfaction: job satisfaction, satisfaction with team, commitment, motivation, customer satisfaction”.

Campion et al (1993) suggested that almost all the job characteristics of Hackman and colleagues (e.g., Hackman & Lawler, 1971; Hackman & Oldham, 1980) can be applied to groups for work design. However, because of the scope of this research, significant work design indicators or characteristics relevant to the production setting in construction were identified and investigated. Further, several meta-analytic findings from the theoretical literature were identified to investigate the work design indicators or characteristics.

Relative size is the number of individuals in a team/crew/group and has shown to be related to effectiveness or performance (Steiner, 1972; Gladstein 1984; Nieva et al 1985; Campion et al. 1993; Guzzo and Shea 1992; Cohen and Bailey 1997; Hackman 2002; Morgeson et al 2005;

Leach et al 2005; Ogungbamila et al 2010). Campion et al. (1993) identified that group size was positively related to both productivity and satisfaction; and suggested that the groups need to be of feasible size in order to accomplish the work assigned to them. According to Huchman et al (2009) increasing the size of a work team may lead to certain benefits such as more resources available and increased capacity resulting in high overall productivity for a work team.

However, "an increase in resources (because of more team members) is often counterbalanced by the team's increased difficulty in arriving at a decision and a decrease in the average personal and work space of each team member" (Ogungbamila et al 2010). In addition, increase in size beyond a feasible limit might also lead to increased coordination problems and unequal participation of group members (Hackman 20002). Too many or too few individuals in a work team have been shown to reduce performance and that size of a work team has an inverted U-shaped relation to effectiveness (Nieva et al 1985). However, depending on the nature of work and its environment, the U-shaped relationship might not be true for all types of teams (Cohen and Bailey 1997; Kozlowski and Bell 2003).

Task significance, task variety and task identity are significant characteristics affecting performance or effectiveness (Cummings, 1978; Campion et al 1993; Morgeson and Humphrey 2008; Medsker and Campion 2007). *Task significance* means the extent to which the group's work has significant consequences inside and outside the organization and the impact it has on the lives of others. *Task variety* means the extent to which workers (same skill level) are involved in a variety of tasks (Hackman 1987; Morgeson & Humphrey 2006; Campion et al 1993); it relates to the concept of job-enlargement from socio-technical theory allowing both interesting and dull tasks to be shared among members (Davis and Wacker, 1987; Walton, 1972). *Task identity* is the degree to which the group/individual completes an entire or separate piece of work from start to finish (Campion et al 1993) and it may increase worker motivation by instilling a feeling of pride (Hackman and Oldham 1976; Hackman 1987).

Meta-analytic findings such as (Humphrey et al., 2007) have shown that *task significance* impacts job satisfaction (ρ = .41) and work motivation (ρ = .45); also *task variety* is positively related to job satisfaction (ρ = .46) whereas, *task identity* is modestly related to worker motivation (ρ = .26) and job satisfaction (ρ = .31).

Task complexity is the extent to which a given task is difficult to perform or the "extent to which a task/job is multifaceted" (Humphrey et al 2007). Task/job complexity can be considered as a mechanistic aspect of work (Morgeson and Humphrey 2008) and it can be well argued that reducing the complexity or simplifying work should generally lead to efficiency gains. However, Morgeson and Humphrey (2008) presented findings indicating that higher complexity is related to higher subjective performance ratings (ρ = .37) (Humphrey et al 2007).

Task experience is the amount of time spent by a team/individual in performing a task or the number of times a similar type of task has been performed. In addition, it can also refer to the prior amount of knowledge an individual has in performing that task. Morgeson and Humphrey (2008) suggested that "having higher task experience will help workers perform successfully in jobs that have high task variety (i.e., breadth of knowledge) or specialization (i.e., depth of knowledge)". A higher *task experience* may also have causal effects in terms of higher costs, improved performance, and technical support for the group/team members.

Interdependence primarily exists in the form of *task interdependence*, *goal interdependence*, *or outcome interdependence*. Campion et al (1993) suggested that "*Interdependence* may increase the motivational properties of work or the efficiencies with which the work is done, and thus may be related to effectiveness".

Task interdependence exists when a group of individuals get together and depend on one another to perform a certain work consisting of several tasks; and either start or finish of one task is dependent on the other tasks. *Task interdependence* exists in the form of pooled, sequential and reciprocal interdependence (Thompson 1967). The manner it affects work performance has been discussed in the previous sections of this literature review. *Goal or outcome interdependence* exists in the form of clearly defined objective/mission or has also been defined as the “degree to which the significant outcomes an individual receives depend on the performance of others” (Campion et al 1993; Wageman 1995). It is considered to be a significant characteristic for group effectiveness (Davis and Wacker 1987; Gladstein 1984; Guzzo and Shea 1992; Hackman, 1987). Campion et al (1993) suggested that “individual members' goals must be linked to the groups' goals to be maximally effective”.

Autonomy means the “amount of freedom and independence an individual has in terms of carrying out his or her work assignment (Morgeson and Campion 2003). Also, autonomy can be of different types such as: *work scheduling autonomy, work methods autonomy, decision-making autonomy* (Morgeson and Humphrey 2006, 2008; Humphrey et al 2007). Autonomy stems from the research in organizational psychology (Hackman & Oldham 1980) and socio-technical theory (Trist 1981) where it is recommended that increased autonomy in execution of work leads to increased work satisfaction and motivation among the workers.

This view is also supported by Leach et al (2005), recommending that increasing autonomy could be a worthwhile strategy from both team and individual perspective for enhancing team performance ($p < .05$). Further, results from the meta-analytic findings (Humphrey et al., 2007) shows that autonomy can be related to both objective ($\rho = .17$) and subjective ($\rho = .23$) performance ratings. Also, autonomy was shown to reduce a number of well-being outcomes such as anxiety (ρ = -.10), stress (ρ = -.23), and burnout (ρ = -.30). In addition, autonomy is related to job satisfaction (ρ = .48), organizational commitment (ρ = .37), and internal work motivation (ρ = .38). Among work scheduling autonomy, work methods autonomy and decision making autonomy has a large impact (ρ = .58) on job satisfaction (Humphrey et al., 2007).

Self-management is the group level analogy to *Autonomy* and is presumed to enhance performance or effectiveness by increasing the workers sense of responsibility and ownership of work (Campion et al 1993; Manz & Sims 1980; Morgeson and Humphrey 2008; Medsker and Campion 2007).

Feedback is considered to be a significant characteristic and is recognized in several research studies (Guzzo and Shea 1992; Gladstein, 1984; Hackman, 1987; Steiner, 1972; Sundstrom et al 1990). In the theoretical literature, although feedback has generally been considered to be originating from a single source; Morgeson and Humphrey (2008) made a distinction between the type of *feedback* present into *feedback from others* and *feedback from the job*. *Feedback from others* is the "extent to which members of the organization provide information about job performance whereas *feedback from the job* is the extent to which a job imparts information about an individuals' performance" (Humphrey et al 2007; Morgeson & Humphrey, 2006).

Meta-analytic findings from Humphrey et al (2007) show that feedback from the job relates positively with work outcomes such as work motivation (ρ = .42) and job satisfaction (ρ = .43). Further, results also demonstrate that a timely and effective feedback leads to reduction in role ambiguity (ρ = -.43) and role conflict (ρ = -.32).

Social support is another characteristic recognized in research studies (Gladstein 1984; Morgeson and Humphrey 2006, 2008; Humphrey et al 2007; Campion et al 1993; Medsker and Campion 2007). It can be defined as the "extent to which there are opportunities for gathering assistance and advice from supervisors and coworkers," (Morgeson & Humphrey, 2006, 2008).Campion et al (1993) suggested that "*effectiveness* may be enhanced when members help each other and have positive social interactions."

From the meta-analytic findings (Humphrey et al., 2007) it has been found that social support is strongly related to job satisfaction ($\rho = .56$). Shea and Guzzo (1987) argued that given that resources such as material and information are controlled and allocated by the management, then managerial support is the key to group functioning. Campion et al (1993) built on this and suggested *managerial support* is logically related to group effectiveness.

2.7 Chapter Summary

This chapter provided an overview of the existing construction models and crew and work analysis methods followed by the review of production theories such as Lean Production, Lean Construction and Socio-Technical System theory. Production theories reviewed such as Socio-Technical, Lean Production, Lean Construction and Social and Organizational formed the basis for developing the guidelines for lean crew design.

3 MODELING AND SIMULATION IN CONSTRUCTION

3.1 Introduction to Modeling and Simulation

The purpose of this chapter is to review the concepts and techniques regarding the modeling and simulation to gain better understanding of the use of simulation in a construction system. A detailed view on simulation approaches such as discrete event simulation and system dynamics modeling is presented. Further, advantages and limitations of each of the modeling techniques are reviewed to gain better understanding of the process of building simulation models.

According to Bellinger (2004) *Modeling and Simulation* "is a discipline for developing a level of understanding of the interaction of the parts of a system, and of the system as a whole". Although in general, *Modeling* and *Simulation* have been used interchangeably, they have very specific meanings in the modeling and simulation scientific discipline.

According to the Department of Defense (1998) *Modeling* is defined as "application of a standard, rigorous, structured methodology to create and validate a physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process"; whereas, *Simulation* is the "method for implementing a model over time" (DoD 1998) or it can also be defined as the operation of a model, which is a representation of that particular system itself.

In addition, according to Borshchev and Filippov (2004), *Modeling* is a "way of solving problems that occur in the real world". In general, *Modeling* is carried on in order to reduce the costs associated with analyzing, experimenting or implementing any changes to the real system; this way performance of real systems could be optimized before implementing any change to it.

However, *Simulation* is the "process of *model execution* that takes the model through (discrete or continuous) state changes over time" (Borshchev and Filippov 2004). Also, *Simulation* is the "process of designing a model of a real system and conducting experiments with this model for the purpose of either understanding the behavior of the system or evaluating various strategies (within the limits imposed by a criterion or set of criteria) for the operation of the system" (Shanon 1975).With advances in computer technologies, simulation models have been used and developed for decades to help analyze complex systems. Simulation is one of the most widely used operations research and management-science techniques (Law and Kelton 2000).

There are several key concepts underlying modeling and simulation. Discussion of these concepts is essential in understanding and performing simulation. Some of the key concepts are system, model, and event. These concepts have been explained in detail in Carson (1993), Banks et al (2000), and Law and Kelton (2000).

A *system* can be defined as a group of objects coexisting and mutually interacting towards the accomplishment of a common purpose. According to Shannon (1975) a *model* is a representation of an object, a system, or an idea in some form other than that of the entity itself. A *model* is developed in order to have a simplified representation and gain better understanding of a *system*, *entity*, or *process*. A *model* should always be similar and a close approximation to the system but at the same time it should also be able to represent a complex system in much simpler form in order to have easy experimentation and also to have a better understanding of the system. An *event* can be defined as an occurrence that changes the state of the system it takes place in. And these events can be internal and external events also known as endogenous and exogenous depending on whether the event occurs within the system or outside the system.

3.2 Classification of Simulation Models

In general, *Modeling* and *Simulation* is the use of models either *Physical* (emulators, prototypes, scale models, etc.) *or Mathematical* constructs to analyze and evaluate the system's performance and help in decision making. *Mathematical* models are also known as *logical* models which can be either:

1. *Analytical* models (linear programming, queuing theory, differential equations, etc.) or
2. *Simulation* models (discrete event simulation models, system dynamics models, agent based models, etc.).

In addition, due to the complex interaction among units in a system's environment, *Analytical* models can be applied to only a limited number of cases; whereas *Simulation* models are more flexible and can be easily developed, analyzed, and experimented with for a majority of actual processes, phenomenon or systems to optimize performance and help in decision making.

A number of system/process problems ranging from strategic (macro) level to operational (micro) level have been successfully addressed using modeling and simulation. For example, it has been used for designing, analyzing and optimizing manufacturing systems, military weapons systems or tactics, policies for business systems, construction systems, transportation facilities, financial or economic systems, supply chain systems, health systems, etc.

Further, *Simulation* models can be classified as:

1. Deterministic and Stochastic,
2. Static and Dynamic,
3. Discrete and Continuous.

In all these models, there is a set of input variables driving the simulation and producing a set of outputs to be observed.

3.2.1 Deterministic and Stochastic Simulation Models

Deterministic models can be defined as those models that do not have any random or probabilistic element present; these models do not account for any uncertainty that may occur in a real system. Whereas in *Stochastic* models, randomness and probabilistic element are present and they account for the uncertainty present in a real system by the use of probability distributions.

According to Banks and Carson (1984) *Deterministic* models of a known (deterministic) set of input variables which result in a unique set of outputs whereas *Stochastic* models have one or more random variables as inputs leading to random outputs. Also as the outputs are random, they represent only estimates of the real system and in general require a number of runs of the model to get an effective estimate of the real system.

3.2.2 Static and Dynamic Simulation Models

In addition, both the *Deterministic and Stochastic* models can be static or dynamic in nature. Static models do not account for the element of time and they represent a system at a particular point of time; whereas, dynamic models account for the time element and represent a system as it changes over time.

3.2.3 Discrete and Continuous Simulation Models

Simulation models can be *Discrete or Continuous* depending on if the variables present in the simulation model changes continuously over time or at discrete points of time; for example, "If alterations to the model occur continuously as time varies, the model is continuous; if such changes occur only at discrete instants of time, the model is discrete" (Hoover and Perry 1989).

Figure 3.1 compares how continuous/discrete simulation models are time or state models depending on if the state is defined continuously at all times or only at some discrete time and if the state variables are either continuous or discrete (Jain 1991).

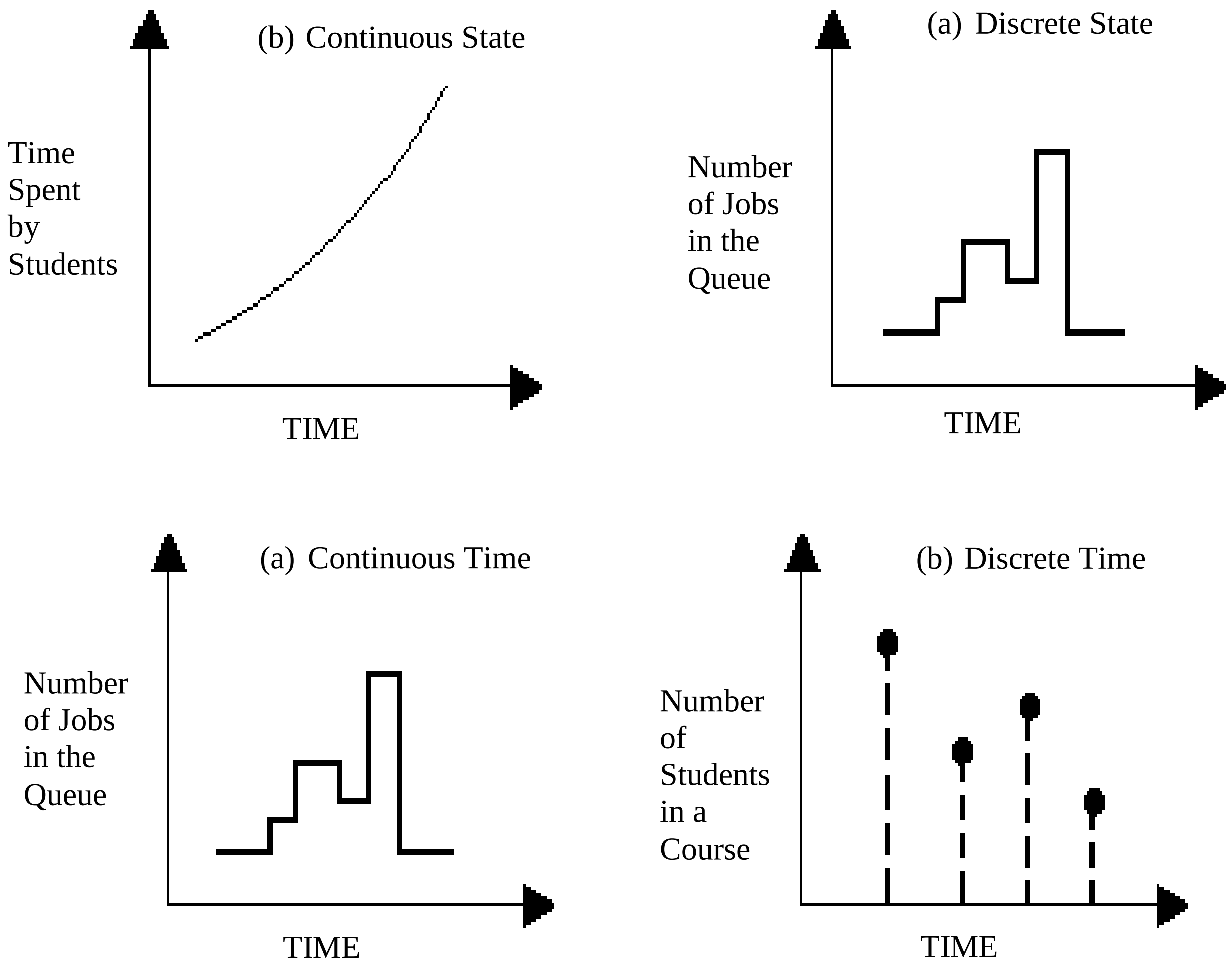


Figure 3.1: Graphical representation of discrete and continuous models (Jain 1991)

In addition, according to Law and Kelton (2000), simulation models can be discrete in two ways, namely, time-stepped or event-stepped. In time-stepped models the state of the system changes at each time step whereas in event-stepped models the state of the system changes at the occurrence of some event in the system.

Both *Discrete* and *Continuous* simulation approaches have been used in construction industry to predict and improve the performance of the construction projects. They have been successfully used by managers, engineers and researchers to design, understand and improve the construction process. Simulation makes it possible to analyze different construction processes and predict the best possible methods without actually implementing them in real practice.

For example, simulation has been used to determine construction alternatives (Ioannou and Martinez 1996); map and improve the production process of manufactured housing factory (Senghore et al 2004); to minimize the production time and cost of concrete batch plant production process (Zayed and Halpin 2001); to explore the interaction between project and business-level processes involved in bidding (Bayer and Gann 2006); to understand change and rework in construction project management systems (Love et al 2002); to explore performance enhancement in a construction organization (Ogunlana et al 2003); to investigate the effects of resource allocation policies on project durations (Lee et al 2004); and to investigate crew design alternatives (Naveen and Abdelhamid 2010).

The reason simulation has been so useful is because it provides for a faster, less expensive and simple method of analyzing a real process consisting of multiple interdependent components involving multiple feedback and nonlinear relationships present at the strategic (macro) and production (micro) level. Discrete (Discrete event simulation) and continuous (system dynamic modeling) simulations contribute in evaluating and improving both the macro and micro level construction processes.

3.3 Discrete Event Simulation (DES)

3.3.1 DES Introduction

Discrete event simulation (DES) is a simulation technique based on statistical analysis and queuing theory where state changes occur at discrete points of time whereas system dynamics (SD) is a modeling technique consisting of a system of stocks and flows where continuous state changes occur over time (Brailsford and Hilton, 2001). The main objective in both simulation approaches is to model the real system and understand how systems behave over time and to compare their performance under different conditions (Sweetser, 1999).

Discrete event simulation (DES) has been widely recognized as an effective technique to design and analyze construction operations for over three decades by virtue of its ability to handle complexity and uncertainty (Halpin 1973; Martinez and Ioannou 1999, Halpin et al 2003). Discrete event simulation is a useful technique to imitate the real world systems over time by modeling repetitive processes where variables representing the state of the system change at discrete points of time along with many resource interactions (Law and Kelton 2000). In discrete-event simulation, the operation of a system is represented as a chronological sequence of events where each event occurs at an instant in time and marks a change of state in the system (Robinson, 2004).

3.3.2 DES Modeling Concepts

Page (1994) suggested that in discrete event simulation two concepts of time and state are of major importance and defined the relationship between them in the terms of event, activity and process shown in Figure 3.2.

1. Instant: value of system time at which the value of at least one attribute of an object can be altered.
2. Interval: duration between two successive instants.
3. Span: contiguous succession of one or more intervals.
4. State: enumeration of all attribute values of that object at a particular instant.
5. Activity: state of an object over an interval.
6. Event: change in an object state, occurring at an instant, initiating an activity.
7. Process: succession of states of an object over a span.

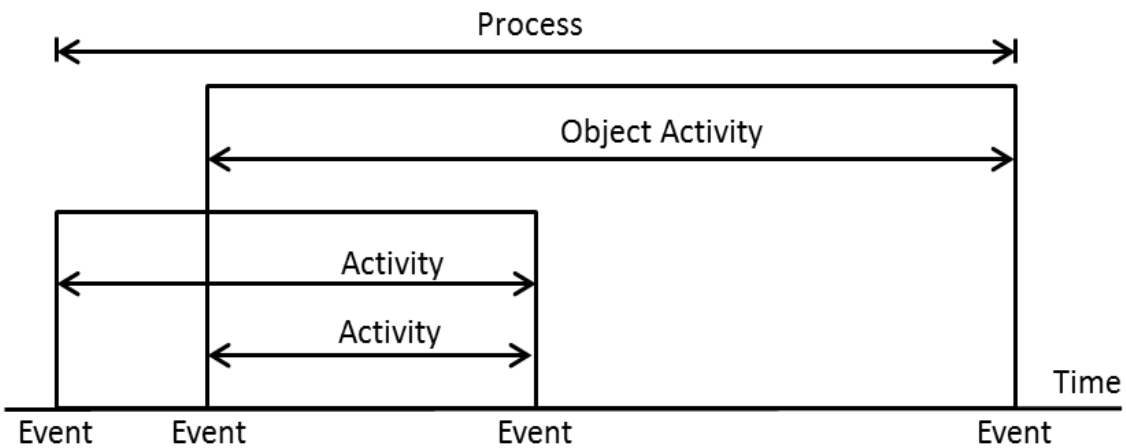


Figure 3.2: Graphical representation of event, activity and process in DES (Page 1994)

In addition to the terms defined by Page (1994), other important terms in DES are *entities* known as the objects in a system, *attributes* representing the properties of the entities in a system and *simulation clock* representing the simulation time or the variable that keeps the current value of (simulated) time in the model (Law, 2007). Simulation time may not be equal to the real time.

3.3.3 DES World Views

In DES the conceptual framework (world view) or the simulation strategy guides model development (Page 1994; Pritsker et al 1997; Pidd 1998; Martinez and Ioannou 1999; Martinez 1996) in the following three ways:

1. Event scheduling view (ES) is governed by the occurrence of the events in a system. In this view the occurrence of events that change the state of the system are determined by the model developer. Time is advanced to the next scheduled event that is the end of an activity and next scheduled activities are examined to determine if they can start or not (Abu-Taieh and El Sheikh 2008). "The event based simulation model is driven by the scheduling and execution of the events which in turn schedule and execute other events," (Martinez 1996). The event scheduling paradigm/view is shown in Figure 3.3.

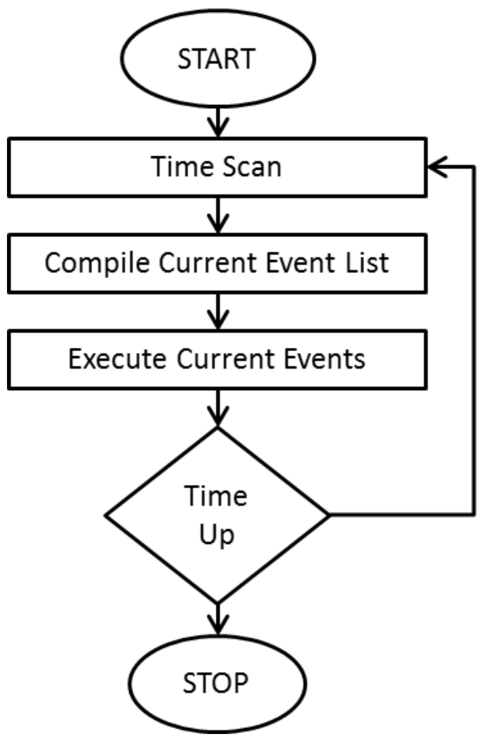


Figure 3.3: Graphical representation of event scheduling paradigm/view Pidd (1998)

2. Activity scanning view (AS) is governed by the occurrence of activities (generally represented as pairs of start and end events) in a system. In this view a model developer determines which activities should be present and under what conditions they can take place. It is also known as a two phase approach (Figure 3.4); where in the first phase, time is scanned and advanced if the activities meet the conditions specified, and then executed; and in the second phase, the system is updated if an event occurs (Abu-Taieh and El Sheikh 2008).

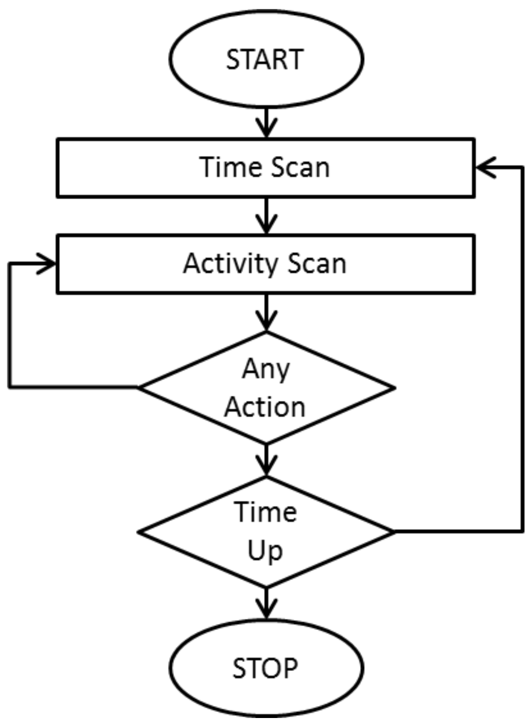


Figure 3.4: Graphical representation of activity scanning paradigm/view Pidd (1998)

3. Process interaction view (PI) is governed by the flow of entities through a system. “These entities undergo a process in which they attempt to acquire, take hold of, and release scarce resources” (Martinez 1996). Also, the flow or movement describes all of the states that an entity can attain in the system (Abu-Taieh and El Sheikh 2008).

In addition to the three world views, there is another approach known as the *Three-Phase (AS)* that combines both the activity scanning (AS) and event scheduling (ES) views (Martinez 1996; Balci 1988). This *three-phase (AS)* approach was first developed by Tocher (1963) in his book, The Art of Simulation.

In this approach there are two different types of system activities; one which are bound to happen known as *bound activities* (B activities) and other as *conditional activities* (C activities) that would take place only when the activity conditions are satisfied.

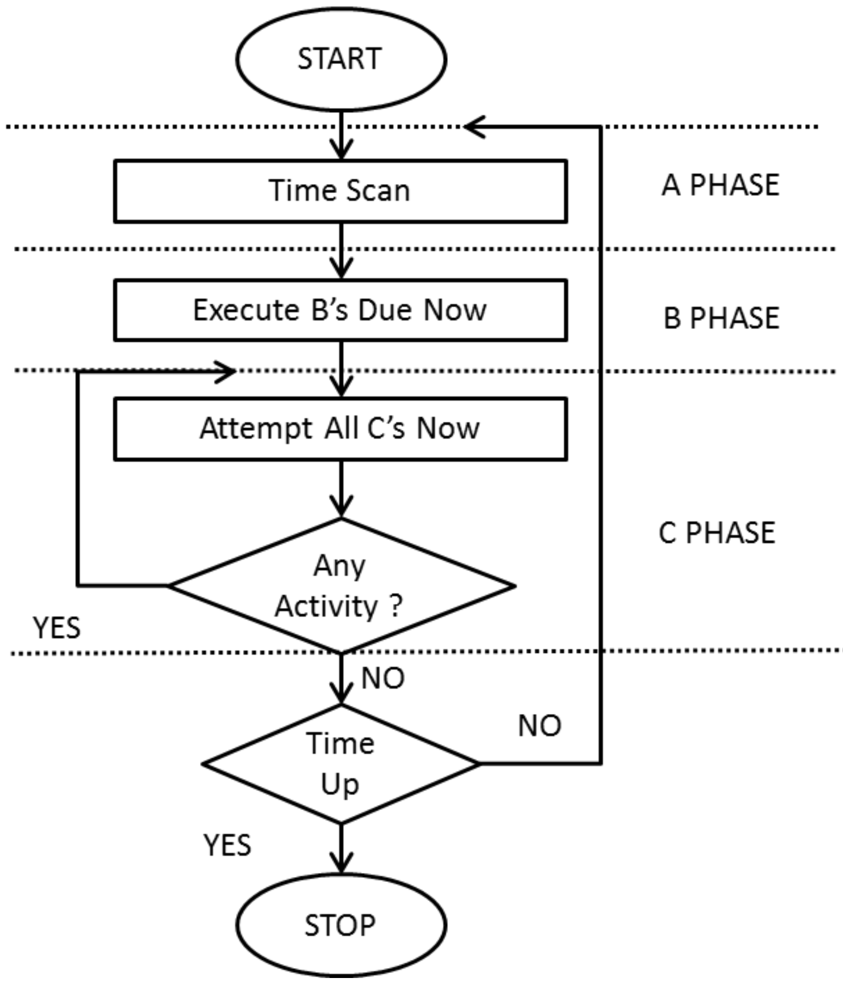


Figure 3.5: Graphical representation of Three-Phase (AS) paradigm/view Pidd (1998)

3.3.4 DES Software Tools

In general, discrete event simulations (DES) can be executed through the use of either "specific purpose simulation (SPS) tools" or "general purpose simulation (GPS) tools".

Specific purpose simulation (SPS) tools target a very narrow range of systems. They are designed for specific tasks or operations and can also be classified as *simulators* (Law and Kelton 1991). AbouRizk and Hajjar (1998) define SPS as "a computer-based environment built to enable a practitioner who is knowledgeable in a given domain, but not necessarily in simulation, to model a project within that domain in a manner where symbolic representations, navigation schemes within the framework, creation of model specifications, and reporting are completed in a format native to the domain itself."

An example of specific purpose simulation tools is SIMPHONY, which is a Microsoft Windows based system for the development as well as the utilization of construction SPS tools (Hajjar and AbouRizk 1999). Other SPS tools developed for construction include AP2-Earth, CRUISER and CSD, all targeting specific construction operations such as large earth moving projects, aggregate production plants, and construction site dewatering operations (Hajjar and AbouRizk 1996, 1998; Hajjar and AbouRizk and Xu 1998).

On the other hand, *general purpose simulation* (GPS) tools can model wide variety of real systems. GPS tools are more flexible and can be designed to represent a variety of construction operations. These tools make use of general purpose programming languages (C, C++, FORTRAN, etc) to describe the model by providing a set of instructions to represent the real system (Fathi et al 2003). For example, CYCLONE, RESQUE, COOPS, CIPROS, STEPS, STROBOSCOPE etc are few of the general purpose simulation tools present for modeling and representing general systems.

Most of the general purpose simulation tools are based on activity cycle diagrams (ACDs) making them more suitable for modeling construction operations. One of the earliest and most used GPS tool based on ACDs of construction operations is CYCLONE (CYClic Operation Network). CYCLONE was developed by Dr. Halpin at the University of Maryland in the early 1970's and is one of the best known DES tool used for modeling construction operations. Since the development of CYCLONE (Halpin and Woodhead 1976), there have been several proposed improvements to extend its merits, including INSIGHT (Kalk 1980), UM-CYCLONE (Ioannou 1989), Micro-CYCLONE (Halpin 1990) and STROBOSCOPE (Martinez 1996).

STROBOSCOPE (STate and ResOurce Based Simulation of COnstruction ProcEsses) is one of the more recent general purpose simulation tool developed for modeling construction operations (however it is also possible to model other type of systems apart from construction systems). STROBOSCOPE is programmable and can be extended for modeling complex operations (Martinez 1996). It is based on the concept of Activity Cycle Diagrams (ACDs) and supports the Three Phase Activity scanning approach.

STROBOSCOPE (and a Visio-based version called EZStrobe) has been extensively used in modeling the construction process at the operation level. A construction project or operation can be defined in terms of processes (Halpin and Riggs 1992). And the model developed in STROBOSCOPE can represent these processes in the form of collection of activities involved in that particular operation. In STROBOSCOPE, heterogeneous types of labor, equipment or materials can be included in the model where resources of the same type can be distinguished from one another and each can have individual properties (Martinez and Ioannou 1999).

The STROBOSCOPE/EZStrobe (based on the ACDs and the Three Phase Activity scanning approach) consists of the following modeling elements (Martinez 2001) shown in Figure 3.6:

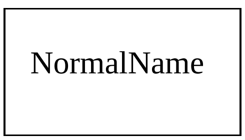
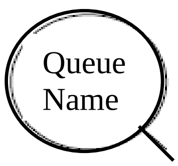
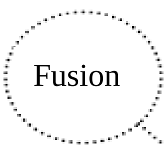
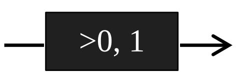
Modeling Element	**Definition/Function**
	Conditional Activity - A named element that represents tasks that can start whenever the resources that are available in the Queues that precede it are sufficient to support the task. In a Conditional Activity start priorities and probabilistic duration can also be included.
	Bound Activity - A named element that represents tasks that starts whenever an instance of any preceding Activity ends. A Bound Activity can follow any node except a Queue, and can precede any node except a Conditional Activity.
	Queue - A named element that holds idle resources. The number of resources it holds is usually shown at the beginning of the simulation. A Queue can follow any other node except another Queue and can only precede a Conditional Activity (Combi).
	Fusion Queue - A named element that similar to Queue used to hold resources. Its main function is to connect parts of the model that cannot be modeled together due to space limitations by representing and connecting with an earlier Queue used in the model.
	Draw Link – It connects a Queue to a Conditional Activity. A Draw Link shows two pieces of information separated by a comma. The first part is the condition necessary for the successor and the second part is the amount of resource that the Conditional Activity will attempt to remove from the predecessor Queue in the event that the Conditional Activity does start.
	Release Link - It connects an Activity to any other node except a Conditional Activity. It indicates the amount of resource that will be released after each instance of the predecessor activity ends.
	Branch Link – It connects a Fork to any other node except a Conditional Activity.

Figure 3.6: Graphical representation of the modeling elements in EZStrobe (Martinez 2001)

3.3.5 DES Application

DES has been the most widely used operations research tool (Banks and Carson 1984). Successful application of DES has been seen in numerous construction management areas such as simulation of earth-moving operations (Smith et al 1995), investigation of lead time buffering (Srisuwanrat and Ioannou 2007); resource management, concrete batch plant production process, pile productivity assessment (Zayed and Halpin 2001, 2002, 2004); simulation of large precast operations (Balbontin-Bravo 1998); pull-driven scheduling for pipe-spool installation (Tommelein, 1998).

3.3.6 DES Advantages and Limitations

In general, DES has overcome the "inability of the project-level models commonly used in industry practice (critical-path method or CPM scheduling tools, cost control systems, materials management databases, etc.) to model the construction process" (Tommelein 1998). It has gained wide popularity in modeling the construction process at the operation level because of its capabilities of conducting detailed analysis of complex systems where state of the system changes occur at specific points of time in a very linear fashion. Further, use of DES permits analysis of construction operations providing information about expected cost, duration, and other process level details such as resource utilizations, rate of production, idleness of resources, waiting/delays etc. In addition, it is a suitable approach to perform bottleneck analysis at the process level to determine the cause of the delays in work-in-process, information, materials, or other processes (Banks 1999).

The limitation in DES is that it is more suited for modeling at the operation level where the entities are passive objects, representing a low level of abstraction. When the systems get more complex and integrated, discrete event simulation faces serious challenges to keep up with the high level of abstraction present in the systems. In discrete event simulation, it is also difficult to model "softer" aspects of projects such as learning, pride or morale, trust, reliability, and incorporate managerial actions which are important in determining the project behavior (Williams 2002).

3.4 Continuous Simulation - System Dynamics (SD)

As discussed above, DES has proved a suitable approach for addressing operational level issues and is more focused towards cost, duration, and other process level state variables (resource utilizations, rate of production, idleness of resources, waiting/delays, etc.) at low level of abstraction that change at discrete points of time.

To model various nonlinear cause-and-effect relationships, feedback, and time delays existing in the complex construction processes, continuous simulation models, where state variables change continuously over time, may be more suitable. The cause-and-effect relationships and interactions among the state variables can be analyzed more effectively using continuous simulation.

3.4.1 System Dynamics (SD) Introduction

System Dynamics (SD) is a *systems thinking* approach for continuous simulation and an aspect of *systems theory* that aims at understanding the dynamic behavior of complex *systems*.

A *systems thinking* approach incorporates several tenets such as “Hierarchy” (where complex wholes are made up of smaller subsystems), “Interdependence” (independent elements can never form a system, but interdependence of objects and their attributes is inherent in a real system), “Regulation” (a method of feedback is necessary for the system to operate predictably) (Skyttner 2006). Kirkwood (1998) suggested that a *systems thinking* approach emphasizes that a *system* is made up of interacting parts; hence it requires a shift from focusing on event orientation (i.e., focusing on isolated events and their causes) to focus more on the internal system structure (interacting parts in a system) in order to avoid resurfacing of problems in the system. *Systems' thinking* focuses on cyclical rather than linear cause and effect relationship among parts of the system.

System Dynamics was developed in the mid-1950's by Professor Jay W. Forrester of the Massachusetts Institute of Technology. It was originally developed by applying principles of *systems theory* to industrial systems to improve understanding of the industrial process. And since then it has been continuously used for policy analysis and design and has been broadened to include social and economic systems other than industrial systems.

"System dynamics is a powerful methodology and computer simulation modeling technique for framing, understanding, and discussing complex issues and problems" (Radzicki and Taylor 1997). SD follows an integrative perspective in modeling systems; it recognizes the "information feedback characteristics so as to show how organizational structure (in policies), and time delays (in decisions and actions) interact to influence the behavior of the system" (Forrester, 1965).

In this context, it is an appropriate modeling approach to simulate complex systems by capturing (or sometimes just exploring) the cause-and-effect relationships of the various factors affecting the behavior of the system. In *system dynamics* both qualitative and quantitative modeling approaches are adopted to analyze complex system problems (Morecroft and Sterman 2000). For example, in the qualitative modeling approach, the feedback loop structure is recognized to develop casual loop diagrams (influence diagrams) by analyzing the cause-and-effect relationships of the various factors affecting the behavior of the system. And then in the quantitative modeling approach, stock and flows are used in the form of mathematical equations that represent the rate of change of the state variables over time.

3.4.2 SD Modeling Concepts

The key modeling elements and concepts such as dynamic and complex systems, casual and feedback loop diagrams, stocks and flows etc., are reviewed in more detail in the following discussion.

As defined in the previous section, a *system* can be defined as a group of objects coexisting and mutually interacting towards the accomplishment of a common purpose. A system has also been defined as “an entity that maintains its existence through the mutual interaction of its parts" (Gene Bellinger 2004); or as “a combination of parts or elements or components intended to act together to accomplish an objective” (Dukkipati 2007).

According to Berard (2010), a *system* is said to be “complex due to the multiplicity of its elements (natural, technical, economic and social) and of their interactions, but also because of the diversity of behaviors and properties it can exhibit (dynamic, emergent, etc.)”. Also, Sterman (2000) suggested that in a *system*, three main aspects determine the amount of *complexity* such as number of elements, number of interrelationships and connection between the elements. And *complex systems* are *dynamic* due to the presence of interactions, dependency on time, complex internal structure, and delayed behavioral reactions (Sterman, 2000).

Kirkwood (1998) used the term system “to mean an interdependent group of items forming a unified pattern”. The main part in a systems’ definition in a system dynamics paradigm is the “interactions of parts” and “interrelationships among elements involved”; these interactions and interrelationships results in important *patterns of behavior* of a system. It is important to identify the *patterns of behavior* in order to build a model that can represent the system characteristics. The main *patterns of behavior* that elements/variables present in a system display (Kirkwood 1998; Senge 1990; Senge et al 1994) are shown in Figure 3.7. It represents how a system variable (such as performance) changes over time showing different patterns of behavior.

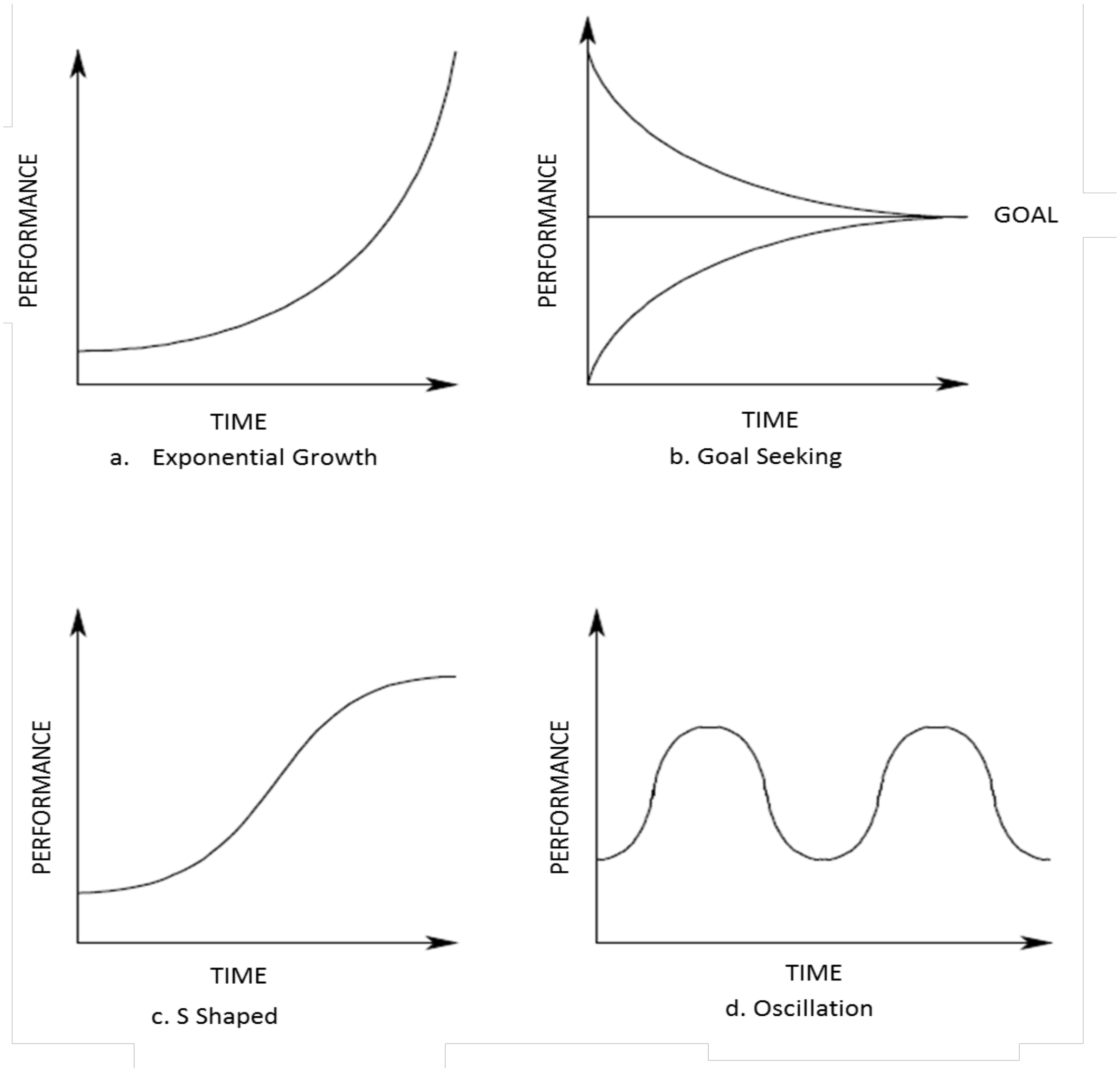


Figure 3.7: Graphical representation of patterns of behavior of systems (Kirkwood 1998)

In *system dynamics,* "causal thinking" is used to better understand the internal system structures and the reasons that cause the patterns of behavior. A cause, affect, or influences are the key elements used to describe the interacting elements in a system in terms of *feedback or causal loops diagrams*. “Feedback is defined as the transmission and return of information” and a “*feedback loop (causal loop)* is a closed sequence of causes and effects, that is, a closed path of action and information,” (Richardson and Pugh 1981). In system dynamics, a system can be represented either as open or closed, depending on whether output elements influence the input elements or not; open systems do not take into account feedback whereas closed systems involve feedback and influence their past system variables (Forrester 1968).

The causal loop diagram consists of system elements and arrows (known as causal links) with a positive or negative sign on each link to represent the positive or negative influence on the succeeding element. In a closed system, there are two types of feedback loops: positive loops (reinforcing) and negative loops (balancing or counteracting loops). Figure 3.8 represents the positive and negative feedback or causal loop diagram.

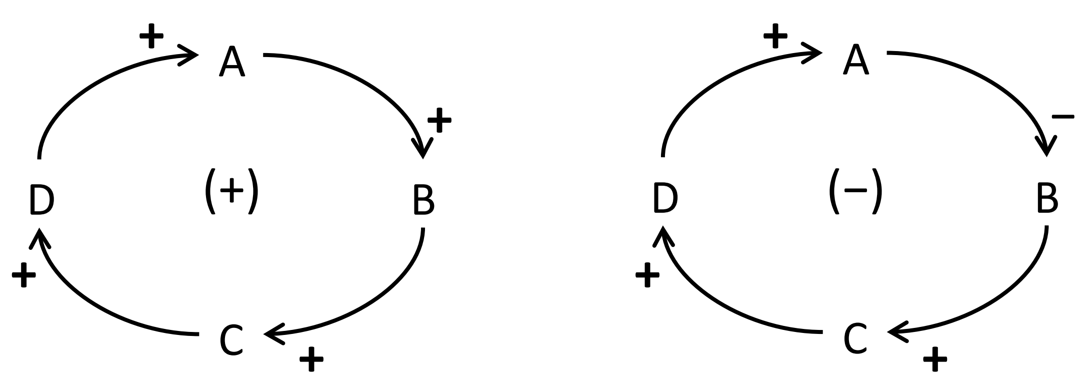


Figure 3.8: Graphical notation of positive and negative feedback or causal loops diagram.

In the above Figure 3.8, the sign at the arrow head represents the influence that a preceding element would have on the next element. A positive (+) sign indicates that a change in element A would produce a positive change in element B or a change in the same direction. And a negative (-) sign indicates that a change in element A would produce a negative change in element B or a change in the opposite direction. And the positive or negative sign in the middle denotes whether the causal loop is reinforcing or balancing. If the causal loop contains an "even" number of negative signs then it is a positive (reinforcing) causal loop and if it contains "odd" number of negative signs then it is a negative (balancing) causal loop.

For example, Figure 3.9 shows an example for sales growth having a combination of positive and negative casual loops (Kirkwood 1998).

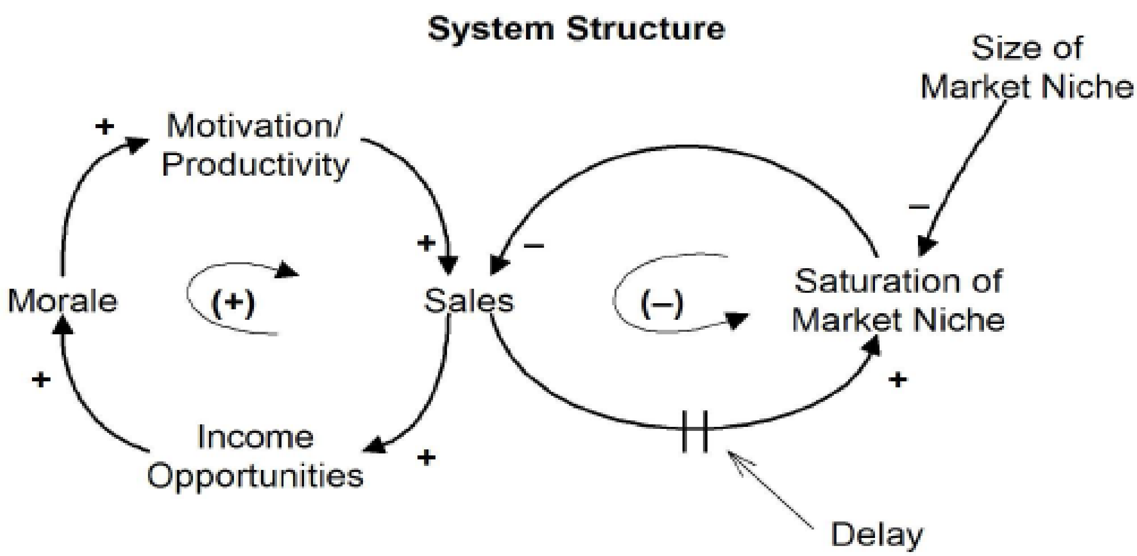


Figure 3.9: Sales Growth example for combination of positive and negative causal loops (Kirkwood 1998).

A positive (reinforcing) causal loop reinforces change or amplifies the behavior of the system with more change in the same direction. This usually leads to rapid growth or decline at an ever increasing rate leading to destabilizing the systems. And thus positive loops are often known as vicious or virtuous cycles/loops. A negative (balancing) causal loop tends to show to a goal-seeking behavior aimed at moving the system towards a desired state. These loop structures aim at either increasing or decreasing the value of the elements present in order to stabilize the system and reach equilibrium. When both the positive and negative causal loops are present in a feedback diagram, interactions of both of positive and negative loops may results in a combination of system behaviors of linear or exponential growth, decline, oscillations, and other patterns of behavior (Sterman, 2000).

In *system dynamics* modeling, apart from the patterns of behavior, feedback and casual loop diagrams, other main building blocks are *stocks and flows* representing the structure of the system. Radzicki and Taylor (1997) suggest that the dynamic behavior in system dynamic modeling "is thought to arise due to the Principle of Accumulation; according to which all dynamic behavior in the world occurs when flows accumulate in stocks". The causal loop diagrams are converted into stock and flow diagrams to represent the dynamic behavior of a system with the help of mathematical equations that cannot be accomplished with only feedback or casual loop diagrams.

The stocks (also known as levels) are used to represent the state variables that undergo a change in a system. Stocks are defined at a particular point of time and have a definite value. They can be a measure of the quantity accumulated in them by inflows and depleted by outflows. The flows (also known as rates) are used to represent the actions that produce or control the changes in the stocks. They are usually measured over a period of time and represent both the inflows and outflows from the stocks. Stocks can be represented by rectangles and flows by valves.

3.4.3 SD Modeling Tools

In system dynamics, modeling and analysis of complex dynamic system is done with the use of computer simulation tools. These simulation tools help to visually depict and communicate the mental models of complex dynamic systems with much ease and better understanding of the real system.

Sterman (1992) provided the following advantages of using computer models over mental models (Sterman 1992):

1. Mental models are "dynamically deficient, omitting feedbacks, time delays, accumulations, and nonlinearities"
2. Computer models are explicit and their assumptions are open to all for review.
3. They can accurately compute the logical consequences of the modeler's assumptions.
4. They can be simulated under controlled conditions, allowing analysts to conduct experiments which are not feasible or ethical in the real system.

In the late 1950s and early 1960s, System Dynamics evolved from hand-simulation of mental models to computer modeling and simulation due to the efforts of Forrester and a team of graduate students (Radzicki and Taylor 1997). SIMPLE (Simulation of Industrial Management Problems with Lots of Equations) was the first system dynamics computer modeling language developed by Richard Bennett in 1958 and a year later in 1959, an improved version of SIMPLE known as DYNAMO (DYNAmic MOdels) was developed by Phyllis Fox and Alexander Pugh that was used in the industry for several decades (Richardson and Pugh 1981; Forrester 1995). DYNAMO is based on "writing source equations and lacks a modern graphical user interface" (Madachy 2008). After DYNAMO, the system dynamics simulation tools have evolved and improved to a great extent and now include visual interface along with custom programming and extensive numerical analysis features. Some of the present system dynamics simulation tools are Extend, iThink/Stella, Powersim, and Vensim.

3.4.4 SD Application

System dynamics can be applied to a wide range of systems where state variables change over time. It was originally developed to analyze business management systems but since its origin it has been successfully applied to a number of social-economic systems (Forrester, 1961), business systems (Sterman 2000), environmental systems (Ford 1999), healthcare systems (Homer and Hirsch 2006), agricultural systems (Saysel et al 2002), urban and global systems (Forrester and Collins 1969, Forrester 1971) etc.

System dynamics has proven to be an effective tool for modeling and aiding the decision making process for engineering and construction project management. Several issues ranging from high number of construction changes, rework, resource allocation, quality issues, and risk analysis have been successfully addressed with the help of system dynamics.

For example, Love et al (2002) used system dynamics to better understand change and rework in construction project management systems. Quality issues facing the construction industry were identified by modeling the internal and external dynamics in a project using the feedback loop diagrams. Change and rework issues were also addressed by Park and Pena-Mora (2003) by providing a dynamic planning and control methodology (DPM) model to predict the changes in construction affecting the project performance. The model identified the feedback process resulting from construction changes by determining the behavior patterns of construction change and analyzed change impact on the construction performance using system dynamics. However, uncertainties resulting from changes were not explicitly addressed by the DPM model. Lee et al (2005) developed an enhanced DPM model, aimed at protecting the planned performance against resulting from errors and changes. Feedback processes on quality and change management process were identified along with development of construction process model with the help of system dynamics.

In addition, system dynamics has been successfully applied in construction systems to explore performance enhancement in construction organizations (Ogunlana et al 2003), construction risk analysis (Nasirzadeh et al 2008), dynamic resource management for construction projects (Park 2005), for managing constructibility reviews to reduce highway project durations (Damron et al 2004), to explore the effects of resource allocation policies on project durations (Lee et al 2004), for managing the dynamics of projects and changes (Cooper and Lee 2009), Lean Construction (El-Gafy and Abdelhamid 2010),evaluating the alternative of type in construction and demolition waste (Zhao et al 2011).

3.4.5 SD Advantages and Limitations

Sterman (1992) suggested that large scale projects belong to a class of complex dynamic systems and are characterized by the following:

1. High complexity, involving multiple interdependent components
2. Highly dynamic
3. Multiple feedback processes
4. Non-linear relationships
5. Both hard (direct) and soft (indirect) data

System dynamics has proven useful in representing the construction system involving these above characteristics that are difficult to model in the DES. However, SD is unable to represent the process details involved in construction operations that can be easily modeled using DES

(Williams 2002). DES models have mainly addressed the operational issues whereas SD models have been more successful in addressing the management and strategic issues.

3.5 Chapter Summary

This chapter provides an overview of the simulation approaches such as Discrete Event Simulation and System Dynamics modeling in detail along with discussing the applications, advantages and limitations of each of the modeling techniques in order to gain better understanding of the process of building simulation models.

4 LEAN BASED CREW DESIGN

4.1 Introduction

Construction work is executed by a variety of speciality trades, using group of workers commonly known as crews. Yet decisions regarding how to design crew make-up and improve their performance are seldom formally addressed. Designing a crew to carry out an operation in a dynamically changing construction environment is a complex task; still it has usually been approached with assumptions or self-discretions of the supervisor/foreman that rarely materialize and at times lead to low performance.

Performance of these crews is very crucial to the work being executed and consequently for the overall project performance. Any change in the crew size, composition, and other important crew design parameters might result in irreversible spiralling consequences to the cost, duration, and other performance outcomes. However, despite the clear significance of crew design, only a modest scholarly interest in this area has been seen in the last two decades.

The aim of this research was to develop a lean-based crew design model that integrate both existing *crew design* and *work design* research and lean principles for designing and improving the performance of crews. This was achieved by conducting an extensive literature review and investigating and synthesizing research studies on "work design/team design" that have well developed theoretical and empirical foundations in *lean production*, *lean construction*, *socio-technical system theory*, *social and organizational psychology.* This chapter presents the resulting model, parts of which will be tested in the following chapter between Discrete Event Simulation and Systems Dynamics.

4.2 Crew and Work Design Concept

Crew design is often confused with construction process design (method or operation design). However, in this research we use crew design as an integral part of any production process that involves the analysis and redesign of crew make-up. As discussed in the previous sections, crew design involves both the design of "*group of workers/people*" and the "*work/job*" that needs to be executed by them.

There are numerous decisions to be made regarding how the work is to be executed, how many workers need to be in a crew/team, what should be the composition of workers in a crew, sequencing of tasks, how the work should flow among the workers in a crew, and so on. Design of only one aspect would not lead to a joint optimization of both *work* and *team/crew*. Work teams have been common both in manufacturing and service industry. Optimizing the performance of crews (production work teams) is a very essential element as "work teams are considered to be an integral tool aiding continuous improvement in work operations" (Cutcher-Gershenfeld and Associates 1994).

For this research, the Cohen and Bailey (1997) and Sundstrom (1990, 1999) classification is used where work teams are defined as "continuing work units responsible for producing goods and providing service," as it fits very well with the description of a "crew" for a production setting in construction.

4.3 Lean Crew Design Characteristics

The lean crew design characteristics were developed by synthesizing the existing crew and work design approaches from *lean production, lean construction, socio-technical system theory, and social and organizational psychology* (as conceptually depicted in Figure 4.1).

The crew design characteristics are those that should be considered during the crew design process.

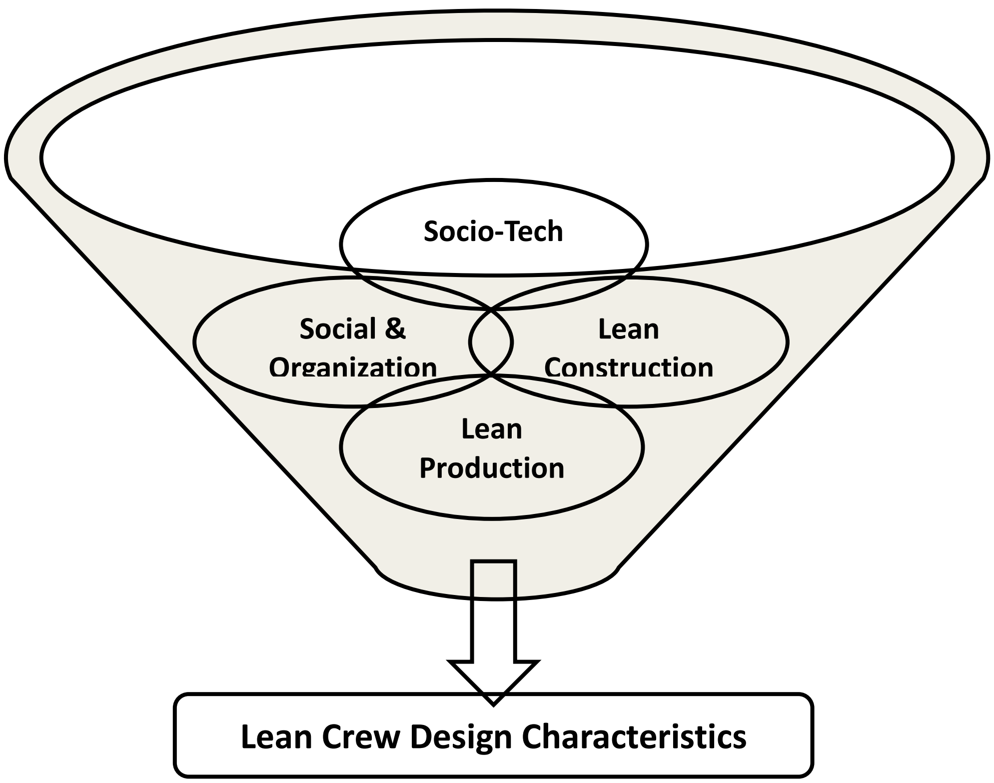


Figure 4.1: Synthesis of existing crew and work design approaches.

In general, performance is the ability to meet preset targets or standards. In this research, targets for a crew are set based on: (1) satisfaction; (2) motivation; (3) learning; (4) pride in work performed; (5) cost of work performed; (6) duration of work performed; (7) quality for work performed; (8) productivity. The lean crew design characteristics that would lead to high crew performance are shown in Figure 4.2. In Figure 4.2, lean crew design characteristics are comprised of “primary crew design characteristics”, “intermediate crew design characteristics and outcomes” and “final crew performance outcomes”. The primary crew design characteristics are divided into two groups (1) work characteristics and (2) flow characteristics. These are discussed in the following sections.

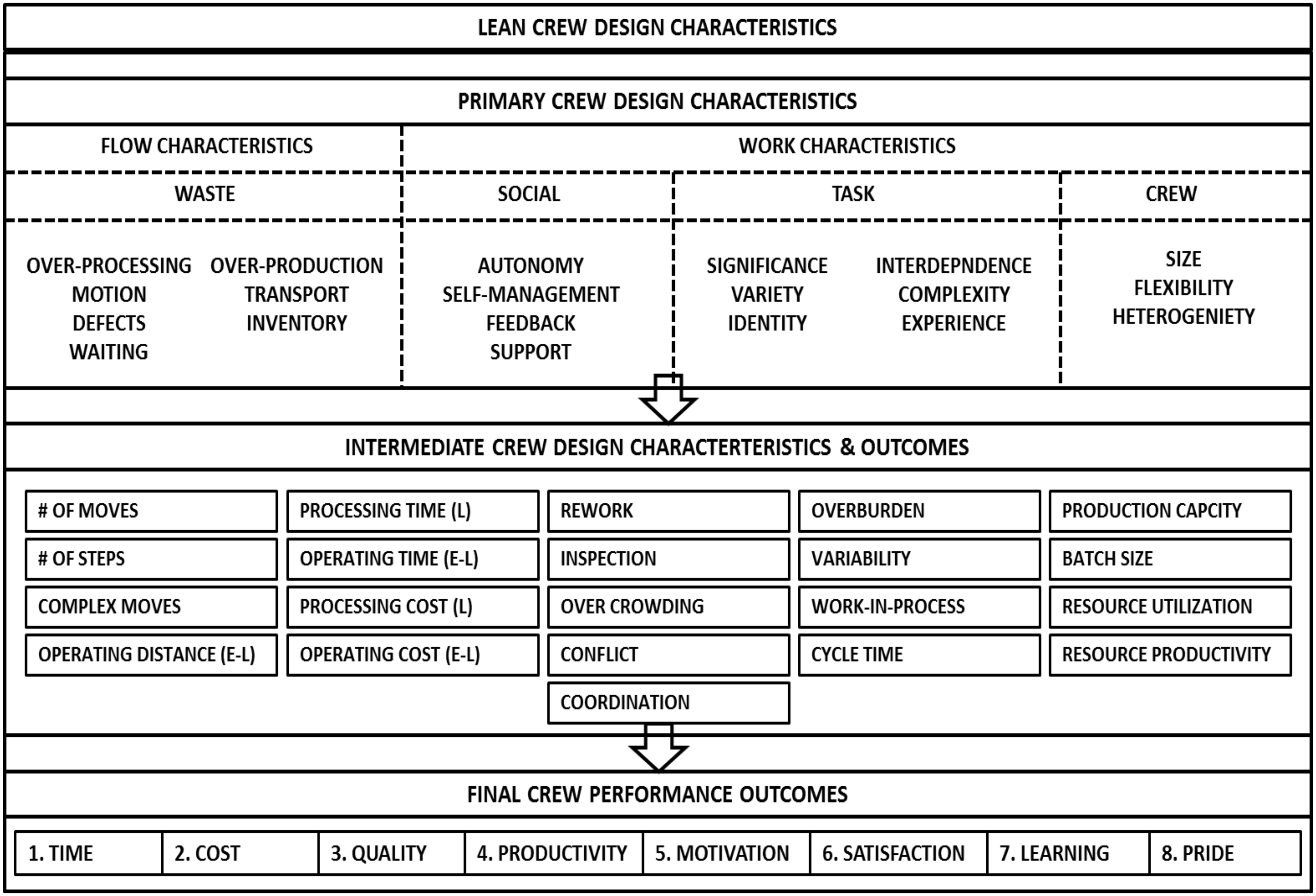


Figure 4.2: Lean Crew Design Characteristics

4.3.1 Flow Characteristics

The flow characteristics have been derived from Lean Production (Shingo 1989; Ohno 1988; Womack et al. 1990; Womack and Jones 1996) and Lean Construction (Howell and Ballard 1999; Koskela 1992, 2002). The primary flow characteristics are aimed at the elimination of waste in order to achieve continuous flow for the operations executed by the crew.

The flow characteristics are grouped into 7 types of waste characteristics: (1) Motion; (2) Transport; (3) Over-processing; (4) Over-production; (5) Inventory; (6) Waiting; (7) Defects. These primary flow characteristics are further divided into intermediate crew design characteristics and outcomes. The causal relationships are provided in Figure 4.3 to better understand and develop the feedback or casual loop diagrams in the next chapter of simulation model building. In Figure 4.3, the plus sign denotes an increase (positive effect) and a minus sign denotes a decrease (negative effect) on the characteristic or outcome.

The crew should be designed in a way that reduces or eliminates all the seven types of wastes. Excessive *Motion* (Figure 4. 3) is one of the seven wastes in the flow characteristics that should be kept to minimum in order to enhance crew performance in terms of duration and cost of operations. Excessive motion may lead to more moves than needed for the crew. Any increase in the number of moves or the complexity of moves would increase the processing time a crew takes to execute an operation. In turn, this increases the processing time, leading to an increase in cycle time and the processing cost associated with an increase in the labor cost. Hence, in order to improve the crew performance, excessive motion should be reduced and eliminated.

Excessive *Transport* (Figure 4. 3) has also been found to have a direct correlation with cycle time and operating costs. More transport would mean that both the labor and equipment are subjected to travel and operate over long distances that would increase the operating time leading to an increase in cycle time and operating costs for both labor and equipment. Hence in order to improve crew performance, excessive transport should be reduced or eliminated.

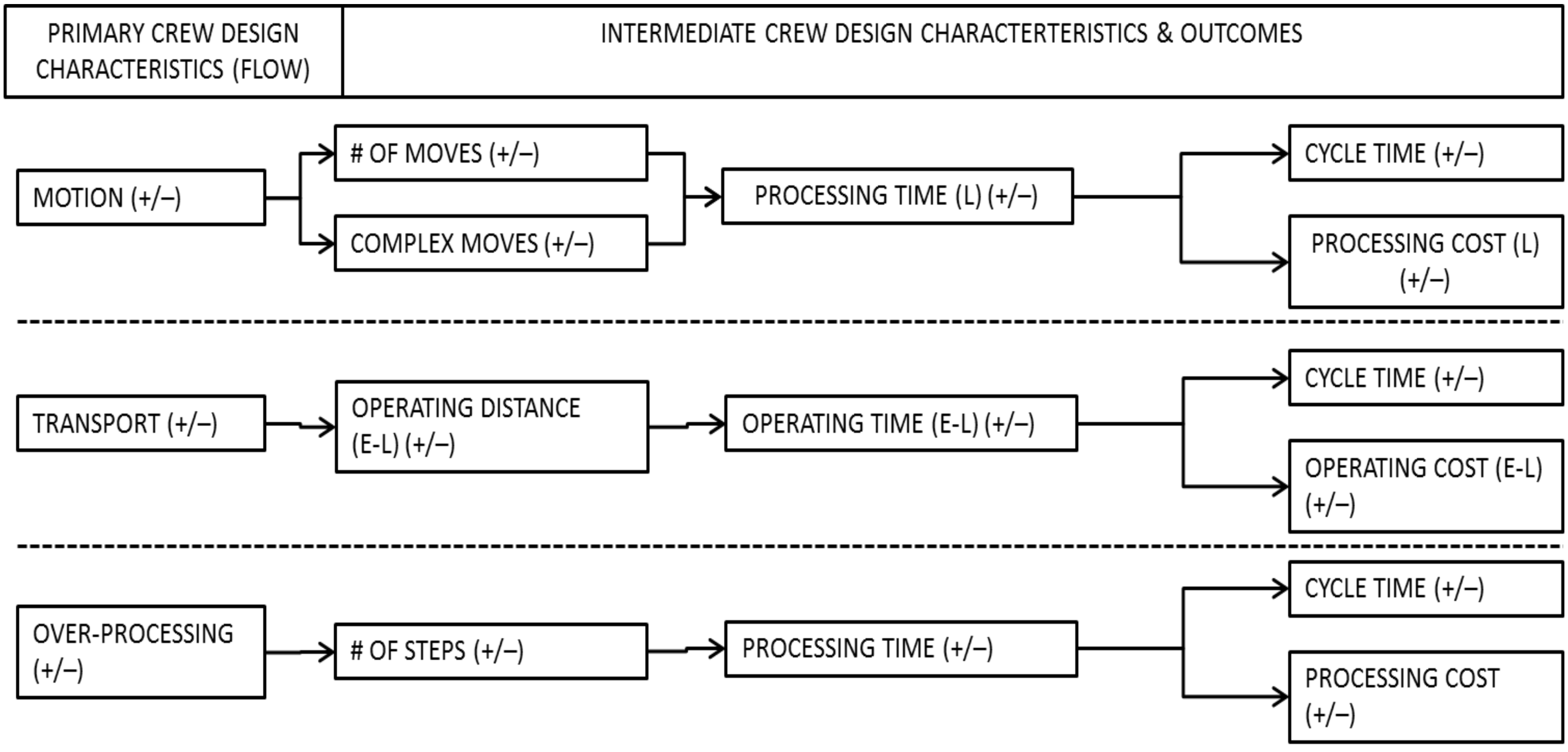


Figure 4.3: Causal relationships between primary & intermediate crew design (flow) characteristics and the final crew performance outcomes (Part A).

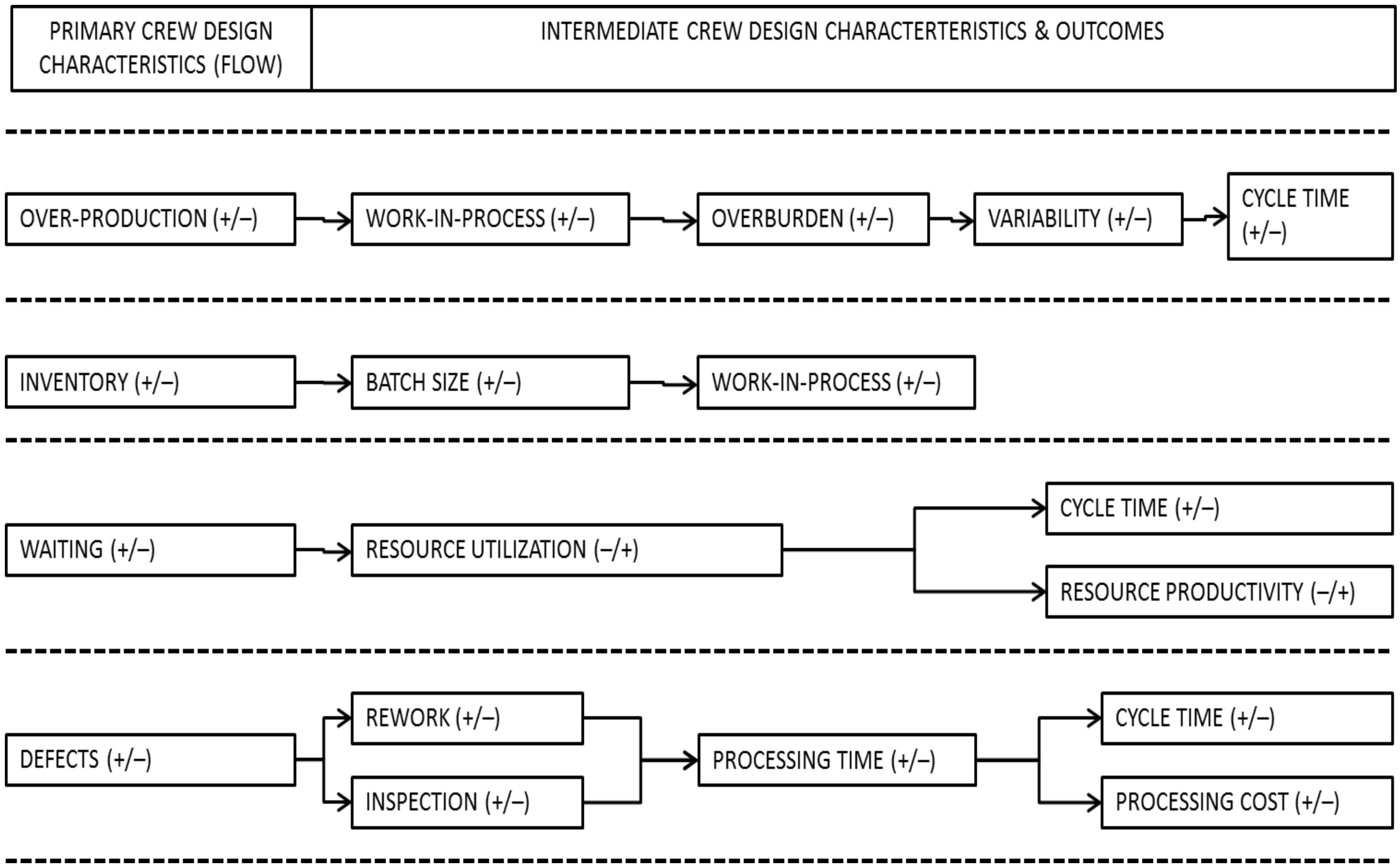


Figure 4.4: Causal relationships between primary & intermediate crew design (flow) characteristics and the final crew performance outcomes (Part B).

Another waste that has direct correlation with increasing the *cycle time* and *processing cost* is *Over-processing* (Figure 4. 3) increases the *numbers of steps* that are employed to carry out an operation by a crew than that are actually required to deliver value. Increased *number of steps* then in turn increases the *processing cost* and *cycle time* of the operation. Hence in order to improve crew performance, over-processing should be reduced or eliminated.

Over-production (Figure 4.4) is considered to be the most serious waste, and should be avoided whenever possible. Over producing products/work that cannot be completed or finished leads to *work-in-progress* in the intermediate steps involved in an operation. This is a major cause for *overburden* among the workers executing the operation. This *overburden* among the workers in turn may lead to *variation* in the operation leading to non-uniform flow that in turn leads to increase in the *cycle time* of operations. Hence, a crew, and their work, should be designed in way that it is not *over-producing*

Another waste that leads to work-in-progress is excessive *Inventory* (Figure 4.4). More *inventory* than necessary at times leads to an increase in the *batch-size*. And increasing the batch size without increasing the production capacity of the crew would lead to more *work-in-progress* along with other kinds of wastes (e.g., transportation). Hence in order to improve crew performance, minimum *inventory* should be kept that can be finished/completed by the crew without leading to any *work-in-progress*.

In addition, a crew should be designed in way that minimizes the waste of *Waiting*. Wait-time among the crew would mean a decrease in the *resource utilization* of the crew leading to an increase in the *cycle time*. Also if the crew is not utilized close to, but not at, its maximum capacity, that would mean a decrease in the overall *productivity* of the crew.

And finally, a crew should be designed in such a way that they execute an operation with minimum *Defects* (Figure 4.4). An increase in the number of *defects* would lead to an increase in amount of *inspection* and *rework* that needs to be done. Both *rework* and *inspection* would lead to an increase in the *processing time* that would in turn increase the *cycle time* and *processing cost*.

4.3.2 Work Characteristics

The "Work Characteristics" (derived from socio-technical system theory, social and organizational psychology) have been based on significant studies conducted by other authors (Gladstein 1984; Hackman 1980, 1987; Hackman and Oldham 1980; Guzzo and Shea 1992; Niepcel and Molleman 1998; Steiner, 1972; Davis and Wacker, 1987; Campion et al 1993, 2005; Morgeson and Campion 2003; Morgeson et al 2005, 2006, 2008; Medsker and Campion 2007; Cohen and Bailey 1997; Leach et al 2005; Kozlowski and Bell 2003).

Crew, Task, and Social, are the further division of "Work Characteristics" (Figure 4.2). For 'Crew', the factors are *size, flexibility* and *heterogeneity*.

Crew size (Figure 4.5) is the number of individuals in a crew/team. Increasing the *size* of crew does increase the *production capacity* of crew and thereby may increase the overall ou*tput* of crew for that operation. But at the same time, increasing *size* also increases the cost of labor increasing the *total cost* to execute that operation. Increasing the crew *size* may also lead to over-*crowding* if sufficient space is not available. And *over-crowding* may lead to more *conflict* and less *coordination* among the crew members that may finally lead to less *motivation, satisfaction* and *learning* among the crew members to work together to execute an operation.

Crew flexibility (Figure 4.5) is the ability of the crew members to perform each other's' task/work; it could also be known as synonym for *multi-tasking*. If there is more flexibility among the crew members, it would mean that apart from performing their own tasks, they would be able to help their crew members in their tasks/work if required. This would save *time* taken to execute an operation by a crew as idle crew members would be able to perform others' tasks and shorten the operation duration. Also this would lead to direct savings in the number of workers needed in a crew reducing the labor *costs*, as the need for specialized labor would be reduced having crew members which can multi-task. Finally, having more crew *flexibility* would also lead to *satisfaction* and *learning* among the crew members arising from the feeling of helping their team/crew members and learning from them as a result of working together.

Crew heterogeneity relates to how a crew is composed in terms of its member's experience, skills, etc. A more *heterogeneous* crew would mean crew members have a more variety of skills, knowledge, and experience level. If there is variety in the crew, then the more experienced crew members would be able to provide *support* (technical) in terms of sharing their expertise and knowledge with other crew members and encourage *learning* of other crew members. Having a more heterogeneous crew may also lead to more *motivation* among the crew either to provide *support* or to *learn* from others crew members.

The 'work characteristic' *Task* is itself made of *significance, variety, identity, interdependence, complexity, and experience,* all are significant characteristics affecting the crew performance.

Task significance means the extent to which the crews' work has significant consequences and impact on the project success. It would be logical to say that if a crew is involved in a *significant* task/work, they would be more *motivated* towards executing the task/work with the best of their abilities compared to if they are involved in a mundane or not so significant task/work. Consequently, with an increase in task/work significance, a crew may be more *satisfied* of executing it than if the task/work was simple and not so significant.

Task variety means the extent to which workers are involved in a variety of tasks; it relates to the concept of job-enlargement from socio-technical theory allowing both interesting and dull tasks to be shared among members. Having more task variety would mean crew members would be more satisfied while executing an operation as they would not be involved with doing the same task/work over and over again. This would also mean more learning among the crew as they would be involved in a variety of tasks.

Task identity is the degree to which the group/individual completes an entire or separate piece of work from start to finish. And more the crew members can relate themselves with a particular task/work and be able to take ownership of the work performed, the logical it seems that it may increase worker *motivation* by instilling a feeling of *pride*. And also completing a *task* from starting to end may also lead to feeling of *satisfaction* among the crew members.

T*ask complexity* can be defined as the extent to which a task/work is difficult to perform. Increase in the *complexity of tasks/work* performed by the crew may lead to an increase in the *processing time*, and may also reduce the quality of work performed due to the complex nature of work. And as discussed earlier, any increase in the processing time would lead to an increase in the *processing cost* and *cycle time*. Further, it is also argued that reducing the complexity or simplifying work should generally lead to productivity gains for the crew.

Task experience is the amount of time spent by a team/individual in performing a task; the number of times a similar type of task has been performed; or the prior amount of knowledge an individual has in performing that task. More task experience would mean having more expertise and knowledge in carrying out a particular task. It may lead to higher productivity of crew members having higher experience and consequently may lead to higher labor costs of crew members having higher experience. Another benefit of having crew members with high task experience would be in terms of support (technical) they can provide to other members of the crew and also lead to learning among the crew members.

Task Interdependence exists when a group of individuals get together and depend on one another to perform a certain work consisting of several tasks; and either start or finish of one task is dependent on the other tasks. It is related to *cycle time*, *work-in-progress* or *in-process inventory, overburden,* and *work flow disruptions*. High interdependence may lead to a continuous overburden leading to work flow disruptions (high task interdependence makes it essential to finish the task on or before time so that the tasks down the line are not stopped or waiting because of the incomplete tasks preceding them). And as discussed earlier high overburden is directly correlated with *variability, low quality,* and *non-uniform flow* leading to an increase in *cycle time*.

The 'work characteristic' *Social* is itself made of *autonomy, self-management, feedback, and support,* all are also significant characteristics affecting the crew performance.

Autonomy means the "amount of freedom and independence an individual has in terms of carrying out his or her work assignment. Increased autonomy in execution of work leads to increased work *satisfaction* and *motivation* among the workers.

Self-management is the group level analogy to Autonomy and is presumed to enhance performance or effectiveness. Providing increased autonomy to the crew would make them more responsible towards the outcomes of their work by increasing their sense of ownership of the work. However, the literature indicates that moderate amount of autonomy works better than no or full autonomy to teams/crews to execute their work. Usually a top-down approach is adopted by management to improve the performance of the crews/teams; but giving a team/crew moderate level of autonomy would only help them to identify and suggest solutions for root cause problems occurring at the production level in the tasks/work executed by them. Also self-management of work by the team/crew increases the sense of pride in the crew as they are able to manage their work by themselves by increasing the worker's sense of ownership of the work.

Further, both *Feedback* and *Support* are significant characteristics in the design of crews/teams. Proper feedback from the supervisors or management about the work executed by the crew/team would lead to less conflict among the crew members. Having timely feedback would also provide a feeling of satisfaction among the crew and also motivate them to improve their performance if required. This would finally lead to learning among the crew as they would be aware of their performance about the work executed by them.

Support is ability to get assistance, help, and advice from crew/team members, supervisors and management in both the technical and social aspects. Opportunities for either technical or social support would logically lead to a higher team/crew performance by increasing the motivation, satisfaction and learning among the crew.

As a summary of the causal relationships among the primary and intermediate crew design characteristics and final crew performance outcomes, Figure 4.5 was constructed. The knowledge of these cause and effect relationships is of value in determining the optimal crew design. In this graphical representation, the plus sign denotes an increase (positive effect) and a minus sign denotes a decrease (negative effect) on the characteristic or outcome.

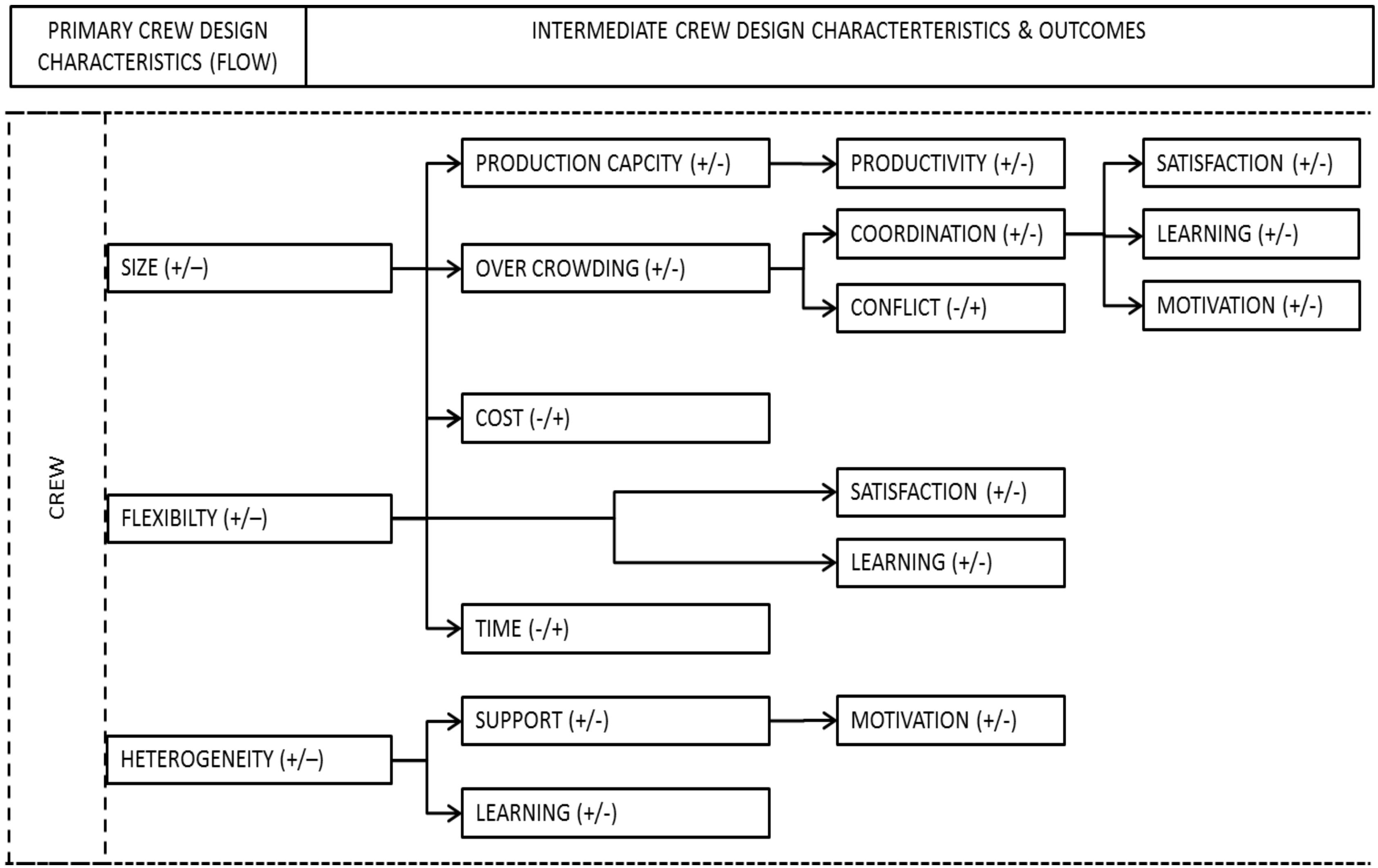


Figure 4.5: Causal relationships between primary & intermediate crew design (work) characteristics and the final crew performance outcomes (Part A).

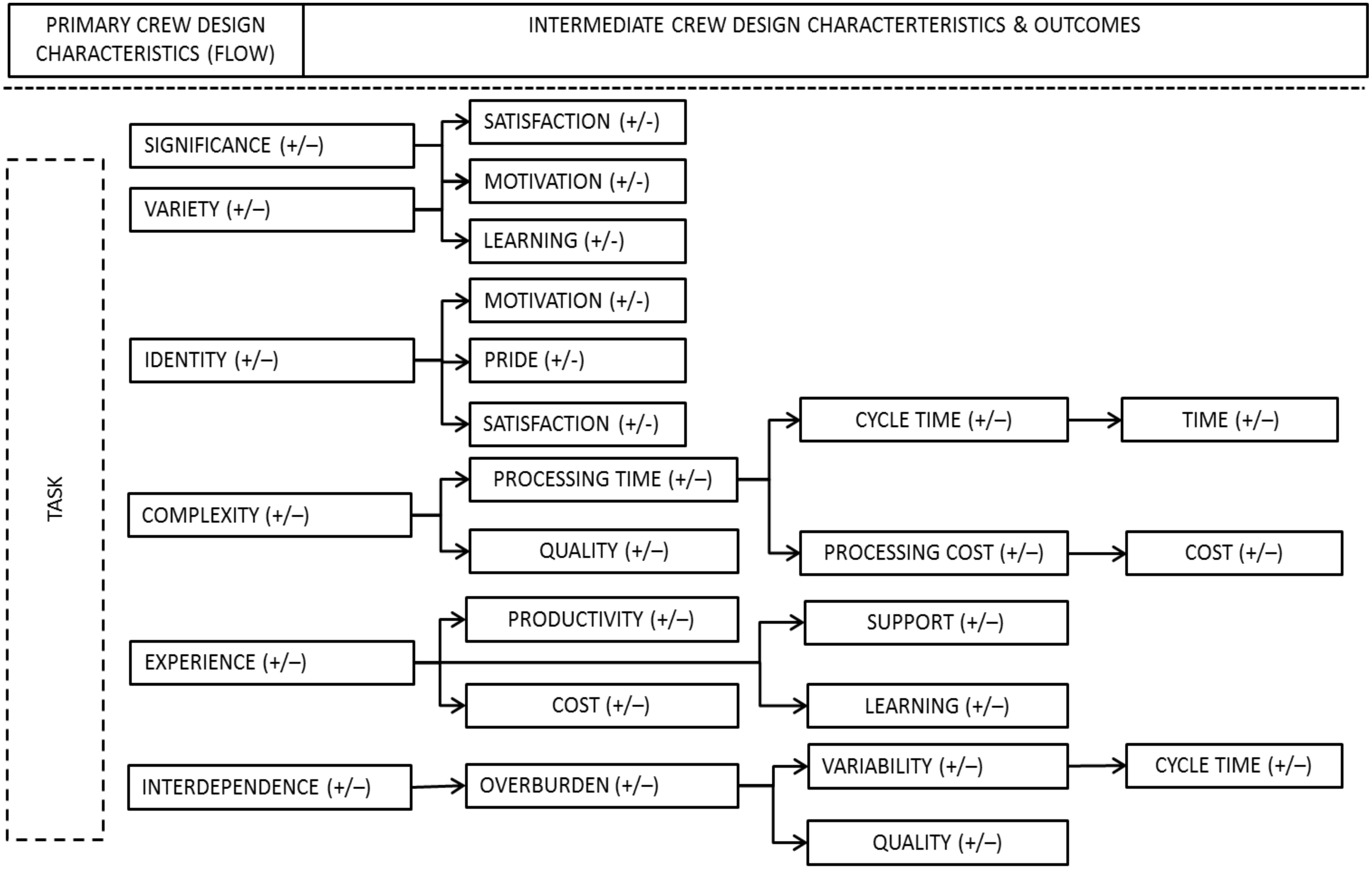


Figure 4.6: Causal relationships between primary & intermediate crew design (work) characteristics and the final crew performance outcomes (Part B).

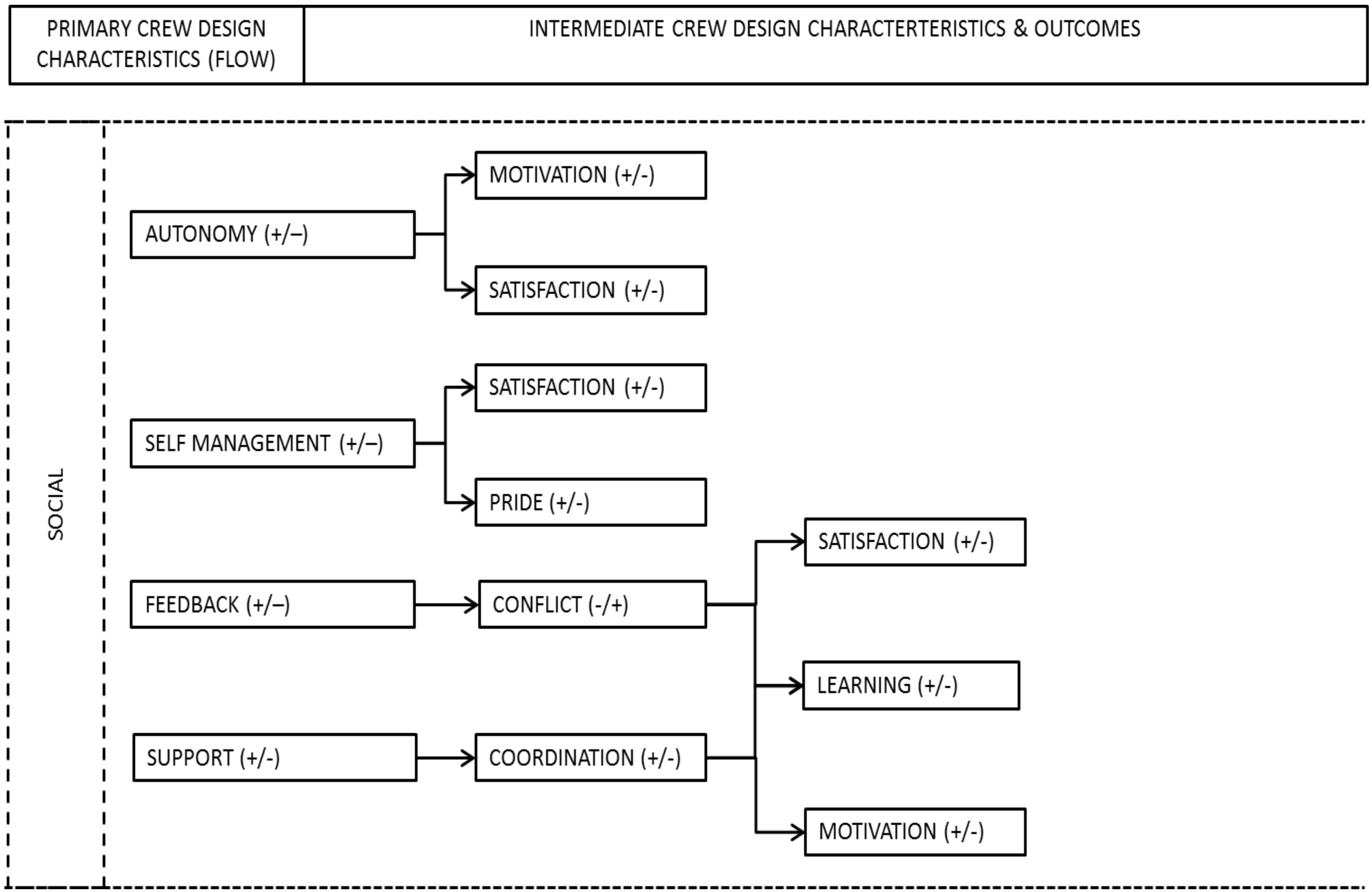


Figure 4.7: Causal relationships between primary & intermediate crew design (work) characteristics and the final crew performance outcomes (Part C).

The primary team/crew design (flow and work) characteristics and intermediate crew design characteristics and performance outcomes can be defined in terms of hard (direct factors affecting the crew performance) and soft (indirect factors affecting the crew performance) factors (Figure 4.5 and 4.6).

HARD FACTORS AFFECTING THE CREW PERFORMANCE				
CREW SIZE	PROCESSING	OPERATING	PRODUCTION	RESOURCE
# OF MOVES	OPERATING	OPERATING	CYCLE TIME	RESOURCE
# OF STEPS	PROCESSING	WORK-IN-	BATCH SIZE	

Figure 4.8: Hard factors affecting the crew performance.

SOFT FACTORS AFFECTING THE CREW PERFORMANCE				
CREW SIZE	TASK	AUTONOMY	COMPLEX	CONFLICT
CREW	TASK VARIETY	SELF-	REWORK	COORDINATIO
CREW	TASK IDENTITY	FEEDBACK	INSPECTION	OVER-
	TASK	SUPPORT	DEFECTS	OVERBURDEN
	TASK	TASK		VARIABILITY

Figure 4.9: Soft factors affecting the crew performance.

4.4 Lean Crew Design Guidelines

The objective in this stage is to make sure that the crew has a design that would lead to maximizing their performance. The guidelines for Lean Crew Design are proposed by primarily reviewing research studies on “work design/team design” that have well developed theoretical and empirical foundations in *lean production, lean construction, socio-technical system theory, and social and organizational psychology.*

The proposed guidelines lead to the joint optimization of both the *crew* and the *work* performed, resulting in better overall *crew performance*. In this research, *crew performance* is defined in terms of: (1) *duration* of work performed; (2) *cost* of work performed; (3) *productivity*; (4) *quality* of work performed; (5) worker *satisfaction*; (6) worker *learning*; (7) worker *motivation*; (8) *pride* in work performed.

The *crew performance* is optimized by (1) "Minimizing Waste" in the construction operations and (2) "Maximizing Value" generation in the construction operations. "Minimizing Waste" in the work performed by the crew is achieved by eliminating or reducing the seven types of wastes discussed in the previous section (integrated lean crew design framework) namely: (1) Transport; (2) Inventory; (3) Motion; (4) Waiting; (5) Overproduction; (6) Over Processing; (7) Defects. And "Value" in the design of crews is maximized by optimizing the (1) *duration* of work performed; (2) *cost* of work performed; (3) *productivity*; (4) *quality* of work performed; (5) worker *satisfaction*; (6) worker *learning*; (7) worker *motivation*; (8) *pride* in work performed. Maximum "Value" in the design of crews is delivered by optimizing all the eight performance outcomes; however the crew could also be designed based on the either of the targeted performance criterion. Guidelines for optimizing each of the eight performance outcomes are presented in the following section:

(1) The ***"Duration of Work performed"*** can be optimized by improving and keeping the cycle time of the operation to the minimum. Steps involved in reducing the cycle-time of operations are as follows:

1) *Simplification of process and reduction of processing time*

i. Reduce the number of unnecessary steps in a process

A construction operation consists of a number of processes and each process has number of steps known as activities. The design of the crew in terms of crew size and crew composition depends on the number of steps required to execute a particular process. More number of steps in a process would increase the total processing time resulting in higher cycle time and increasing the duration of work performed by a crew. Hence, crew design (design of "*group of workers/people*" and the "*work/job*" that needs to be executed by them – see section 4.2) should target a minimum number of steps in a process.

ii. Reduce the number of moves required to execute each step in a process

A number of moves (tasks) are required to execute each step (activity) in a process. More number of moves to execute each step in a process would increase the total processing time resulting in higher cycle time and increasing the duration of work performed by a crew. Hence, crew design should target a minimum number of moves required to execute each step in a process.

iii. Reduce the task complexity/number of complex moves in each step in a process

Task complexity or the number of complex moves in each step of the process is directly proportional to the processing time of the work performed by the crew. Higher task complexity or more number of complex moves in a process would increase the total processing time resulting in higher cycle time, leading to longer overall work duration. Hence, crew design should focus on simplifying tasks and moves involved in the process.

iv. Reduce the operating distance to execute each step in a process

The operating distance required to execute each step in a process is directly proportional to the processing time of the work performed by the crew. Higher operating distance to execute the steps in a process would increase the total processing time resulting in higher cycle time, leading to longr duration of work. Hence, crew design should consider minimizing the operating distances that crew has to traverse.

v. Increase the movement speed for the operating distances

Increasing the movement speed for the operating distances to execute the steps involved in a process would decrease the processing time resulting in reduced cycle time. Crew design should therefore increase the movement speed over the operating distances.

2) *Reduction of non-processing time*

i. Reduce transportation/motion time

Non-processing time such as excess transportation/motion time does not add value and increases the cycle time of the process and correspondingly the duration of the work performed. Any change in either the size or composition of the crew affects the amount of transportation/motion required to execute a process. Hence, crew design should target a minimum transportation/motion involved in the work performed by a crew.

ii. Reduce wait time

Wait time in a process increases the cycle time and correspondingly results in the increase in duration of the work. Wait time in a process does not add any value.

Any change in the crew size and composition would also change the wait time in the process being executed by the crew. Crew design should therefore minimize wait times where possible.

iii. Reduce set-up time

Set-up time in a process increases the cycle time and correspondingly results in the increase in duration of the work. Set-up time does not have any direct value to the process. A crew design should consider reductions in set-up times using administrative or engineering interventions.

iv. Reduce inspection time

Inspection time in a process increases the cycle time and correspondingly results in the increase in duration of the work. Inspection time does not add any direct value to the process. Hence, crew design should incorporate in-line or built-in inspections (manual or automated) to reduce the overall inspection times.

v. Reduce rework

Rework in a process takes up considerable amount of time in delivering the finished product while increasing the cycle time and correspondingly resulting in the increase in duration of the work. Rework time does not add any direct value to the process. It could be reduced by doing the work correct the first time, which is a critical component of a crew design process often known as built-in quality (job done right the very first time leading to reduced rework in the process).

3) *Reduction of Variation*

i. Level the work load among each step of the process

Variation in a process leads to an increase in the cycle time and correspondingly results in the increase in duration of the work. Variable workload may lead to increased wait times in a process and uneven flow of work in a process. It can be reduced by leveling the workload among the different production units (production steps) in a process. Hence, crew design should target making the operation production rate of each production unit (production step) to be equal to the maximum production rate in that process leading to continuous and uniform flow of work.

ii. Reduce overburden (muri)

Overburden (muri) results in variable work rate resulting in increased variation in a process; that may again increase the cycle time and the duration of the work. Hence, a crew design that eliminates or reduces overburden is critical.

iii. Reduce work-in-process (WIP)

Work-in-process occurs when more products are produced than can be processed or installed completely; it is the work that has been started but not completed and is still in process. It leads to overburden, variation and finally increases the cycle time to finish each product and correspondingly results in the increase in duration of the work. Hence, crew design is to reduce the work-in-process as much as possible.

iv. Reduce the batch size

The batch size has significant effect on the cycle time and duration of work. Increased batch size leads to increase in wait times, work-in-process, overburden, and more variability in a process. Hence, crew design should consider a set-up that leads to minimum batch sizes in a process.

v. Apply pull system

Pull systems are very effective in reducing over-production leading to the better cycle time and duration of work. Hence, a crew design should integrate pull systems such that that the products are pulled by the production units (crew members) whenever needed.

(2) The **"*Cost of Work performed*"** can be optimized by the following steps:

1) *Keep the crew size to minimum*
2) *Increase crew flexibility*
3) *Reduce processing cost*
4) *Reduce non-processing cost*
5) *Reduce defective products*

1) *Keep the crew size to minimum*

The crew size has a direct correlation with the cost of labor and correspondingly with the cost of work performed. Increasing the crew size more than is necessary to maintain the flow of work leads to increasing the cost of work performed. Hence, crew design should target the minimum crew size that will accomplish the intended operation. .

2) *Increase crew flexibility*

The crew flexibility is used as a synonym for multi-tasking. It is the ability of the crew members to perform each other's task/work. Increasing crew flexibility enables the crew members to help each other in executing the tasks of a process other than their own tasks. Higher crew flexibility saves times as idle crew members are better utilized leading to shortening the duration of a process and as a result save on labor costs. Also, with increased crew flexibility, and crew members involved in multi-tasking, the need for specialized labor for each task would be reduced leading to further optimizing the cost of work performed. Hence, a crew design should consider opportunities for crew flexibility.

3) *Reduce processing cost*

The cost associated with processing and performing the work should be reduced in order to optimize the total cost of work performed. Guidelines on designing a crew leading to reduced processing cost such as reducing the number of unnecessary steps in a process, reducing the number of moves required to execute each step in a process, reducing the task complexity/number of complex moves in each step in a process, reducing the operating distance to execute each step in a process, increasing the movement speed for the operating distances have been discussed in detail in the previous section.

4) *Reduce non-processing cost*

The non-processing cost associated with unnecessary or excessive transportation/motion time, wait time, set-up time, inspection time, rework should be reduced in order to optimize the total cost of work performed. Guidelines on designing a crew leading to reduced non-processing cost have been discussed in detail in the previous section.

5) *Reduce defective products*

The cost associated with the defective products increases the total cost of the work performed. More number of defective products leads to more rework and inspection required, leading to increase in the processing time, cycle time and correspondingly resulting in increased labor and processing costs. As discussed in detail earlier, crew design should target least amount of rework and inspection involved to complete a process.

(3) The **"*overall crew productivity*"** can be optimized by the following steps:

1) *Increase task experience of crew*
2) *Reduce overburden*
3) *Apply advanced technology to labor and equipment*
4) *Increase resource utilization*
5) *Increase crew flexibility*
6) *Increase crew heterogeneity*
7) *Reduce task complexity*
8) *Reduce task interdependence*

1) *Increase task experience of crew*

Task experience is directly correlated to the crew productivity to execute the work. Higher task experience or inclusion of more experienced workers is associated with higher labor productivity and correspondingly higher overall crew productivity. Hence, crew design should enable improvement of task experience and familiarity to execute more number of tasks in process than a single fixed task. Also, the crew design should include more experienced crew members in order to enhance the overall crew productivity.

2) *Reduce overburden*

Reducing overburden was discussed as a way to reduce variation in crew performance. The same applies here, wherein overburden is also inversely proportional to the productivity. A crew design that eliminates or reduces overburden is critical for overall crew productivity. *Apply advanced technology to labor and equipment*

Applying advanced technology to labor and equipment is associated with higher productivity for work to be performed. Hence a crew design should incorporate advanced technology where suitable and economical.

3) *Increase resource utilization*

Resource utilization is directly proportional to labor productivity. Increasing resource utilization is associated with higher crew productivity. However, in Lean Construction there is caution in making utilization a focus because it is possible to slip into local optimization and not system optimization. In other words, making one crew faster by being more productive will only benefit that crew and not the project as whole. Therefore, while a crew design should target higher resource utilization, this is to be balanced with the productivity of other crews that is possible through the use of the Last Planner System® – a topic outside the scope of this thesis. .

4) *Increase crew flexibility*

Crew flexibility was discussed earlier, and concluded that a crew design should consider opportunities for multi-tasking.

5) *Increase crew heterogeneity*

Crew heterogeneity as discussed earlier is positively associated with crew productivity. Increasing crew heterogeneity leads to higher variety of skills, knowledge, and experience among crew members that correspondingly leads to higher overall crew productivity. Hence, a crew design should target higher crew heterogeneity leading to higher overall productivity.

6) *Reduce task complexity*

As discussed earlier, task complexity has a major impact on work duration, making it directly proportional to productivity. Hence, crew design should focus on simplifying tasks and moves involved in the process..

7) *Reduce task interdependence*

Task interdependence refers to the relation between the series of tasks that a crew has to carry out in order to complete a construction operation – it can also be extended to mean interdependence between construction operations, which is not the focus of this thesis. As discussed in Chapter 2, task interdependence among the crew members can exist in the form of pooled, sequential or reciprocal, pooled being least and reciprocal being the highest form of interdependence. Lower task interdependence is associated with higher work-flow reliability and correspondingly higher overall crew productivity. Hence, crew design should target the least amount of task interdependence (pooled interdependence) among crew members.

(4) The **"*quality of work performed*"** can be optimized by the following steps:

1) *Reduce defective products*

(Proceeding discussion applies)

2) *Increase task experience*

Task experience is positively associated with the quality of work performed. Higher task experience of crew members' results in better quality of work performed, since the crew members are equipped with better knowledge and skills to execute the tasks they are more familiar or have experience in. Hence, crew design should enable improvement of task experience among the workers and inclusion of more experienced workers leading to better quality of work performed.

3) *<u>Reduce task complexity</u>*

(Proceeding discussion applies)

4) *<u>Reduce overburden</u>*

(Proceeding discussion applies)

5) *<u>Reduce task interdependence</u>*

(Proceeding discussion applies)

(5) The **"*<u>worker satisfaction</u>*"** can be optimized by the following steps:

1) *Reduce conflict*
2) *Increase coordination*
3) *Increase crew flexibility*
4) *Increase crew heterogeneity*
5) *Increase support*
6) *Increase task significance*
7) *Increase task variety*
8) *Increase task identity*
9) *Increase self-management*
10) *Provide reasonable autonomy*
11) *Increase feedback*

1) *<u>Increase coordination</u>*

Crew coordination is associated with crew satisfaction. Higher coordination is likely to produce more satisfaction among the crew to work together. Further coordination among crew members is influenced by over-crowding/congestion that is influenced by the change in crew size. Increase in over-crowding/congestion provides fewer opportunities for coordination and therefore lower satisfaction among crew members. Hence, the crew size should be selected in such a way that enables maximum coordination leading to higher satisfaction among crew members.

2) *Reduce conflict*

Conflict among crew members is also associated with crew satisfaction. Higher conflict is likely to produce less satisfaction among the crew to work together. Further conflict among crew members is influenced by over-crowding/congestion that is influenced by the change in crew size. Increase in over-crowding/congestion provides more chances for conflict and therefore lower satisfaction among crew members. Hence, the crew size should be selected in such a way that enables least conflict leading to higher satisfaction among crew members.

3) *Increase crew flexibility*

(Proceeding discussion applies)

4) *Increase crew heterogeneity*

(Proceeding discussion applies)

5) *Increase support*

Support in terms of both social and technical as discussed in Chapter 2 is associated with crew satisfaction. More support (social or technical) is likely to produce higher satisfaction among crew members. Hence, a crew should be designed in such a way that enables support in the form of assistance, help, and advice from crew members, supervisors and management leading to higher satisfaction among crew members.

6) *Increase task significance*

(Proceeding discussion applies)

7) *Increase task variety*

Task variety is associated with crew satisfaction. Higher task variety leads to higher satisfaction among crew members, since with increased task variety crew members would be able to execute and perform a variety of tasks and not restricted to only a fixed task over and over again. Hence, a crew design that enables inclusion of a variety of tasks in a process and also provide equal opportunities to all crew members to perform them is highly desirable.

8) *Increase task identity*

Task identity is also associated with crew satisfaction. Higher task identity leads to higher satisfaction among crew members, since the crew members can relate themselves with a particular task and be satisfied in completing it from start to finish. Hence, crew design should target high task identity leading to higher satisfaction among crew members.

9) *Increase self-management*

Self-management is also positively related to crew satisfaction. It is the group level analogy to autonomy and means how well a crew is able to manage and execute a process on its own without much external support (social/technical). Higher self-management in the crew would lead to higher satisfaction among the crew members, since they would be able to manage and execute a process on their own with the need of external support. Hence, crew design should enable higher self-management in the crew leading to higher crew satisfaction.

10) Provide reasonable autonomy

Autonomy is the amount of freedom and independence a crew member has in performing his tasks/work. Reasonable autonomy is positively associated with higher satisfaction among crew members, since it is more likely that if certain autonomy is given to the crew members to decide about how to execute a given task and if top down management approach is avoided, reasonable autonomy will lead to higher crew member satisfaction. Hence, crew design should afford reasonable crew autonomy in order to optimize crew satisfaction.

11) Increase feedback

Feedback is also associated with crew satisfaction. Proper feedback within the crew members and from the supervisors and higher management leads to less conflict in the crew as the crew is likely to be more aware of their performance of work after a timely feedback, and correspondingly be more satisfied. A crew design should therefore provide for proper and timely feedback, leading to higher crew satisfaction.

(6) The **"*worker learning*"** can be optimized by the following steps:

1) Increase coordination

Crew coordination is also associated with crew learning. Higher coordination leads to more interaction among the crew members; and correspondingly results in learning induced in the crew while coordinating and working together towards a common goal. Hence, a crew should be designed in such a way that enables maximum coordination leading to higher learning among crew members.

2) Increase crew flexibility

(Proceeding discussion applies)

3) *Increase crew heterogeneity*

(Proceeding discussion applies)

4) *Increase task experience*

(Proceeding discussion applies)

5) *Increase task variety*

(Proceeding discussion applies)

6) *Increase feedback*

(Proceeding discussion applies)

(7) The **"*worker motivation*"** can be optimized by the following steps:

1) *Increase coordination*

(Proceeding discussion applies)

2) *Reduce conflict*

(Proceeding discussion applies)

3) *Increase crew heterogeneity*

(Proceeding discussion applies)

4) *Increase task significance*

(Proceeding discussion applies)

5) *Increase task identity*

(Proceeding discussion applies)

6) *Provide reasonable autonomy*

(Proceeding discussion applies)

(8) The ***"pride in work performed"*** can be optimized by the following steps:

1) *Increase task identity*

2) (Proceeding discussion applies)*Increase self-management*

   (Proceeding discussion applies)

4.5 LBCD Model Development

In this research, the structure of the Lean-based Crew Design (LbCD) model is patterned after a transformation process structure where in inputs are converted to outputs by means of a conversion process. The proposed LBCD model is shown in the Figure 5.1 below.

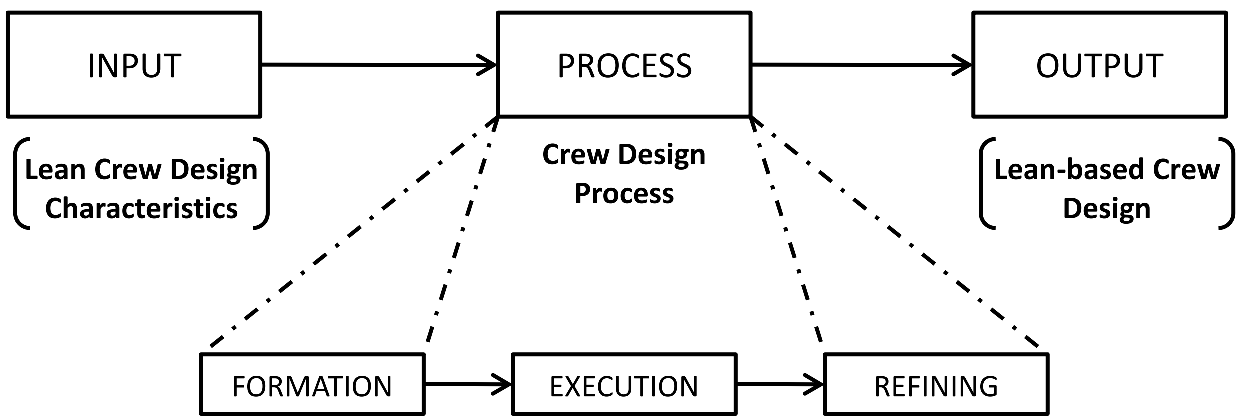


Figure 4.10: Lean-based Crew Design (LbCD) Model

As shown in Figure 4.1, the model input consists of the lean crew design characteristics, developed based on existing crew and work design approaches. The characteristics include both soft and hard factors from several scientific disciplines. The characteristics are used in the design process to develop the final crew design that will achieve the joint optimization of both the crew and work performed. The crew design process itself consists of three main phases, namely, formation, execution, and refining.

4.6 Lean Crew Design Process

The lean crew design process consists of three phases namely: (1) formation, (2) execution, and (3) refining. The three phases are proposed to guide the crew design process in a production setting. It consists of the initial formation of the crew and structuring of work involved, followed by execution and refining of the crew.

In the first phase of *formation,* the initial formation of the crew is done along with structuring of the work. In *formation of crew,* the estimation and scheduling teams determine the standard crew, number of activities required to perform the particular work, list of tasks in a activity and activity/task durations. The initial size and composition of the crew is determined based on the amount of work/quantity that needs to be done generally by the using the standard construction industry data (example RS Means) or the contractors' own data and other work/job specific data. From these data, standard crew productivity is determined, which is used to calculate the activity/task durations or the standard unit crew days/time required to execute the work.

After the initial standard crew size and makeup, list of activity and tasks, and activity/task durations are determined, the structuring of work should be done by determining the sequence of tasks involved in an activity. Once the task sequence is determined, amount of work that needs to be executed by each crew member needs to be determined (including the amount assigned and released from each crew member). In the second phase, execution of work is done by the initial crew determined in the formation phase. In addition, data collection of primary and intermediate crew design indicators is conducted. Then these design indicators are analyzed in the third phase to refine the initial crew design and maximize the crew performance based on the lean crew design guidelines proposed in the previous section.

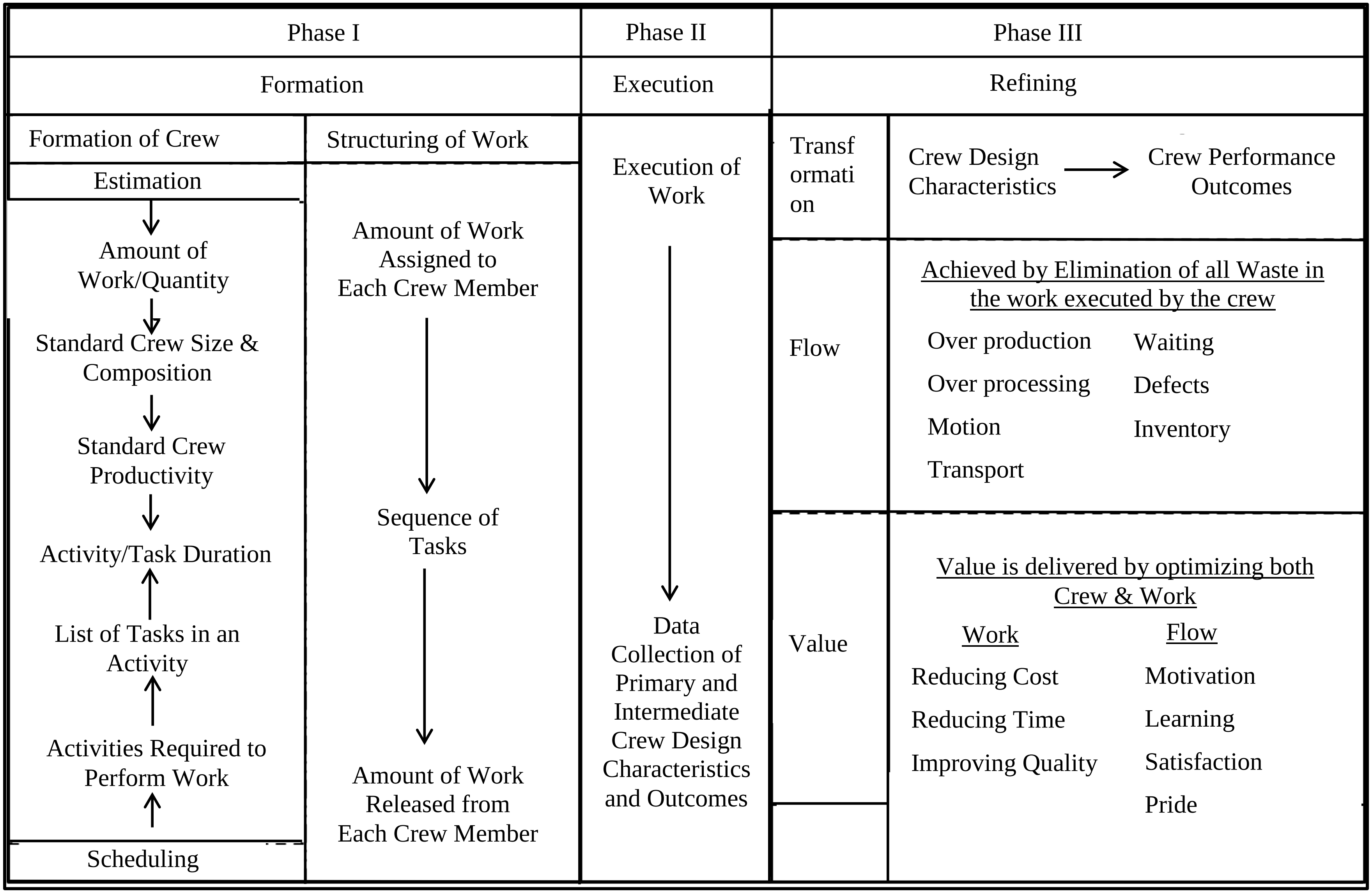


Figure 4.11: Lean-based crew design (LbCD) process

4.7 Chapter Summary

This chapter proposes lean crew design characteristics and guidelines by synthesizing research studies on "work design/team design" that have well developed theoretical and empirical foundations in *lean production*, *lean construction*, *socio-technical system theory*, *social and organizational psychology*.

As, discussed earlier, performance of crews is very crucial to the work being executed and consequently for the overall project performance. Hence, in this chapter all the significant crew design parameters affecting crew performance are synthesized from literature into lean crew design characteristics to guide the design of crews and maximize their performance. The crew design characteristics are classified into two main types: flow and work characteristics that are further divided into four characteristics such as waste, task, social, and crew comprising of both the hard and soft crew design factors.

The proposed guidelines lead to the joint optimization of both the *crew* and the *work* performed, resulting in better overall *crew performance* by optimizing crew performance. The guidelines are proposed for crew performance outcomes, such as duration of work performed, crew productivity, worker learning, worker pride etc.

5 CASE STUDY - MODEL BUILDING, SIMULATION & EXPERIMENTATION

5.1 Introduction

In the previous chapter 4, a lean-based crew design model (LbCD) is proposed that integrates both the existing *crew design* and *work design* research providing a crew design framework (that includes important crew design characteristics) and guidelines for designing and improving the performance of crews.

The purpose of this section is to develop simulation models in order to demonstrate how the crew design characteristics affect the performance of the crew. To develop a simulation model that can effectively identify and demonstrate both the hard and soft crew design characteristics, a combination of Discrete Event Simulation (DES) and System Dynamics (SD) is used. The simulation models are developed first using Discrete Event Simulation (DES) and then moving to System Dynamics (SD) providing the qualitative and quantitative crew design models. The simulation models are developed for a construction operation involving installation of light fixtures from a previous research work conducted by Howell et al (1993). The background of the case study is discussed in detail in the following section.

5.2 Case Study Background

For the purpose of this research, a case study involving a well-documented construction operation from a prior research work conducted by Howell et al (1993) was selected. The case study consists of a real time construction operation focusing on the installation of light fixtures (Figure 5.1) by a construction crew. The initial raw data for this case study was collected by the previous research work by conducting interviews with the construction staff prior to start of the operation, as described in Howell et al (1993). The operation was monitored carefully to keep a record of the initial durations, crew make-up, equipment used, design process of operation and other significant parameters involved during carrying out the operation.

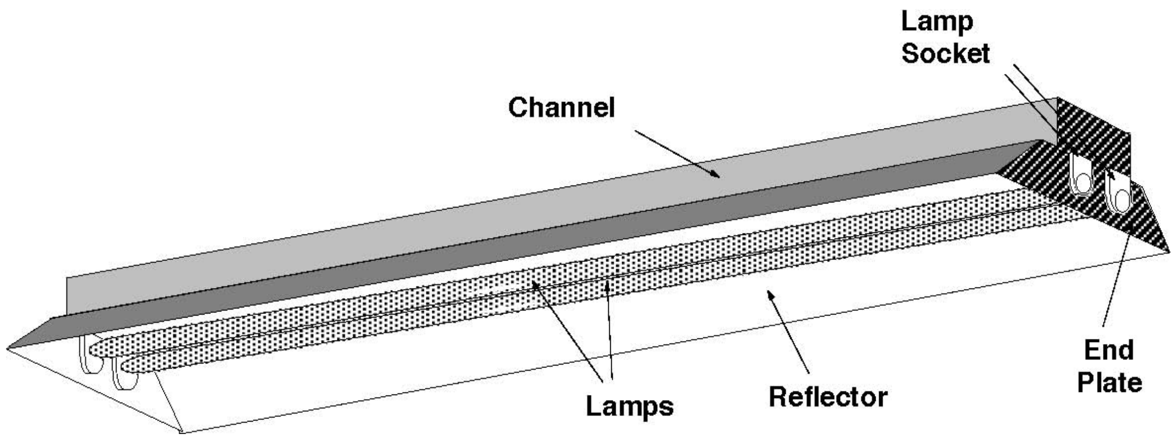


Figure 5.1: Type of light fixture installed (Figure 9 in Howell et al. 1993)

The construction operation involved installation of 314 light fixtures. The initial crew make-up for the installation operation consisted of 1 journeyman, 1 apprentice, and 1 scissor lift. The estimated productivity planned by the construction staff to carry out this operation was 2.5 fixtures per crew hour, or a total of 48 worker-minutes per fixture. The total time of operation was estimated to be 125.6 hours at the rate of 2.5 fixtures per crew hour. The hourly wages of the crew were $13.40 per hour for 1 journeyman, $6.00 per hour for 1 apprentice, and $1.50 per hour for the scissor lift.

The original light fixture installation operation was divided into two main cycles: (1) Assembling Cycle and (2) Installation Cycle. The assembling cycle involved one task of assemble fixture (9minutes) executed by an apprentice and the installation cycle involved three tasks of install fixture (7 minutes), wire & clip (8.5 minutes), and lamp & finish (7.5 minutes) executed by one journeyman. For the purpose of modeling the exact process of installation of light fixtures, the original construction operation was modified from the original two cycles (assembling and installation) to three cycles (assembling, restocking, and installation) shown in the Figure below. The restocking cycle included 3 tasks of restocking (1 minute), lift going up (1minute) and lift going down (1minute).

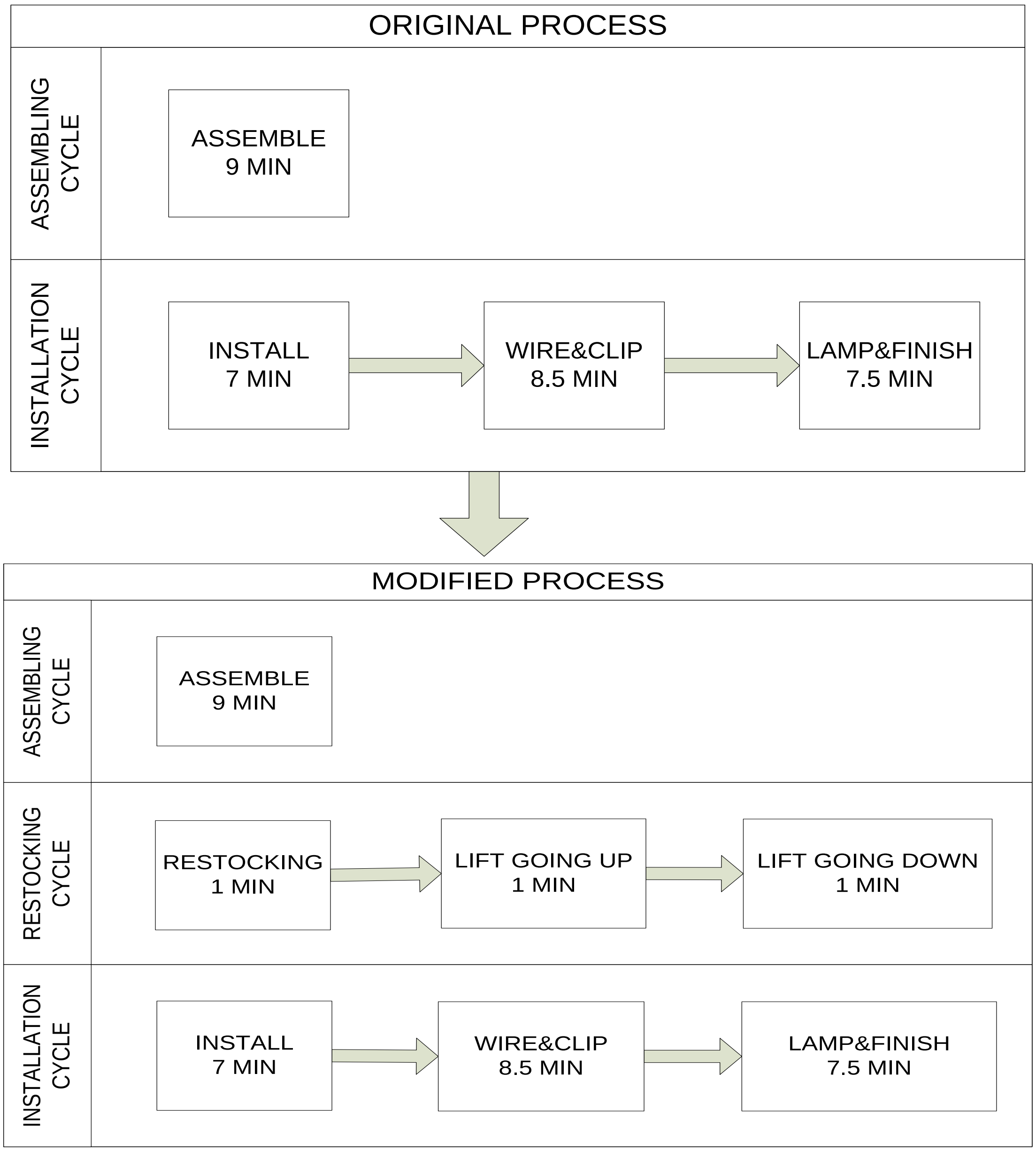


Figure 5.2: Original vs. modified process of installation of light fixtures

5.3 Discrete Event Simulation Model

As discussed earlier in chapter 3, Discrete Event Simulation (DES) has been widely recognized as an effective technique to design and analyze construction operations by virtue of its ability to model repetitive processes. In this research, EZStrobe (Martinez 1996) is used to model the repetitive process of installation of light fixtures.

Three DES models are developed with different crew designs to test the performance of the crew for executing this construction operation involving installation of light fixtures. Having the right crew design is very important, as any change in the design of the crew would also mean a change in how the operation is executed by them. A poor crew design could lead to an increase in the duration and cost of the operation, a decrease in the productivity and quality of the work performed along with lower levels of satisfaction, motivation, learning and pride among the crew.

5.3.1 DES Base Crew Model

In the "Base" crew case, the amount of work to be performed is the installation of 300 light fixtures. The size of the crew is 2 workers with crew composition of 1 apprentice, 1 journeyman, and 1 lift. Activities required to perform the operation of installation of light fixtures are assemble, restocking, lift going up, install, wire & clip, lamp & finish, and lift going down. Depending on the standard crew productivity activity duration determined by the construction staff is shown in the Table 5.1. Once the initial crew is formed, structuring of the work is done; the apprentice is assigned the responsibility for assembling the fixtures which are then restocked and installed (install, wire & clip, and lamp & finish) by one journeyman. The journeyman uses one scissor lift to restock the light fixtures, complete the installation and then again restock. The crew assembles, restocks and install one light fixture at a time. The sequence of activities for this operation is shown in the Figure 5.3 and the activity, entity, resource, crew make-up and time data used to develop the base model is shown in the Table 5.1.

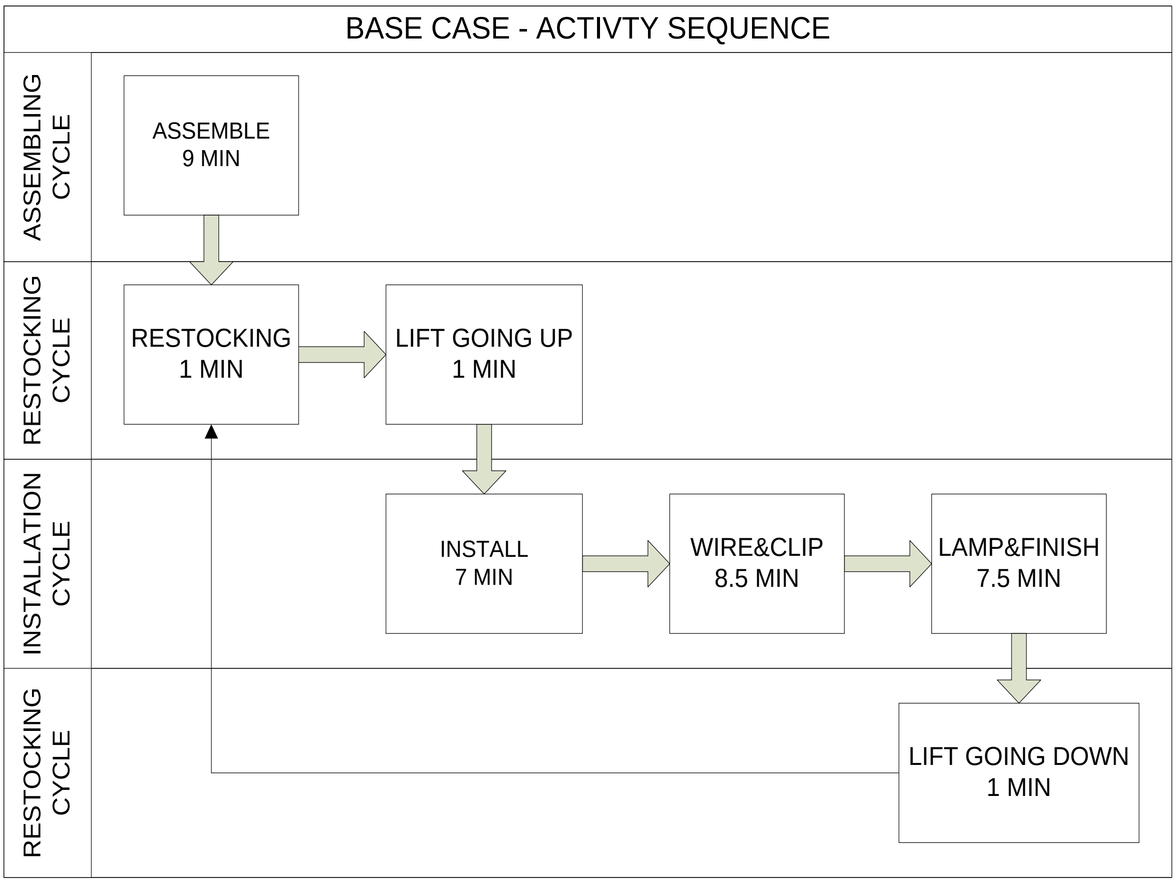


Figure 5.3: Sequence of activities in the “Base” crew case of installation of light fixtures

Table 5.1 shows the activities and their types involved in this process along with the entity and resource types that are needed to execute each type of activity. The two activity types used to model this process are *combi* (conditional) and *normal* along with *queues* where entity and resource types accumulate. As discussed earlier in chapter 3, the Combi activity requires certain condition set by the *draw link* to satisfy in order to start and produce an outcome by use of *release link*. For example, in this model for activity *assemble* (combi) to start; the conditions set by the draw link should be met for both the light fixture and the apprentice. Similarly, for activities *restocking, lift going up, install* to start, the conditions set by the draw link should be met for the *journeyman*, *lift*, and the *light fixture*. The Figures 5.4, 5.5 and 5.6 shows the assembling cycle, restocking cycle and installation cycle of simulation model developed for the "Base" crew case of installation of light fixtures.

Table 5.1: DES "Base" crew model data

DES "BASE" MODEL DATA							
S.NO.	ACTIVITY	TYPE	TIME (min)	ENTITY	RESOURCE		
				Light Fixture	Apprentice	Journeyma	Lift
1	Assemble	Combi	9	√	√	X	X
2	Restocking	Combi	1	√	X	√	√
3	Lift Going	Combi	1	√	X	√	√
4	Install	Combi	7	√	X	√	√
5	Wire & Clip	Normal	8.5	√	X	√	√
6	Lamp &	Normal	7.5	√	X	√	√
7	Lift Going	Combi	1	X	X	√	√
SIZE/NUMBER				300	1	1	1

In this model, initially 300 light fixtures are waiting in the LitFix queue to be assembled. For the conditional activity assemble to start, both apprentice and light fixtures should be available (i.e. AprntcWt and LitFix >0); so once both these are available assembling takes place for 9 minutes and releases one each of apprentice and assembled light fixture that waits in the apprentice wait queue (AprntcWt) and assembled light fixture queue (AsmbdLitFixA) respectively. For conditional activity restocking to start, there should be at least one light fixture assembled, one journeyman and one lift waiting in the AsmbdLitFixA, JrnymnWt, LftDwnWt queue and restocking count (RestockCont) should be equal to one. Once, the light fixture is restocked by the journeyman in the lift, all three go up in 1 minute and wait in the AsmbdLtFxLft, LftUpWt and JrnymnWt queues.

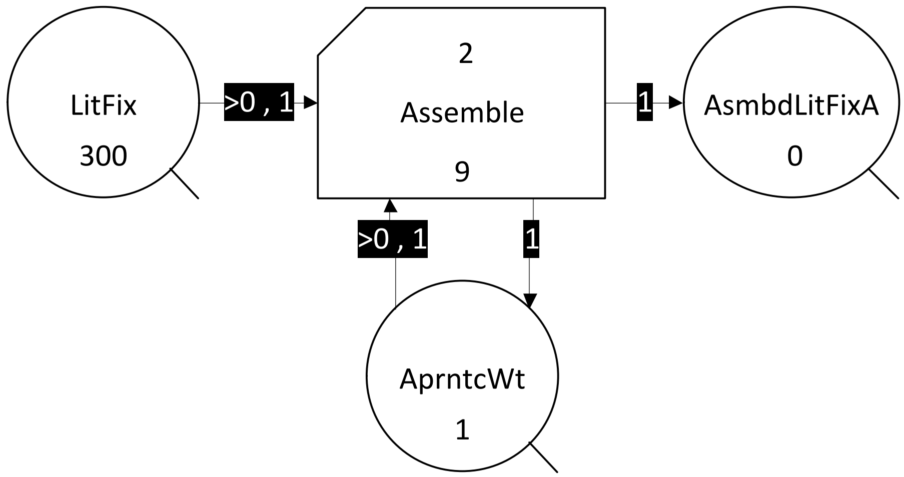


Figure 5.4: Simulation model (Assembling Cycle) for the “Base” crew case of installation of light fixtures

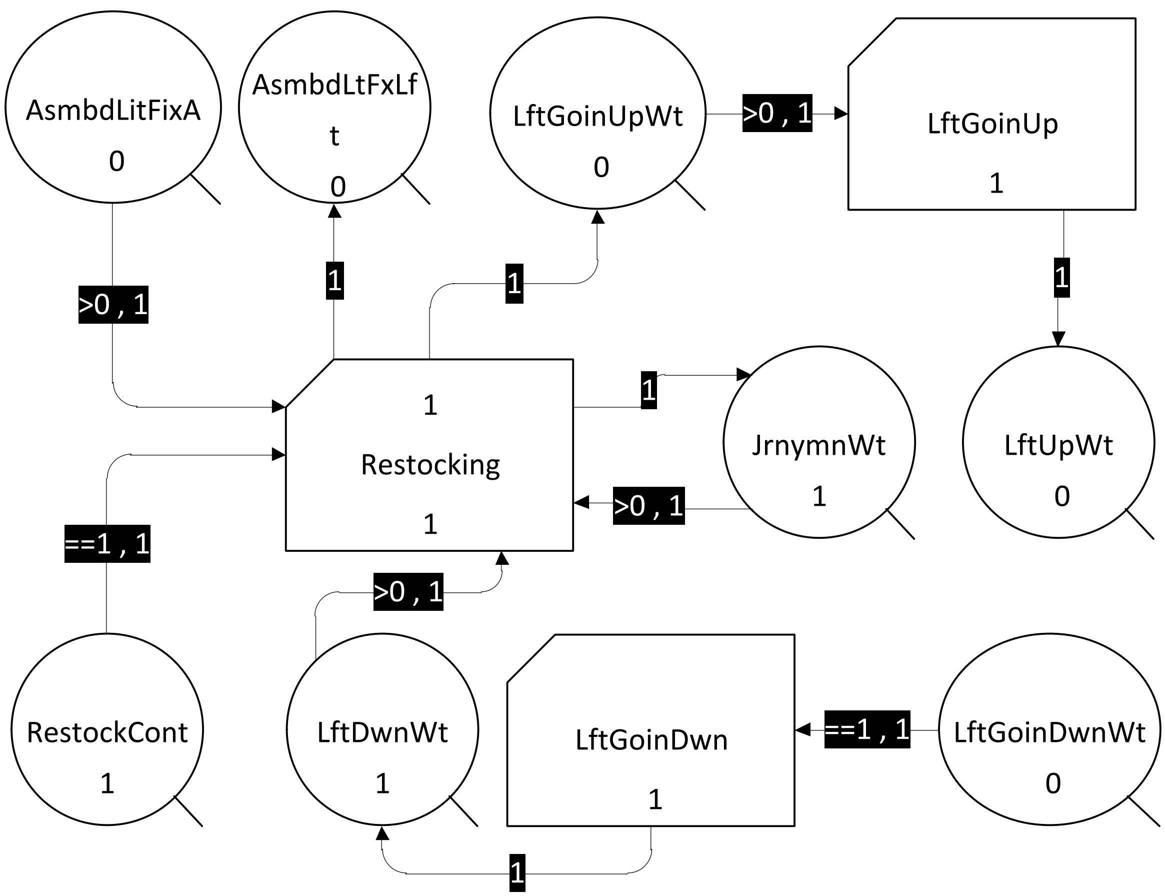


Figure 5.5: Simulation model (Restocking Cycle) for the “Base” crew case of installation of light fixture

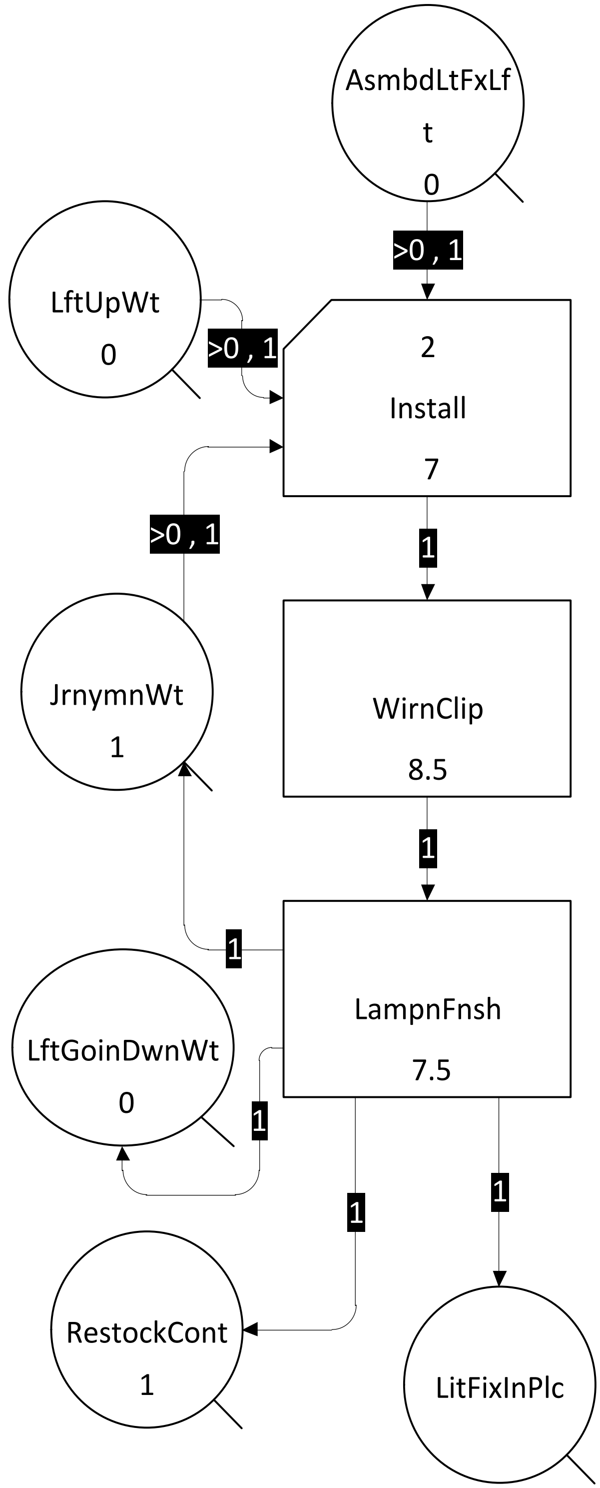


Figure 5.6: Simulation model (Installation Cycle) for the “Base” crew case of installation of light fixtures

The installation cycle starts with the activity *install* taking 7 minutes when journeyman, lift and light fixture are all available (AsmbdLtFxLft, LftUpWt and JrnymnWt >0), followed by *wire & clipping* (WirnClip) taking 8.5 minutes and *lamp & finish* (LampnFnsh) taking 7.5 minutes. After, *lamp & finish* activity is finished one light fixture is released to the LitFixInPlc queue and both journeyman and lift goes down in 1 min to restock the next assembled light fixture. All three cycles of assembling, restocking and installation repeat until 300 light fixtures are finished and in place.

Results from the simulation of the "Base" case of installation of light fixtures have been summarized in Table below.

Table 5.2: Simulation results of the "Base" crew of installation of light fixtures

PERFORMANCE OUTCOMES	BUDGETED	BASE CASE
Time of Operation	125.60 hours	130.15 hours
Unit Cost of Installation	8.32 USD	9.06 USD
Apprentice Utilization	-	34.65%
Journeyman Utilization	-	89.88%
Lift Utilization	-	99.70%
Average Crew Utilization	-	62.26%
Average Apprentice Idle Time	-	16.97 min
Average Journeyman Idle Time	-	1.01 min
Average Work-In-Progress (WIP)	-	97.64 Fixtures
Operation Production Rate (OPR)	-	2.31 Fixtures/Hr
Maximum Production Rate (MPR)	-	6.67 Fixtures/Hr
OPR-MPR Ratio	-	34.63%

The "Base" crew takes 130.15 hours to complete the operation and install 300 light fixtures; that is 4.55 hours more than that was actually budgeted (125.6 hours) by the construction staff.

The unit cost of operation also came out to be $0.72 more than the budgeted unit cost of $8.32. The resource utilization originally not budgeted by the construction staff came out to be 34.65% for apprentice, 89.88% for journeyman, and 99.70% for lift; that shows although the journeyman and the lift were utilized for most of the operation, apprentice was only utilized for around one-third of the operation. This is supplemented by the fact that average idle time for the apprentice is very high at 16.97 minutes whereas average idle time for the journeyman is only 1.01 min. The average work-in-progress (WIP) is also high at 97.64 fixtures that means around 97.64 light fixtures have been assembled but are waiting to be restocked and installed indicating a very low operation production (2.31 fixtures/hr) to maximum production (6.67 fixture/hr) ratio at only 34.63% (Figure 5.7).

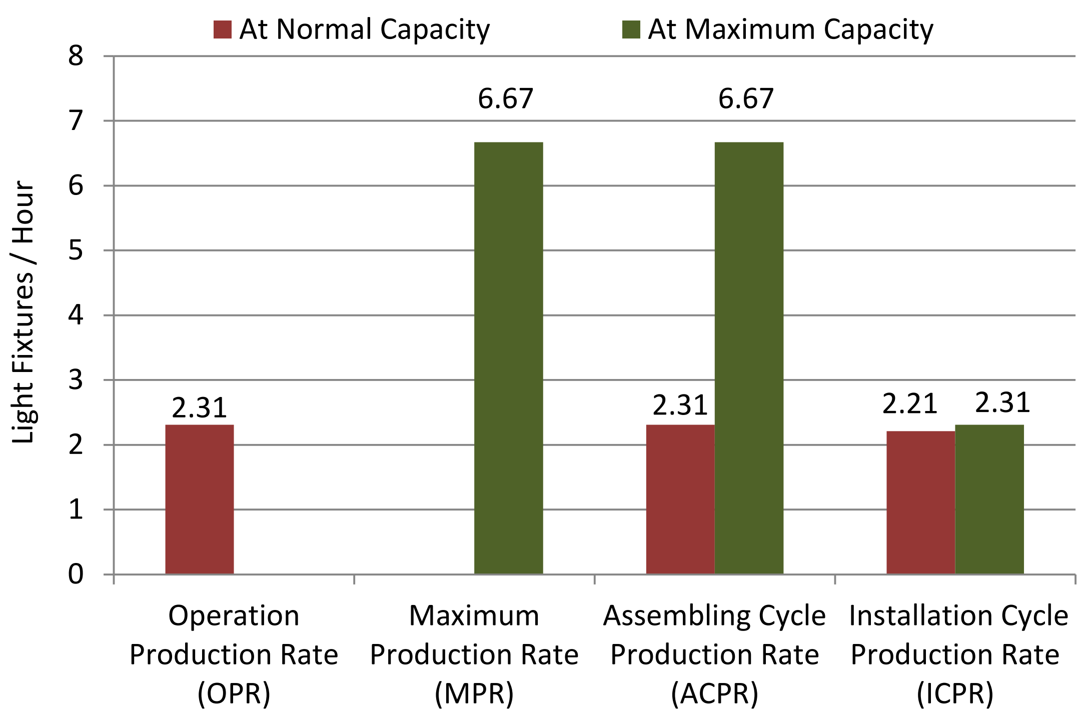


Figure 5.7: Production rates for the "Base" crew case

The simulation results for the “Base” crew of installation of light fixtures are analyzed to evaluate the performance of the crew design in terms of the performance outcomes proposed in the previous chapter 4: (1) *duration* of work performed; (2) *cost* of work performed; (3) *productivity*; (4) *quality* of work performed; (5) worker *satisfaction*; (6) worker *learning*; (7) worker *motivation*; (8) *pride* in work performed.

1. Duration of Work Performed:

   Duration of work performed (time of operation) is directly related to the processing time, non-processing time, and variability in the work performed. The over budget duration (130.15 hours i.e. 7809 minutes vs. 125.60 hours i.e. 7536 minutes) in this case, is due to:

   a. High ***non-processing time*** present in the form of high *wait/idle time* for the apprentice who is waiting an average of 16.97 minutes. The apprentice assembles 300 fixtures @9minutes in total of 2700 minutes and then is just idle for the rest of the operation for approx. 5109 minutes. Also, the non-processing time is increased when the journeyman has to come down to restock for every light fixture and then go up to install leading to waste in terms of high *transportation/operating/motion time*.

   b. High *over-production* present in the form of large *intermediate inventory/work-in-progress* (AsmbdLitFixA), as production rate for assembling cycle (6.67 fixtures/hour) is very high compared to the restocking and installation cycle, that means more number of light fixtures are assembled than that can actually be installed by the journeyman. High work-in-progress in front of journeyman may also lead to overburdening him, potentially leading to lowering his task productivity.

   c. *Non-uniform work load* between the assembling and installing cycle, leading to gap in the cycle times (assembling cycle time – 9 minutes vs. restocking and installation cycle time – 26 minutes) results in *non-continuous flow*, where each light fixture waits in the queue before being restocked and installed. It also implies that a *push system* instead of *pull system* is used.

2. Cost of Work Performed:

   Cost of work performed is directly related to the crew size, crew flexibility, processing and non-processing cost and defective products. The high unit cost of operation ($9.06) in this case is due to:

   a. High ***non-processing cost*** resulting from the high non-processing time as discussed earlier.

   b. Low ***crew flexibility*** is present in this case. As seen from the model results, although apprentice is idle for two-third (65.35%) of the time of operation, he is not being utilized to help the journeyman in the installation cycle or involved in multi-tasking when idle that would lead to shortening the duration of this operation and correspondingly saving the labor costs.

3. Productivity:

   Productivity is related to resource utilization, crew flexibility, overburden, task experience, task complexity etc. In this case, the crew productivity is low as the crew is not very flexible; apprentice being utilized very less. The gap between the operation production rate and maximum production rate (2.31 fixtures/hour vs. 6.67 fixtures/hr) is very high and any reduction in that gap would definitely lead to a higher overall crew productivity.

4. Quality of Work Performed:

   Quality of work is directly related to the defective products, task experience, task complexity, overburden, task interdependence. But in this case, these soft or qualitative crew design characteristics cannot be empirically quantified using discrete event simulation.

5. Worker Learning:

   Worker *learning* is related to crew design indicators such as coordination, crew flexibility, task variety etc. In this case, these soft or qualitative crew design characteristics cannot be empirically quantified using discrete event simulation. But from the model and simulation results, a qualitative inference can be made that there is very less/no team work/crew flexibility/multi-tasking/coordination/task variety present in this case. Hence, learning among crew is minimal to non-existent for the apprentice, except in assembling fixtures.

6. Pride in Work performed:

   Pride in the work performed is related to the task identity and self-management. In this case, these soft or qualitative crew design characteristics cannot be empirically quantified using discrete event simulation. But from the model and simulation results, a qualitative inference can be made that only pride that may be present could be in Journeyman as installation that is the major part of the operation is solely executed by the journeyman and he can identify with the work performed by him and take pride in it.

7. Worker Satisfaction:

   Worker satisfaction directly relates to crew design indicators such as coordination, support, task significance, reasonable autonomy etc. But in this case, these soft or qualitative crew design characteristics cannot be empirically quantified using discrete event simulation.

8. Worker Motivation:

   Worker motivation directly relates to crew design indicators such as coordination, task identity, task significance, reasonable autonomy etc. But in this case, these soft or qualitative crew design characteristics cannot be empirically quantified using discrete event simulation.

5.3.2 DES Improved Crew Model

In the "Improved" crew case, the same amount of work was performed i.e. the installation of 300 light fixtures. The earlier "Base" crew case was improved and following changes (Howell et al 1993) to the "Base" crew design were introduced:

1. Two journeymen with dedicated lifts were added;
2. A temporary rack developed by the crew held pieces for 16-20 fixtures- minimizing loading/restocking frequency;
3. One apprentice and one journeyman prepared the initial buffers of assembled fixtures while the other two journeymen modified the scissor-lifts.

The size of the crew is 4 workers with crew composition of 1 apprentice, 3 journeymen, and 3 lifts. Activities required to perform the operation of installation of light fixtures are same in the "Improved" case i.e. assemble, restocking, lift going up, install, wire & clip, lamp & finish, and lift going down; but in this crew design, structuring of work among the crew was different from the "base" crew design case. Here, the apprentice was again assigned the responsibility for assembling the fixtures in 9 minutes but, each journeyman executed only one activity in the restocking and installation cycle (one executed install, the second executed wire & clip, and the third executed lamp & finish). Also, each of the 3 journeymen would go down using their own lift once they have completed 15 light fixtures to restock and again execute the same activity for another 15 fixtures. For the purpose of modelling and simulation, it was assumed that restocking required 3 minutes with lifts taking 1 minute each in going up and coming down. The sequence of activities for this operation is shown in the Figure 5.8.

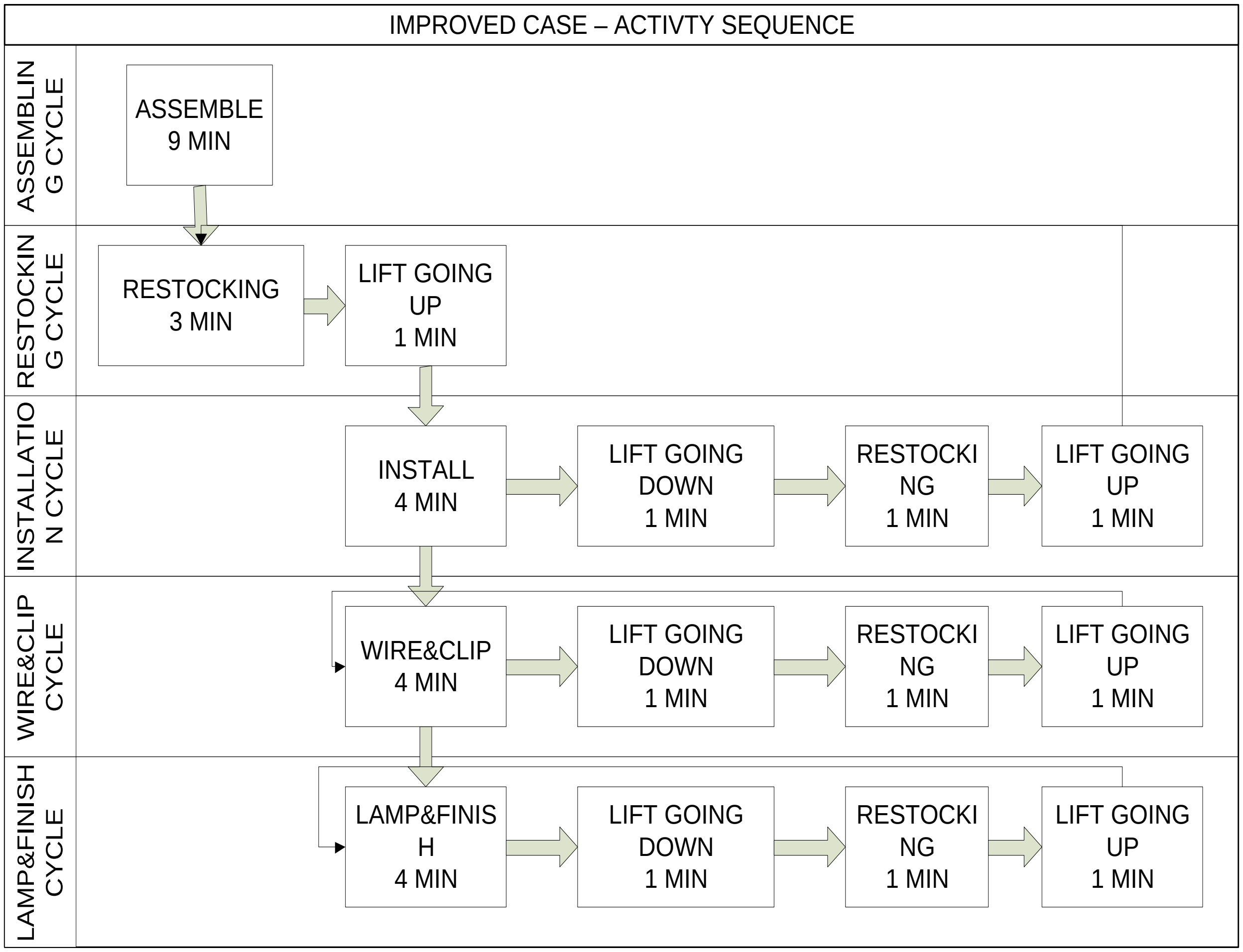


Figure 5.8: Sequence of activities in the “Improved” crew case of installation of light fixtures

For example, in this model for activity *install* (combi) to start; the conditions set by the draw link should be met for the light fixture, journeyman, and lift. Similarly, for activity *lift A going down*, the table shows that only the journeyman A and lift A are needed to execute that activity, as the light fixture is already installed and is not needed in the going back cycle.

Table 5.3 shows the activities and their types involved in this process along with the entity, resource types, time and size data that are needed to execute each type of activity. The two activity types used to model this process are *combi* (i.e. conditional activity) and *queues* where entity and resource types accumulate.

Table 5.3: DES "Improved" crew model data

DES "IMPROVED" MODEL DATA							
S.NO	ACTIVITY	TYPE	TIME (min)	ENTITY	RESOURCE		
				Light Fixture	Apprentice	Journeyman	Lift
1	Assemble	Combi	9	√	√	X	X
2	Restocking A	Combi	C	√	X	√	√
3	Lift A Going Up	Combi	1	√	X	√	√
4	Install	Combi	4	√	X	√	√
6	Lift A Going Down	Combi	1	X	X	√	√
7	Restocking B	Combi	3	X	X	√	√
8	Lift B Going Up	Combi	1	X	X	√	√
9	Wire & Clip	Combi	8	√	X	√	√
10	Lift B Going Down	Combi	1	X	X	√	√
11	Restocking C	Combi	3	X	X	√	√
12	Lift C Going Up	Combi	1	X	X	√	√
13	Lamp & Finish	Combi	4	√	X	√	√
14	Lift C Going Down	Combi	1	X	X	√	√
SIZE/NUMBER				300	1	3	3

The assembling cycle for the improved case simulation model is same as the base case. However, the installation cycle for the three journeymen is different for the “Improved” crew case of installation of light fixtures and is shown in the Figures 5.9, 5.10, 5.11.

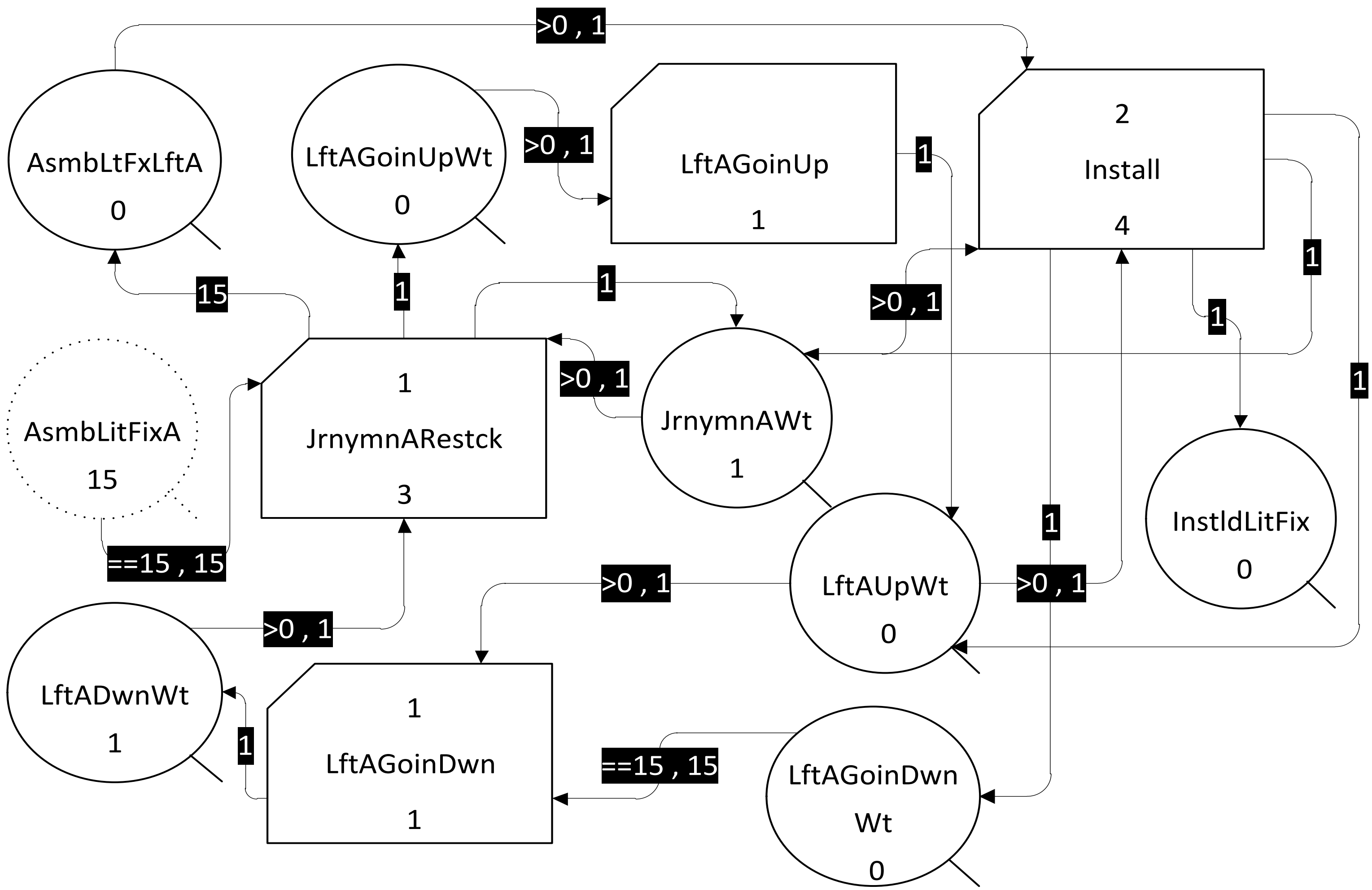


Figure 5.9: Simulation model for the installation activity cycle in the “Improved” crew case of installation of light fixtures

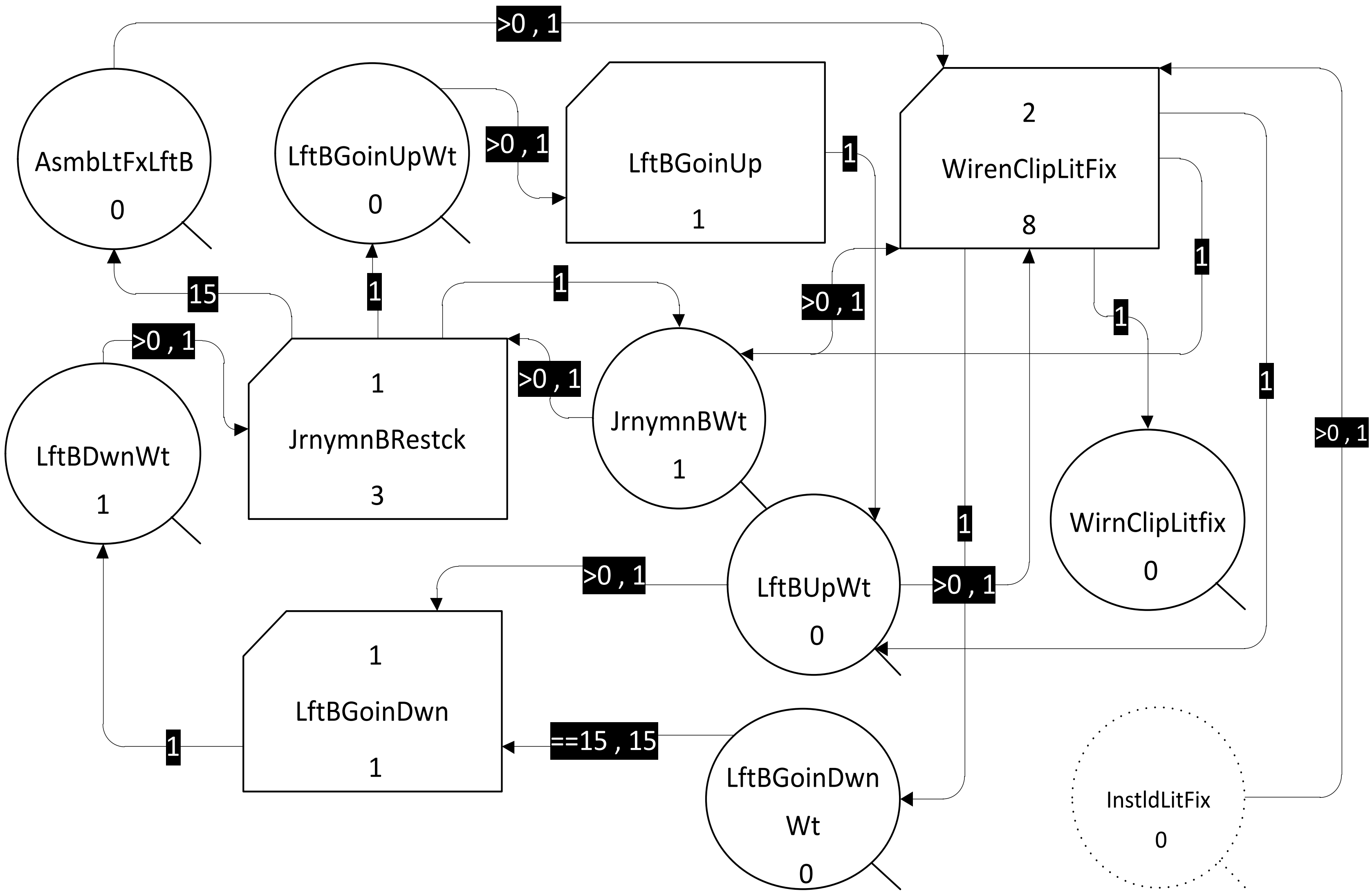


Figure 5.10: Simulation model for the wire and clip activity cycle in the "Improved" crew case of installation of light fixtures

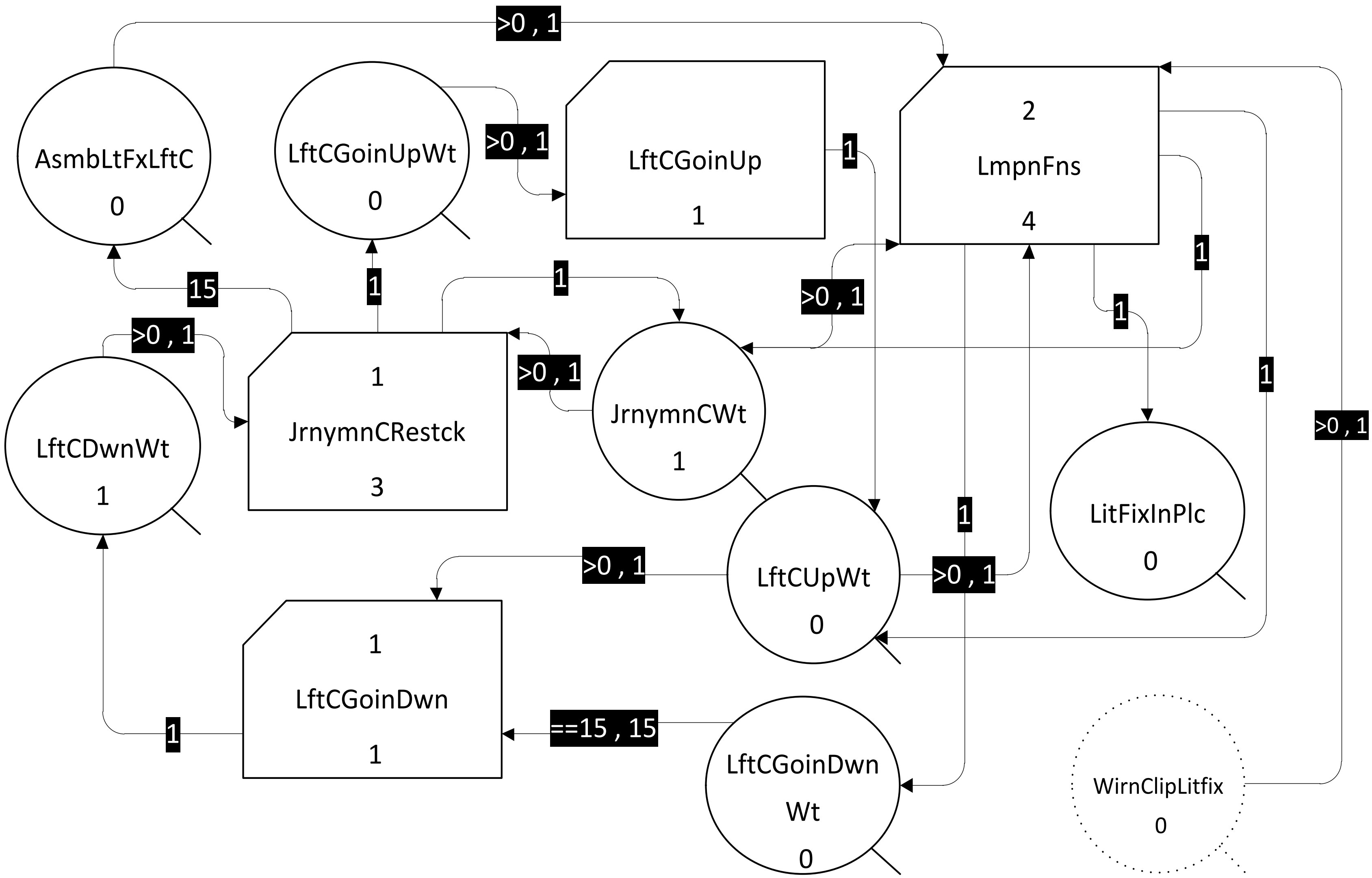


Figure 5.11: Simulation model for the lamp & finish activity cycle in the “Improved” crew of installation of light fixtures

In this model, initially 15 light fixtures have already been pre-assembled and are waiting in the assembled light fixture queue (AsmbdLitFixA) and 285 light fixtures are waiting in the light fixture waiting queue (LitFix) at the start time of simulation. In the install activity cycle, restocking of light fixture (JrnymnARestck) takes place when all journeyman, lift waiting down and 15 assembled light fixtures are waiting (i.e. JrnymnARestck==15, JrnymnAWt & LftADwnWt >0). Once the restocking of light fixtures takes place in 3 minutes, 15 light fixtures go up with the journeyman and lift in 1 minute and wait in the AsmbLtFxLftA, LftAUpWt, and JrnymnAWt queues to be installed. Then, the journeyman installs each light fixture in 4 mins (when AsmbLtFxLftA, LftAUpWt, and JrnymnAWt >0) and goes down (when LftAGoinDwnWt ==15) to restock again only after 15 light fixtures have been installed.

The wire & clip (WirnClip) and lamp & finish (LmpnFns) activity also have same cycles as the install cycle except the fact that journeyman A goes down to restock the 15 assembled light fixtures whereas, journeyman B & C go down the lift to restock the material and tools required to execute their respective activities. Activity WirnClip starts when installed light fixture (InstldLitFix >0), material & tools restocked for 15 light fixtures (AsmbLtFxLftB>0), lift B up waiting (LftBUpWt>0) and journeyman B waiting (JrnymnBWt>0). And activity LmpnFns starts when wire & clipped light fixture (WirnClipLitfix>0), material & tools restocked for 15 light fixtures (AsmbLtFxLftC>0), lift C up waiting (LftCUpWt>0) and journeyman C waiting (JrnymnCWt>0). Note that although Journeyman A can start and continue installing 15 fixtures continuously, but journeyman B can only wire & clip if a complete light fixture has been installed by the journeyman A and is ready to be wire & clipped (although he has the material & tools for 15 light fixtures, there could be wait times if a installed fixture is not ready, same is true for journeyman C for lamp & finishing activity).

Results from the simulation of the "Improved" case of installation of light fixtures have been summarized in Table below.

Table 5.4: Simulation results for the "Improved" crew of installation of light fixtures

PERFORMANCE OUTCOMES	BUDGETED	IMPROVED CASE
Time of Operation	125.60 hours	45.03 hours
Unit Cost of Installation	8.32 USD	7.61 USD
Apprentice Utilization	-	94.94%
Journeyman A Utilization	-	46.63%
Lift A Utilization	-	48.11%
Journeyman B Utilization	-	91.15%
Lift B Utilization	-	92.67%
Journeyman C Utilization	-	46.74%
Lift C Utilization	-	48.26%
Average labor Utilization	-	66.43%
Average Apprentice Idle Time	-	0.48
Average Journeyman A Idle Time	-	4.49 min
Average Journeyman B Idle Time		0.00 min
Average Journeyman C Idle Time		4.47 min
Average Work-In-Progress (WIP)	-	28.29 Fixtures
Operation Production Rate (OPR)	-	6.66 Fixtures/Hr
Maximum Production Rate (MPR)	-	6.67 Fixtures/Hr
OPR-MPR Ratio	-	99.85%

The "Improved" crew takes 45.03 hours to complete the operation and install 300 light fixtures. The time of operation here is 85.12 hours less than the "Base" crew case (130.15), and 80.57 hours less than that was actually budgeted (125.6 hours) by the construction staff. The unit cost of operation also came out to be $0.71 less than the budgeted unit cost of $8.32 and $1.45

less than the “Base” case. There is no significant savings in the cost as compared to the time of operation that can be attributed to the large crew size of 4 workers and 3 lifts. The resource utilization originally not budgeted by the construction staff came out to be 94.94% for apprentice, 46.63%, 91.15%, and 46.74% for journeyman A, B & C and 48.11%, 92.67%, and 48.26% for lift A, B, & C. Also, the average labor utilization in this was slightly more at 66.43% than the “Base” case (62.26%). These above utilizations clearly show that though the apprentice and journeyman B were almost more than 90% utilized, journeyman A & C were only less than 50% utilized and were waiting for more than 50% of the operation time. This is supplemented by the fact that Average Idle Time for both apprentice and journeyman B is almost zero or less than half a minute whereas the Average Idle Time for both the journeyman A & C is around 4.49 and 4.47 minutes respectively.

The average work-in-progress (WIP) was reduced from 97.64 fixtures to 28.29 fixtures, although it was not a single piece flow and a batch and single piece mixed flow. The reduced WIP also supplements the better operation production rates for all the activities and for the operation at 6.66 light fixtures/hour compared to the 2.31 light fixtures/hour in the “Base” case. The individual production rates for all the activities at their normal and maximum capacity for this “improved” crew case has been shown in the figure 5.12.

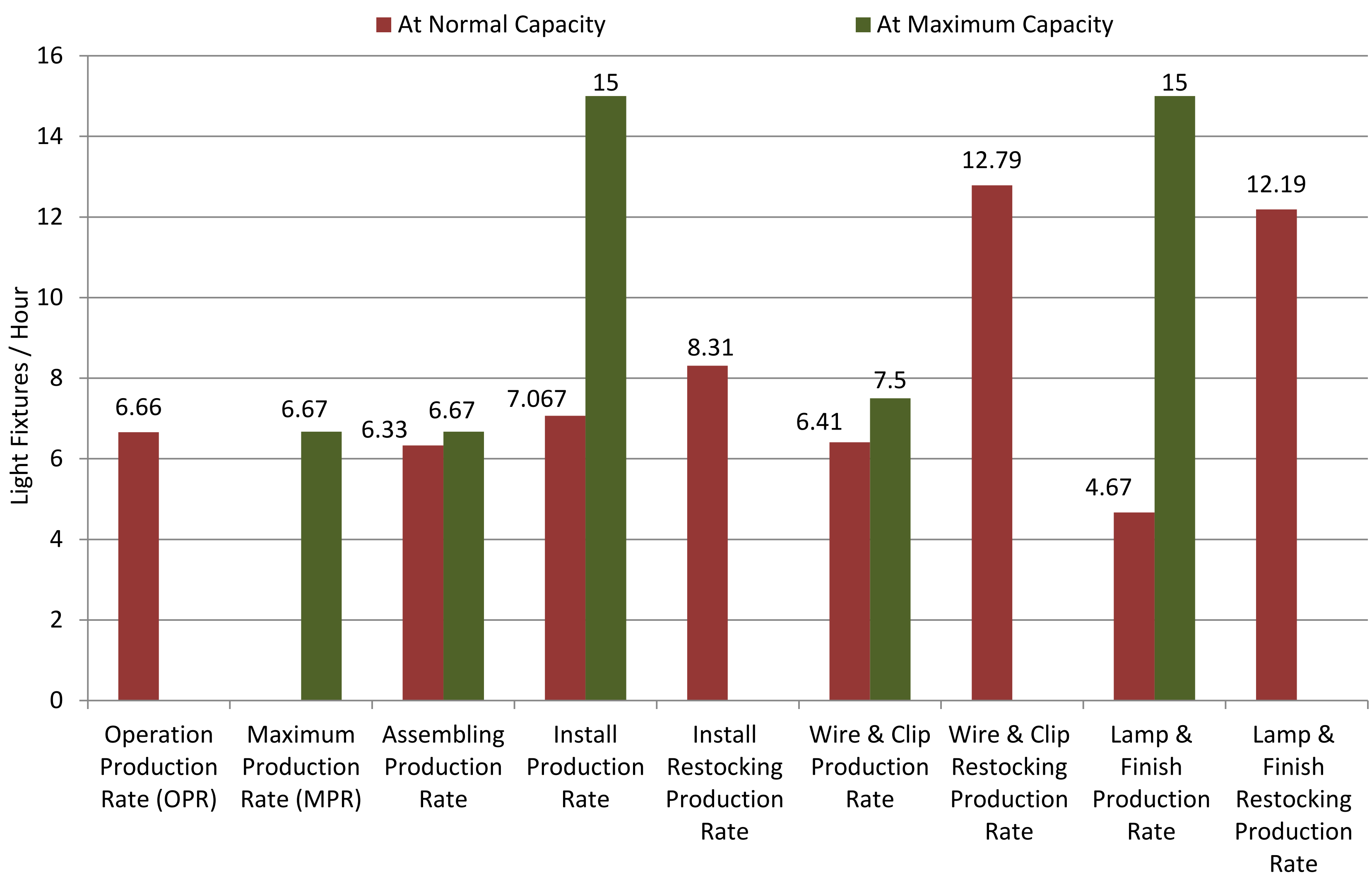


Figure 5.12: Production rates for the "Improved" crew case

The simulation results for the “Improved” crew of installation of light fixtures are analyzed to evaluate the performance of the crew design in terms of the performance outcomes proposed in the previous chapter 4: (1) *duration* of work performed; (2) *cost* of work performed; (3) *productivity*; (4) *quality* of work performed; (5) worker *satisfaction*; (6) worker *learning*; (7) worker *motivation*; (8) *pride* in work performed.

(1) Duration of Work Performed:

The “Improved” case shows significant savings in the hours of operation. The reduced duration of work (45.03 hours i.e. 2701.8 minutes in the “Improved” case vs. 130.15 hours i.e. 7809 minutes in the “base” case) is due to:

a. Reduction in the *processing time*-

In the “Base” crew case, the install, wire & clip and lamp & finish activities were talking 7, 8.5 and 7.5 minutes respectively whereas in this case after the crew was redesigned, the install, wire & clip and lamp & finish activities took 4, 8, and 4 minutes respectively to execute the installation cycle. This reduction in the activity durations considerably reduced the installation cycle time and consequently the duration of operation.

b. Reduction in *non-processing* time-

i. Reduction in *motion and transportation* of light fixtures-

In the “Base” case, each light fixture took 1 minute to restock, 1 minute to go up and 1 minute for the lift to come down to restock the next fixture; making it a total of 3 minutes each for 300 light fixtures requiring 300 moves to restock all the fixtures. Hence a total of 900 minutes (300 moves * 3 minutes each) were spent in motion and transportation of 300 light fixtures.

Whereas, in this "Improved" case, restocking was done by 3 journeymen for a batch size of 15 light fixtures; 3 minutes to restock, 1 minute to go up and 1 minute for the lift to come down to restock the next fixture; making it a total of 5 minutes each for 15 light fixtures requiring 20 moves to restock all the 300 fixtures. Hence a total of 300 minutes ((3*300*({3+1+1}/15)) were spent in motion and transportation of 300 light fixtures.

ii. Reduction in the *wait/idle time*-

The wait time for both apprentice and the journeyman has been considerably reduced from the "base" case. The apprentice average wait time has been reduced from 16.97 minutes to only 0.48 minutes. And, the journeyman average wait time in the installation cycle earlier which was 1.01 minutes has been increased to 4.49 and 4.47 minutes for journeyman A and Journeyman C and reduced to 0.00 minutes for journeyman B (if considered for 15 light fixtures together).

c. *Over-production* is still present in this case present in the form of *intermediate inventory/work-in-progress* (InstldLitFix). This evident from the fact that install activity production rate (7.067 fixtures/hour) is high compared to the wire & clip activity production rate (6.41 fixtures/hour). That means more number of light fixtures are installed by the journeyman A than that can actually be wire & Clipped by the journeyman B.

However, compared to the "Base" case, the work-in-progress in the "Improved" case has been reduced considerably from 97.64 fixtures to 0.53 fixtures. This low WIP leads to less variability resulting in reducing the duration of the work performed.

However, the WIP in front of journeyman B may lead to overburdening him, potentially leading to lowering his task productivity.

d. There is *non-uniform work load* present between the assembling, install, wire & Clip, and lamp & finish activity cycle, leading to gap in the cycle times that results in *non-continuous flow*.

   For example, considering the batch size of 15 fixtures: assembling cycle time is 135 minutes vs. install activity cycle time is 65 minutes), where journeyman A after installing 15 light fixtures waits in the queue for around 70 minutes every time to start restocking the next 15 light fixtures that take 135 minutes to be assembled.

(2) Cost of Work Performed:

Cost of work performed is directly related to the crew size, crew flexibility, processing and non-processing cost and defective products. The reduced unit cost of operation ($7.61) in this case is due to:

a. Reduced *non-processing cost* resulting from reduced non-processing time in the operation as discussed earlier.

b. Reduced *processing cost* resulting from reduced processing time in the operation as discussed earlier.

c. There is increase in the size of the crew from 2 workers and one lift to 4 workers and 3 lifts. Due to this, labor and equipment cost per hour definitely increased from $20.9/hour to $50.7/hour but in this “Improved” crew case due to the significant reduction in the duration of the operation, the total cost of operations is also reduced.

(3) Productivity:

Productivity is related to resource utilization, crew flexibility, overburden, task experience, task complexity etc. In this "Improved" case, the crew productivity is better than the "Base" case, as is evident from the increase in the operation production rate from 2.31 light fixtures/hour (base case) to 6.67 light fixtures/hour (improved case). Also as discussed earlier, an increase in the resource utilizations of overall crew (average system increase rather than single point increase) would increase the overall crew productivity; this is evident from the fact that apprentice utilization has increased from 34.65% to 94.94% along with journeyman B utilization has increased to above 90%.

(4) Quality of Work Performed:

Quality of work is directly related to the defective products, task experience, task complexity, overburden, task interdependence. But in this case, these soft or qualitative crew design characteristics cannot be empirically quantified using discrete event simulation.

(5) Worker Learning:

Worker *learning* is related to crew design indicators such as coordination, crew flexibility, task variety etc. In this case, from the model and simulation results, a qualitative inference can be made that there is very less/no team work/crew flexibility/multi-tasking/coordination/task variety present in this case similar to the "Base" crew case. Hence, learning among crew is minimal to non-existent for the apprentice, except in assembling fixtures.

(6) Pride in Work performed:

Pride in the work performed is related to the task identity and self-management. In this case, from the model and simulation results, a qualitative inference can be made that pride is now lost to everyone involved as the work performed has been divided into sub-activity cycles that are performed by different workers and no crew member can now identify himself with the whole operation and take pride in it, because they only execute a part of the operation.

(7) Worker Satisfaction:

Worker satisfaction directly relates to crew design indicators such as coordination, support, task significance, reasonable autonomy etc. But in this case, these soft or qualitative crew design characteristics cannot be empirically quantified using discrete event simulation.

(8) Worker Motivation:

Worker motivation directly relates to crew design indicators such as coordination, task identity, task significance, reasonable autonomy etc. But in this case, these soft or qualitative crew design characteristics cannot be empirically quantified using discrete event simulation.

5.3.3 DES Lean Crew Model

After evaluating the previous 2 crew cases (base and improved), the "Improved" crew design is enhanced & optimized based on the lean based crew design guidelines proposed in the chapter 4.

For the "Lean" crew case, the size of the crew selected is 3 workers with crew composition of 2 apprentice, 1 journeyman, and 2 lifts. Activities required to perform the operation of installation of light fixtures were kept the same in the "Improved" case i.e. assemble, restocking, lift A going up, install, wire & clip, lamp & finish, and lift A going down; but in this "Lean" crew design, structuring of work among the crew was different from the "Base" and "Improved" crew design case. Here, the apprentice A was again assigned the responsibility for assembling the fixtures in 9 minutes, but he was also assigned restocking of the assembled light fixtures and taking them up in the lift A and coming down in the lift A after handing over the assembled light fixtures to the journeyman A and apprentice B who are on the other lift waiting above to carry out the installation cycle consisting of install, wire & clip and lamp & finish activities taking 3.5, 4.25, and 3.75 minutes respectively. The journeyman A and apprentice B are working together on the same lift B and stay up until they complete 300 light fixtures. In this "Lean" crew case, single piece flow was adopted and only light fixture was assembled, restocked and installed at a time. Also, for the purpose of modelling and simulation, it was assumed that restocking required 1 minute with lift A taking 1 minute each in going up and coming down. The sequence of activities for this operation is shown in the Figure 5.13.

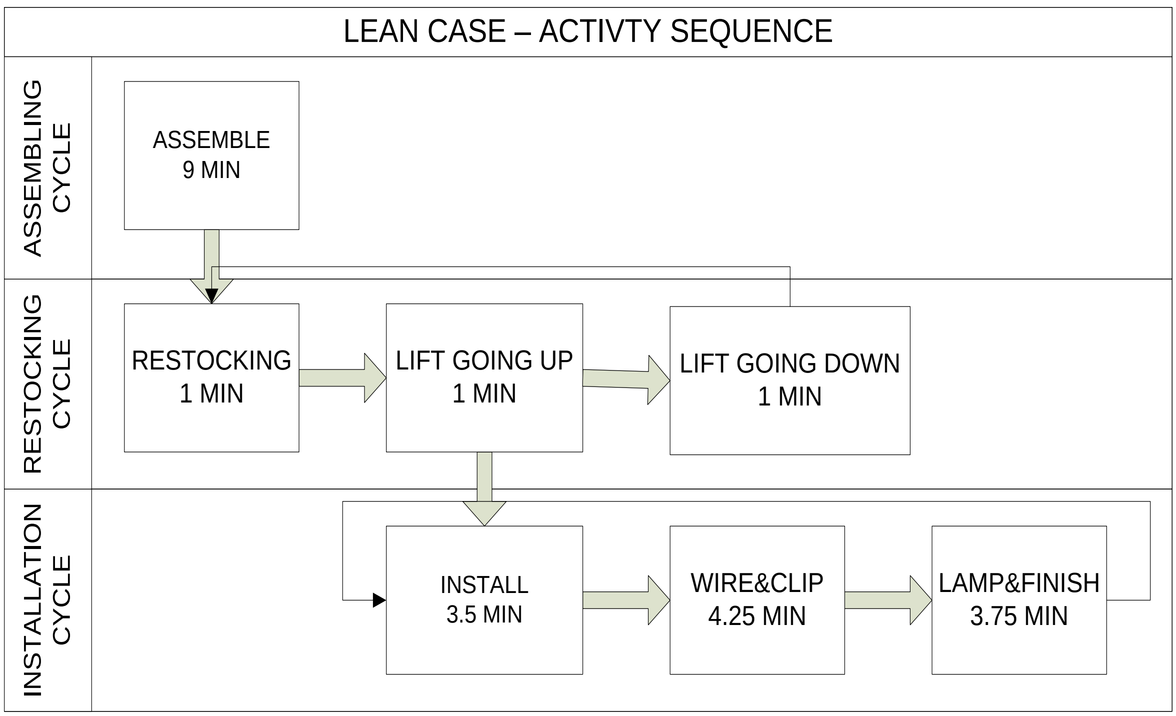


Figure 5.13: Sequence of activities in the "Lean" crew case of installation of light fixtures

Table 5.5 shows the activities and their types involved in this process along with the entity, resource types, time and size data that are needed to execute each type of activity. The two activity types used to model this process are *combi* (conditional) and *normal* along with *queues* where entity and resource types accumulate For example, in this model for activity *restocking* (combi) to start; the conditions set by the draw link should be met for the light fixture, apprentice

A and lift A. Similarly, for activity *install*, the table shows that both the journeyman A, apprentice B, and lift B are needed to execute that activity.

Table 5.5: DES "Lean" crew model data

DES "LEAN" MODEL DATA									
S.NO	ACTIVITY	TYPE	TIME (min)	ENTITY	RESOURCE				
				Light Fixture	Apprentice		Journeyman	Lift	
					A	B	A	A	B
1	Assemble	Combi	9	√	√	X	X	√	X
2	Restocking	Combi	1	√	√	X	X	√	X
3	Lift A Going Up	Combi	1	√	√	X	X	√	X
4	Lift A Going Down	Combi	1	X	√	X	X	√	X
6	Install	Combi	3.5	X	X	√	√	X	√
7	Wire & Clip	Combi	4.25	X	X	√	√	X	√
8	Lamp & Finish	Combi	3.75	X	X	√	√	X	√
SIZE/NUMBER				300	1	1	1	1	1

The Figures 5.14 & 5.15 shows the simulation model developed for the "Lean" crew case of installation of light fixtures. In this model, initially 300 light fixtures are waiting in the LitFix queue to be assembled. For the conditional activity assemble to start, both apprentice and light fixtures should be available (i.e. AprntcAWt and LitFix >0); so once both these are available assembling takes place for 9 minutes and releases one each of apprentice and assembled light fixture that waits in the apprentice wait queue (AprntcAWt) and assembled light fixture queue (RestockCount) respectively. For conditional activity restocking to start, there should be at least one light fixture assembled, one apprentice, one lift A waiting in the RestockCount, AprntcAWt, LftADwnWt queue should be equal to one.

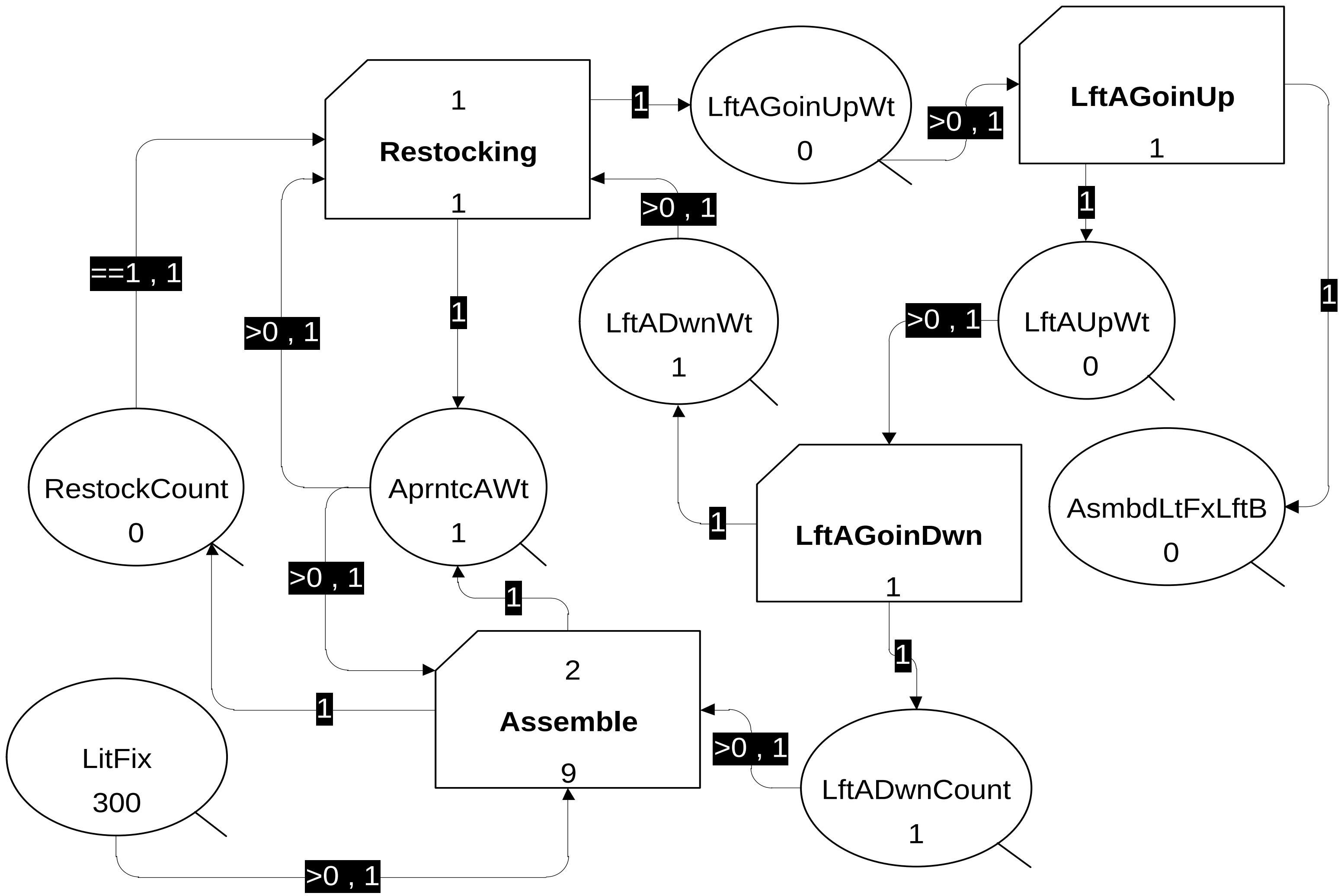


Figure 5.14: Simulation model for the apprentice, assembling & restocking activity cycle in the “Lean” crew of installation of light fixtures

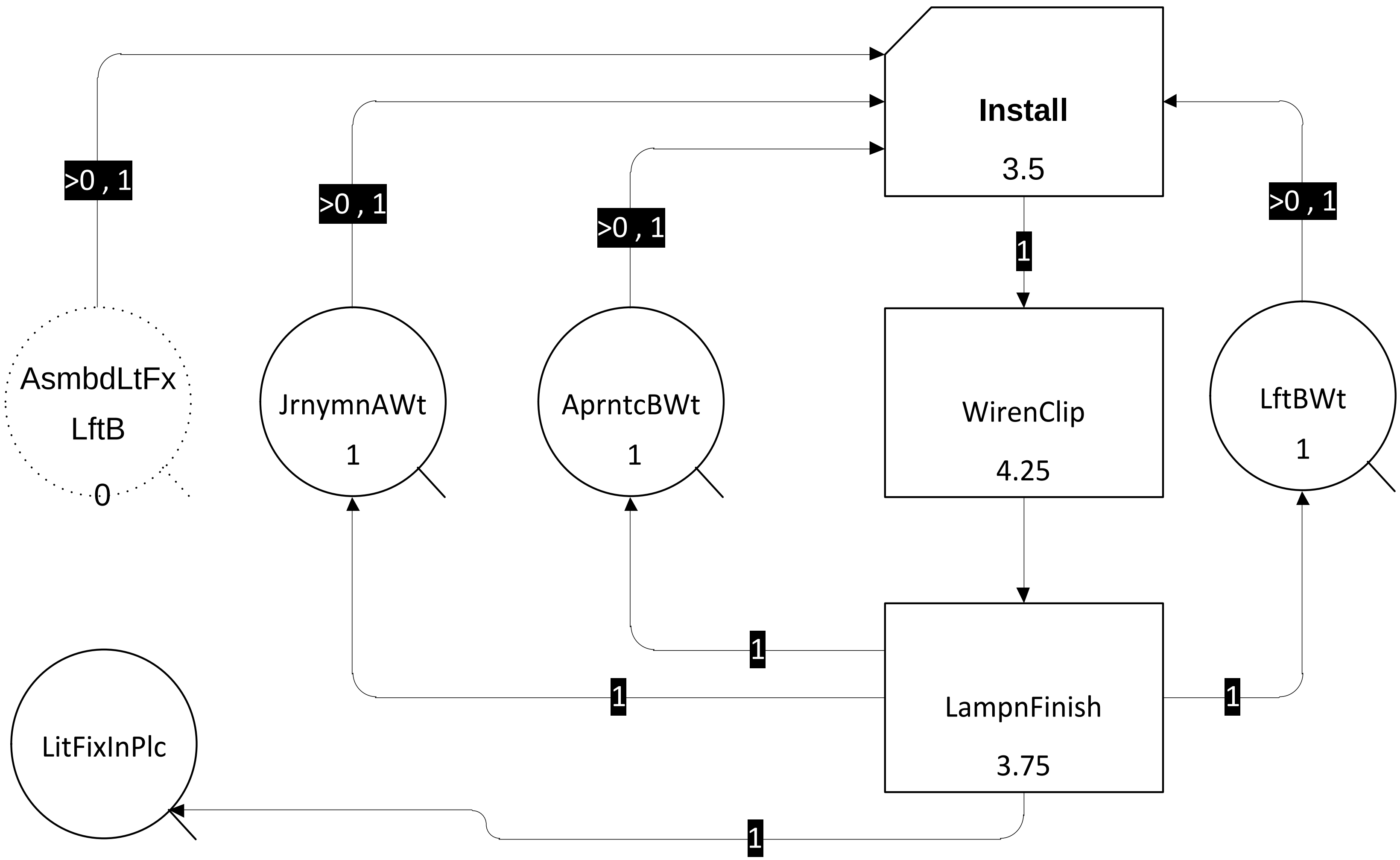


Figure 5.15: Simulation model for the journeyman, installation cycle in the “Lean” crew of installation of light fixtures

Once, the light fixture is restocked by the apprentice A, he goes up and comes down in the lift A in 1 minute each (LftAGoinUp & LftAGoinDwn), releasing one assembled light fixture in AsmbldLtFxLftB queue. The installation cycle starts with the activity *install* taking 3.5 minutes when journeyman A, lift B, apprentice B and assembled light fixture are all available (JrnymnAWt, LftBWt, AprntcBWt, AsmbldLtFxLftB >0), followed by *wire & clipping* (WirenClip) taking 4.25 minutes and *lamp & finish* (LampnFnsh) taking 3.75 minutes. After, *lamp & finish* activity is finished one light fixture is released to the LitFixInPlc queue.

Results from the simulation of the "Lean" crew case of installation of light fixtures have been summarized in Table 5.6. The "Lean" crew takes 60.17 hours to complete the operation and install 300 light fixtures. The time of operation here is 15.14 hours more than the "Improved" crew case (45.03 hours), but is 69.98 hours less than the "Base" crew case (130.15 hours), and 80.57 hours less than the budgeted (125.6 hours) showing significant saving in the duration of the operation. The unit cost of operation also came out to be $2.63 less than the budgeted and $3.37 less than the "Base" case and &1.92 less than the improved case.

The resource utilizations in this case are very high compared to all the previous cases at around 95% apart from lift A utilization that came out to be around 25%. Also, the average labor utilization in this crew case was considerably more at 94.43% than the "Base" case (62.26%). The high resource utilizations are supplemented by the fact that Average Idle Times for both apprentice A and journeyman A (&apprentice B) are very low at 1.02 and 0.53 minute respectively.

Table 5.6: Simulation results of the "Lean" crew of installation of light fixtures

PERFORMANCE OUTCOMES	BUDGETED	LEAN CASE
Time of Operation	125.60 hours	60.17 hours
Unit Cost of Installation	8.32 USD	5.69 USD
Apprentice A Utilization	-	92.19%
Apprentice B Utilization	-	95.55%
Journeyman Utilization	-	95.55%
Lift A Utilization	-	24.92%
Lift B Utilization	-	95.56%
Average Apprentice A Idle Time	-	1.02 min
Average Journeyman A Idle Time	-	0.53 min
Average Apprentice B Idle Time		0.53 min
Average Work-In-Progress (WIP)	-	0.0 Fixtures
Operation Production Rate (OPR)	-	4.98 Fixtures/Hr
Maximum Production Rate (MPR)	-	5.00 Fixtures/Hr
OPR-MPR Ratio	-	99.60%

The average work-in-progress (WIP) was reduced completely from 97.64 fixtures (base case) to 0.0 fixtures (lean case) following a single piece flow by reducing the batch size to light fixture. The reduced WIP also supplements the better operation production rates for all the activities and for the operation at 4.98 light fixtures/hour compared to the 2.31 light fixtures/hour in the "Base" case. The operation production rate is very close to the maximum production rate (5 light fixtures/hour) that can be possible for this operation at maximum capacity. Also, the individual production rates for all the activities at their normal and maximum capacity for this "Lean" crew case has been shown in the figure 5.16.

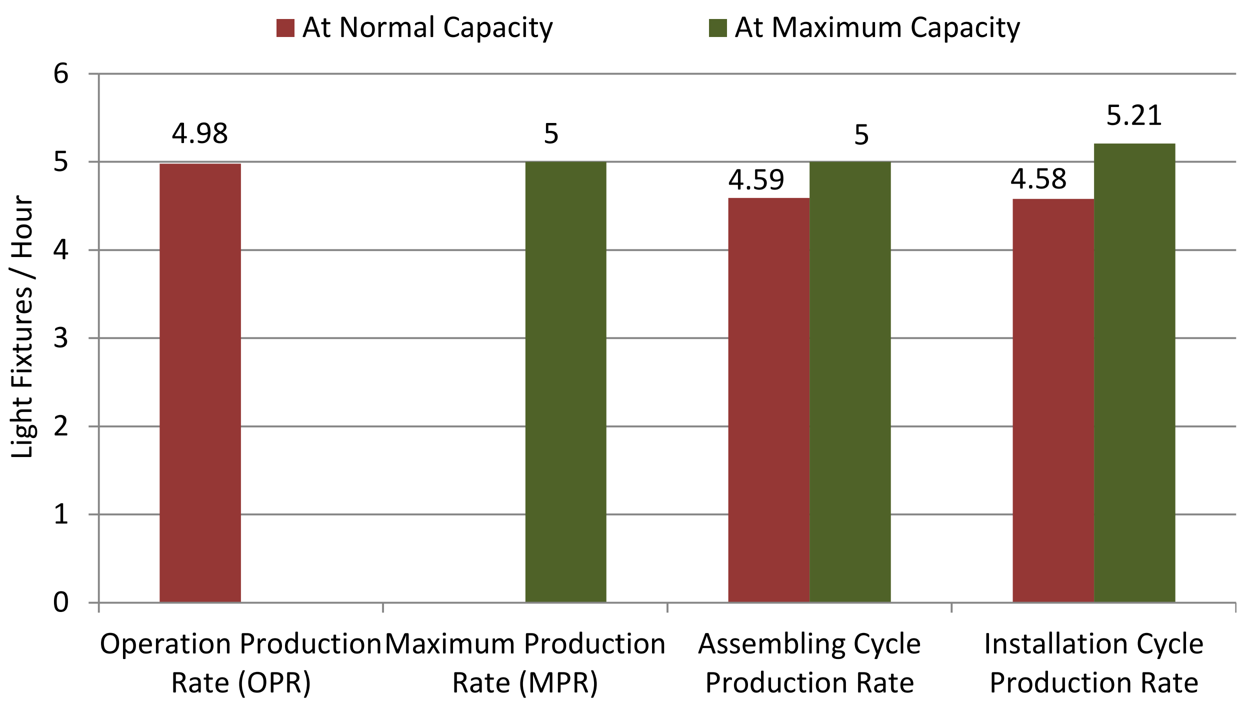


Figure 5.16: Production rates for the "Lean" crew case

The simulation results for the “Lean” crew of installation of light fixtures are analyzed to evaluate the performance of the crew design in terms of the performance outcomes proposed in the previous chapter 4: (1) *duration* of work performed; (2) *cost* of work performed; (3) *productivity*; (4) *quality* of work performed; (5) worker *satisfaction*; (6) worker *learning*; (7) worker *motivation*; (8) *pride* in work performed.

1. Duration of Work Performed:

The “Lean” crew case shows significant savings in the hours of operation. The reduced duration of work (60.17 hours i.e. 3610.20 minutes) is due to:

a. <u>Reduction in the *processing time*</u>-

In this case, after the crew was redesigned, the install, wire & clip and lamp & finish activities took 3.5, 4.25, 3.75 minutes respectively to execute the installation cycle that is lower than compared to both the previous crew cases This reduction in the activity durations considerably reduced the installation cycle time and consequently the duration of operation.

b. Reduction in *non-processing* time-

   i. Reduction in *motion and transportation* of light fixtures-

   In this case, restocking was done for each light fixture by the apprentice A rather than the journeyman. Hence, motion and transportation was reduced for the journeyman that earlier had to go up and down in the lift for restocking. The restocking time that is added on to the apprentice A further helps in balancing the cycle times and work flow among the assembling and installation cycles.

   ii. Reduction in the *wait/idle time*-

   The wait time for both apprentice and the journeyman has been considerably reduced from the previous cases. The apprentice A average wait time has been reduced to only 1.02 minutes. And, the journeyman A (apprentice B) average wait time in the installation cycle 0.53 minutes. This significant reduction in the wait time results in reduced duration of the work.

c. The problem of *Over-production* is controlled in this case that was earlier present in the in the form of *intermediate inventory/work-in-progress*. This evident from the fact that in this case, there is almost no WIP and also, the assembling production rate (4.59 light fixtures/hour) is almost equal to the installation activity production rate (4.58 light fixtures/hour), meaning the number of light fixtures assembled by the apprentice A can now be installed at the almost the same rate without any wait times in between.

d. *Uniform work load* is finally achieved in this case between the assembling and installation cycle leading to continuous flow. This is evident from the fact the assembling and installation cycle times are almost equal (12 minutes vs. 11.5 minutes). Hence now the light fixture don't have to wait in the queue after being assembled and can straight away start getting installed.

2. Cost of Work Performed:

   Cost of work performed is directly related to the crew size, crew flexibility, processing and non-processing cost and defective products. The reduced unit cost of operation ($5.69) in this case is due to:

   a. Reduced *non-processing cost* resulting from reduced non-processing time in the operation as discussed earlier.

   b. Reduced *processing cost* resulting from reduced processing time in the operation as discussed earlier.

   c. Reduction in the size of the crew from the improved crew case. There is decrease in the size of the crew from 4 workers and 3 lifts to 3 workers and 2 lifts. Due to this, labor and equipment cost per hour reduces from $50.7/hour in the "Improved" crew case to $26.9/hour in the lean crew case.

3. Productivity:

   Productivity is related to resource utilization, crew flexibility, overburden, task experience, task complexity etc. In this "Lean" case, the crew productivity is better than the "Base" case, as is evident from the increase in the operation production rate from 2.31 light fixtures/hour (Base Case) to 4.98 light fixtures/hour. Also as discussed earlier, an increase in the resource utilizations of overall crew (average system increase rather than single point increase) would increase the overall crew productivity; this is evident from the fact that apprentice A utilization has increased from 34.65% to 92.19% and with journeyman B (apprentice B) utilization has increased to above 95.55%.

4. Quality of Work Performed:

   Quality of work is directly related to the defective products, task experience, task complexity, overburden, task interdependence. But in this case, these soft or qualitative crew design characteristics cannot be empirically quantified using discrete event simulation.

5. Worker Learning:

   Worker *learning* is related to crew design indicators such as coordination, crew flexibility, task variety etc. In this case, from the model and simulation results, a qualitative inference can be made that there is team work and learning in the crew because the apprentice is working along with the journeyman helping him to install the light fixtures and also learn on the way.

6. Pride in Work performed:

   Pride in the work performed is related to the task identity and self-management. In this case, from the model and simulation results, a qualitative inference can be made that pride is taken by the crew as both the journeyman and the apprentice now work on the major part i.e. installation of light fixtures and can identify themselves with contributing towards the operation and taking pride in the finished product.

7. Worker Satisfaction:

   Worker satisfaction directly relates to crew design indicators such as coordination, support, task significance, reasonable autonomy etc. But in this case, these soft or qualitative crew design characteristics cannot be empirically quantified using discrete event simulation.

8. Worker Motivation:

   Worker motivation directly relates to crew design indicators such as coordination, task identity, task significance, reasonable autonomy etc. But in this case, these soft or qualitative crew design characteristics cannot be empirically quantified using discrete event simulation.

5.4 System Dynamics Model

As, shown in the previous sections, DES is very effective in modeling and evaluating the construction processes at an operational level. The use of DES allowed us to evaluate three different crew designs (base, improved and lean crew design) for the construction operation of installation of light fixtures and determine information about expected cost, duration, and other process level details such as resource utilizations, production rates, idleness of resources, waiting/delays, work-in-progress etc.

However in DES, it is difficult to model the qualitative or softer aspects such pride, learning, satisfaction etc. and to evaluate the various nonlinear cause-and-effect relationships and feedback that exist in a construction process. These cause-and-effect relationships and feedback among the variables/aspects can be analyzed more effectively with the help of system dynamics (SD).

In this section, SD models (qualitative and quantitative) are developed to represent the 3 crew designs for the operation of installation of light fixtures. The SD models are developed to demonstrate how both the quantitative (hard factors/aspects) and qualitative (soft factors/aspects) can be modeled using SD. The proposed qualitative SD model demonstrates the various cause-and-effect relationships and feedback among the crew design characteristics and the crew performance outcomes proposed in the chapter 4. And, the quantitative SD models demonstrate how the operational/process level details can be modeled using stock and flows in the form of mathematical equations representing the rate of change of the crew design variables over the time. The quantitative SD models help in determining and evaluating the pattern of behavior of various crew design characteristics and crew performance outcomes that is not possible with the use of DES. For modeling the SD qualitative and quantitative models Vensim PLE, a free shareware is used.

5.4.1 SD Qualitative Model

In the chapter 4, crew design characteristics and crew performance outcomes are proposed to guide the design of a crew. The crew design characteristics are divided into a number of primary and intermediate characteristics that have various causal and feedback relationships among them affecting the performance of the crew in terms of cost, duration, productivity, learning, pride etc. The causal relationships among the crew design characteristics, intermediate crew design characteristics were shown in the previous chapter 4 (Figure 4.4 and 4.5); however the feedback among these was not shown.

Hence, a SD qualitative model is developed and proposed to demonstrate the causal and feedback relationships among the primary and intermediate crew design characteristics affecting the performance of the crew. First, qualitative models are developed for each of the crew performance outcomes such as cost, duration, productivity, learning, pride etc. proposed in the chapter 4 and then these individual qualitative models are combined together to provide a crew performance model that shows all the causal and feedback relationships present among the primary crew design characteristics, intermediate crew design characteristics & outcomes and final crew performance outcomes.

For example in a SD qualitative duration model, an increase in the processing time will increase the cycle time that in result will again increase the duration of work performed. And in the same way, any increase in the movement speed will decrease the processing time resulting in a decrease in the cycle time and consequently reducing the duration of work performed. Similarly, other models such as cost, productivity, quality, satisfaction, learning, motivation, pride are developed and combined together with the feedback relationships in order to develop the qualitative crew performance model that can be accessed at the following website: https://docs.google.com/file/d/0BxrMYHbElFuNam5keHp1RWVnQTQ/edit

5.4.2 SD Quantitative Models

In this section, SD quantitative models are developed to represent the 3 crew designs for the operation of installation of light fixtures. The SD quantitative models are developed to demonstrate how both the causal/feedback relationships and operational level detail of the construction process of installation of light fixtures can be modeled using continuous simulation such as system dynamics. The accuracy and reliability of SD models are tested by comparing the SD simulation results with the DES results.

In system dynamics quantitative modeling, the causal loop/feedback diagrams developed in the previous section are converted into stock and flow diagrams to represent the dynamic behavior of a system with the help of mathematical equations.

To model a process in SD, the DES modeling elements such as activity, entity and resources can be represented in the form of stock and flows. The two types of activities (normal & combi) and queues are represented by flows and stocks respectively. One of the main differences in modeling a process in SD verses DES is the representation of the activities, entity and resources. In DES (STROBOSCOPE), a resource or entity can be distinguished from the other with the help of different arrows and therefore different type and amount of resources/entities can either enter or released from the same activity. In SD (Vensim), same activity from DES has to be represented by different flows for each of the different stocks (represented by entities/resources in DES). Hence, each cycle in DES would be represented by a number of cycles in SD (equal to the number of entity/resources); this is discussed in detail in the following section of SD quantitative models for the 3 crew design cases.

As, discussed in the previous section, in the "Base" crew design for the construction operation of installation of light fixtures, 300 light fixtures are assembled and installed by 1 apprentice, 1 journeyman, and 1 lift. The entity in this case is the light fixture and the resources are apprentice, journeyman and lift. Now, since there are four different entity and resources, four different cycles of stock and flow diagram is needed to represent the life cycle of each one of them from. Also, the sequence of activities is assembling, restocking, lift going up, install, wire & clip, lamp & finish, and lift going down taking the same time as mentioned in the DES "Base" crew model. Representation of assembling cycle in SD (Vensim) with conversion of activities and queues (in DES) into stock and flows is shown in the Figure 5.17.

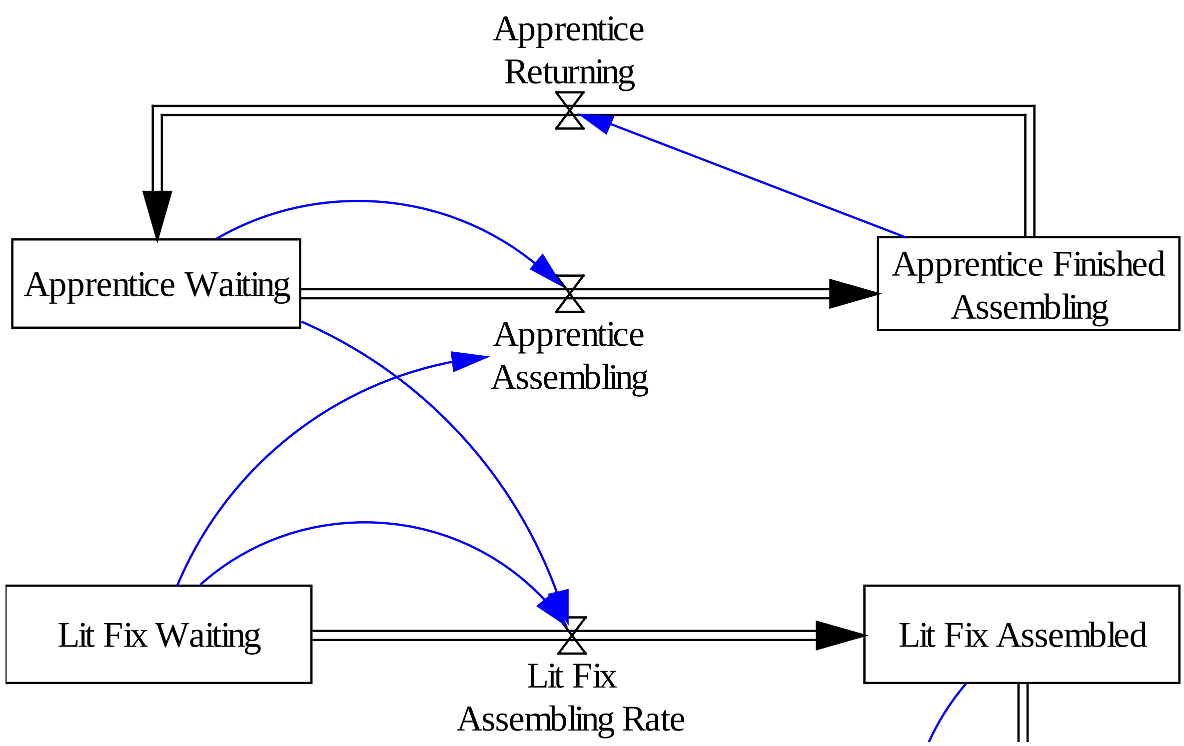


Figure 5.17: Representation of assembling cycle for DES VS. SD "Base" case

In the above Figure 5.17, the activity assembling (DES) is represented by two flows (Lit Fix Assembling Rate and Apprentice Assembling) one for the entity (light fixture) and one for the resource (apprentice) respectively. The accumulation of the entity in DES in shown by the Queues LitFix where light fixtures are waiting; and after each light fixture is assembled in 9 minutes in activity Assemble, it waits in the AsmbdLitFixA queue. This is represented in SD by the rate Lit Fix Assembling Rate that draws out 1/9 light fixture each minute from the stock Lit Fix Waiting into the Lit Fix Assembled stock (hence in 9 minutes one light fixture is assembled). Similarly Apprentice is drawn out of the Apprentice Waiting stock at 1/9 Apprentice each minute into the Apprentice Finished Assembling (hence 1 Apprentice finishes assembling in 9 minutes) and Apprentice is finished assembling in 9 minutes, he returns to waiting again through Apprentice Returning flow into the Apprentice Waiting stock. The Figure 5.18 shows the pattern of behavior of the apprentice in the assembling cycle for the first 50 minutes of assembling cycle.

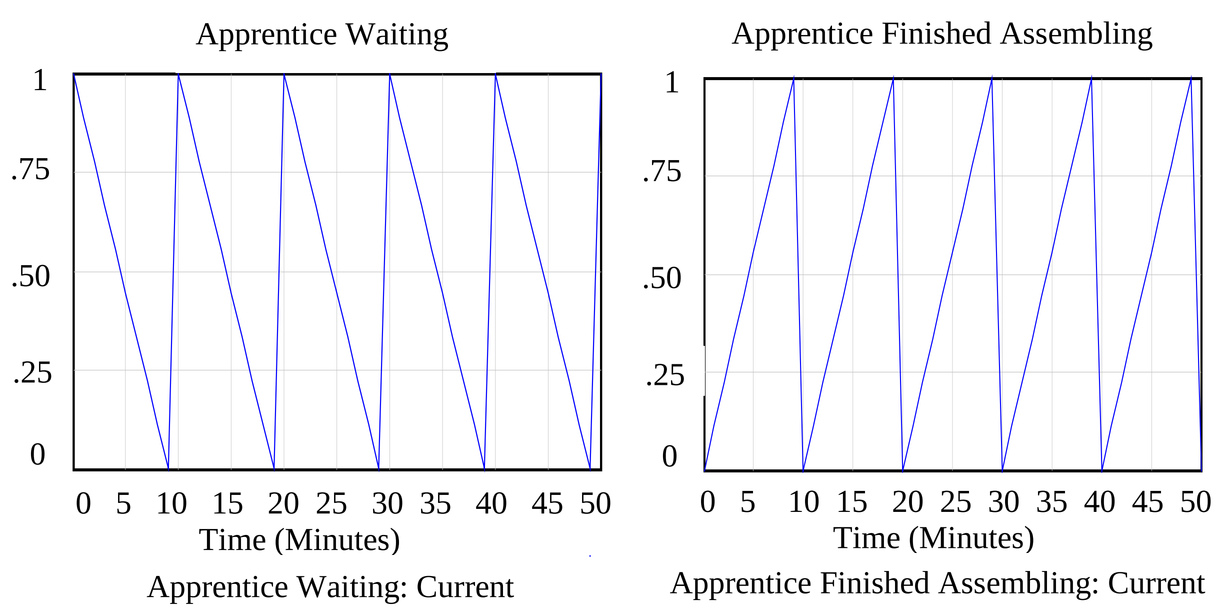


Figure 5.18: Pattern of behavior for the apprentice in assembling cycle for “base” crew case in SD (Part A).

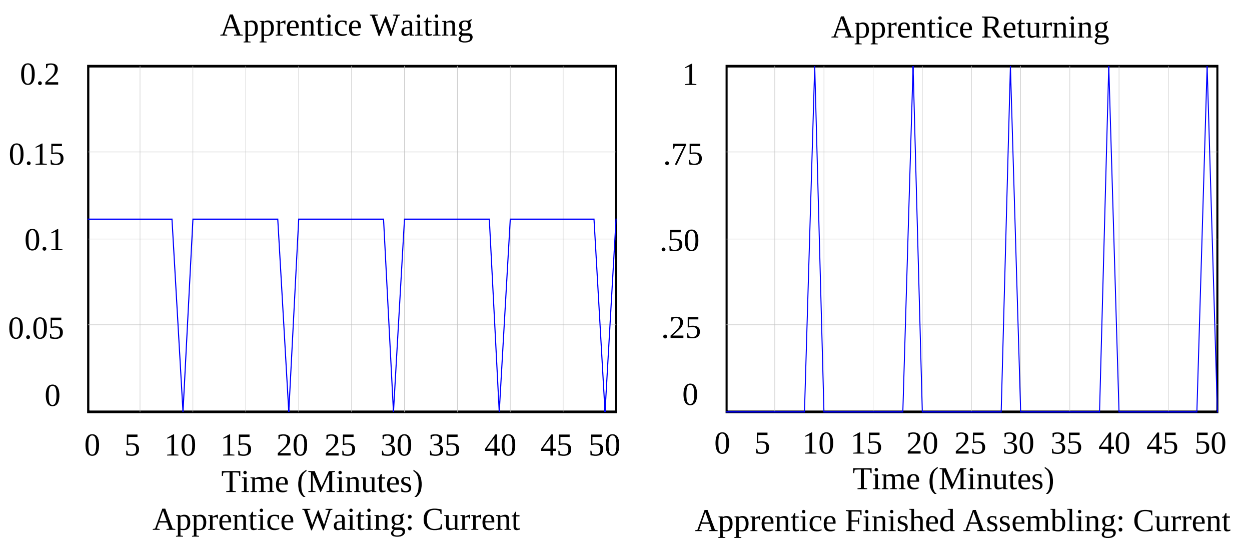


Figure 5.19: Pattern of behavior for the apprentice in assembling cycle for “base” crew case in SD (Part B)

The above Figure 5.19 shows behavior of the apprentice changing over time. The apprentice assembling remains constant at 0.1111 (1/9 apprentice) for every 9 minutes showing that apprentice is busy assembling for 9 minutes; also apprentice waiting value changes between 1 and 0 respectively every 9 minutes showing the apprentice idle and busy states (apprentice waiting==1 shows the idle state whereas apprentice waiting<1 shows the assembling state). Similarly, the light fixture also behaves in the same pattern (Figure 5.20).

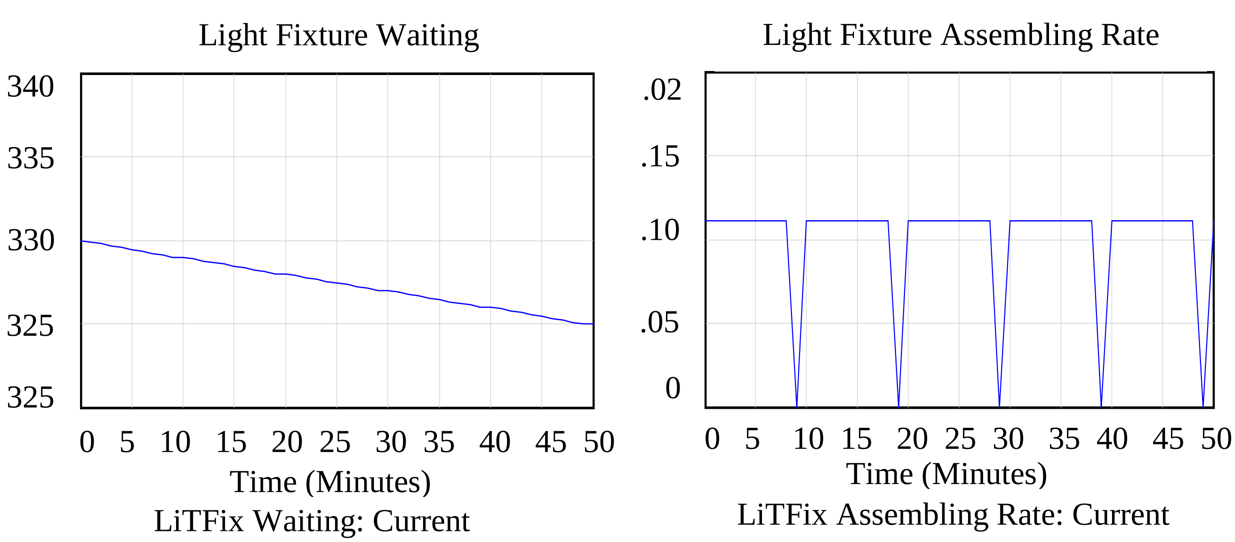


Figure 5.20: Pattern of behavior for the light fixture in assembling cycle for “base” crew case in SD (Part A)

The above discussion proves that assembling cycle in SD has been built right and is a correct representation of the assembling process developed in DES (STROBOSCOPE).

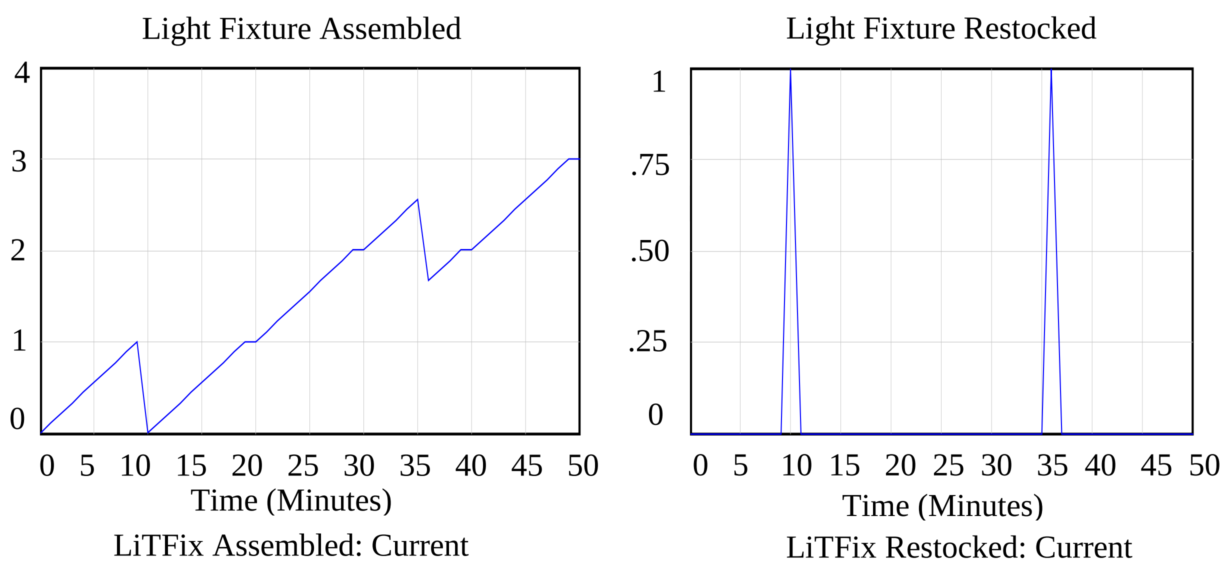


Figure 5.21: Pattern of behavior for the light fixture in assembling cycle for "base" crew case in SD (Part B)

The restocking and installation cycle for the "Base" crew case in DES (Figure 5.4) is converted into the SD using stock and flows. Three different flow cycles (light fixture cycle, journeyman cycle and lift cycle) were developed to represent the construction operation of installation of light fixtures in the quantitative SD model. The complete quantitative SD model for the "Base" crew case is shown in the Figure 5.22. The mathematical equations used to develop the model and graphs for pattern of behavior for the quantitative SD model for "Base" crew case are provided in the appendices. After modeling the quantitative SD model for the "Base" crew case of installation of light fixtures; the "Improved" and "Lean" crew cases are also converted into quantitative SD models. The complete quantitative SD model for the "Base" crew case is shown in the Figure 5.23. The mathematical equations used to develop the model and graphs for pattern of behavior for the quantitative SD model for "Base" crew case are provided in the appendices.

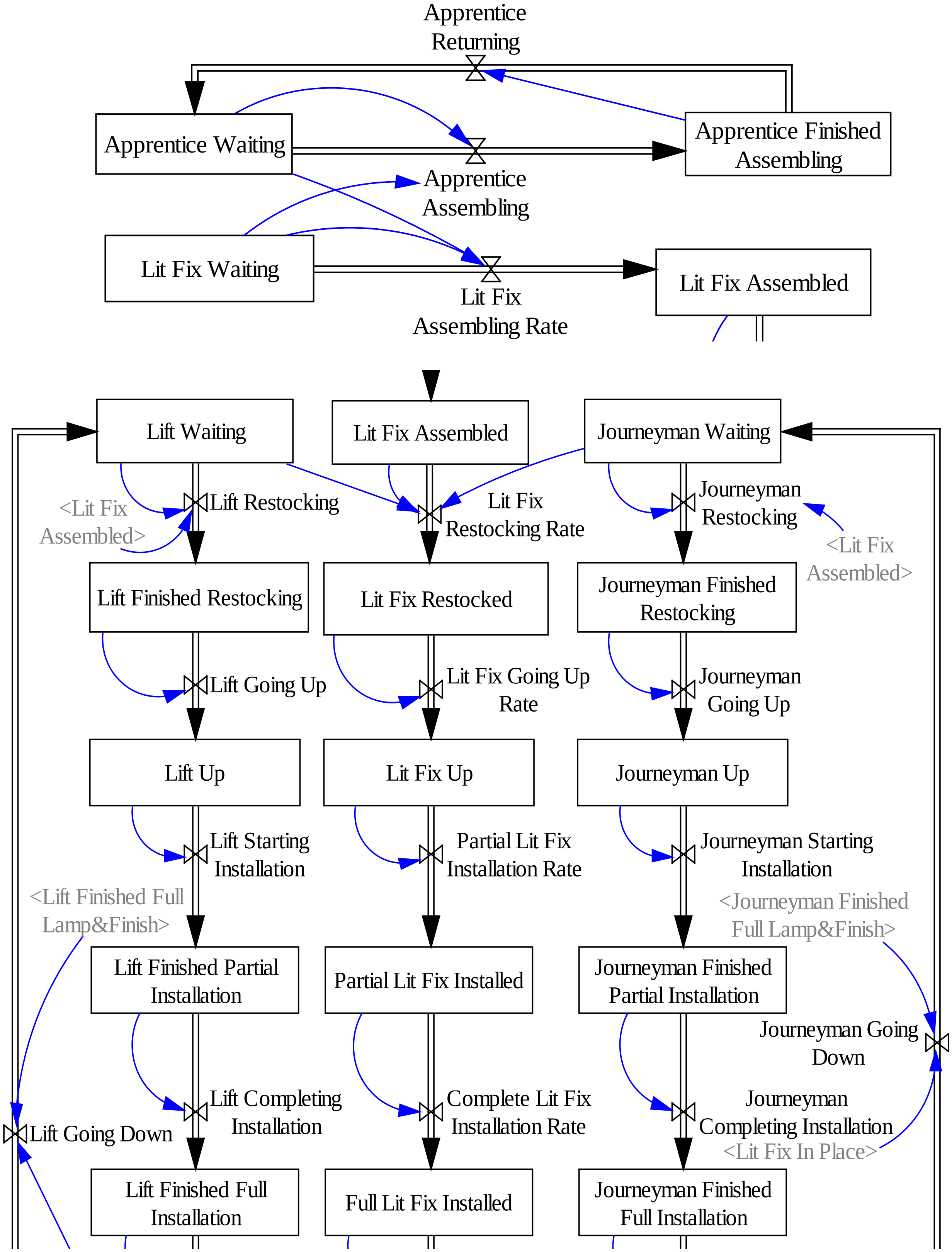


Figure 5.22: Representation of the quantitative SD model for “Base” crew case (Part A)

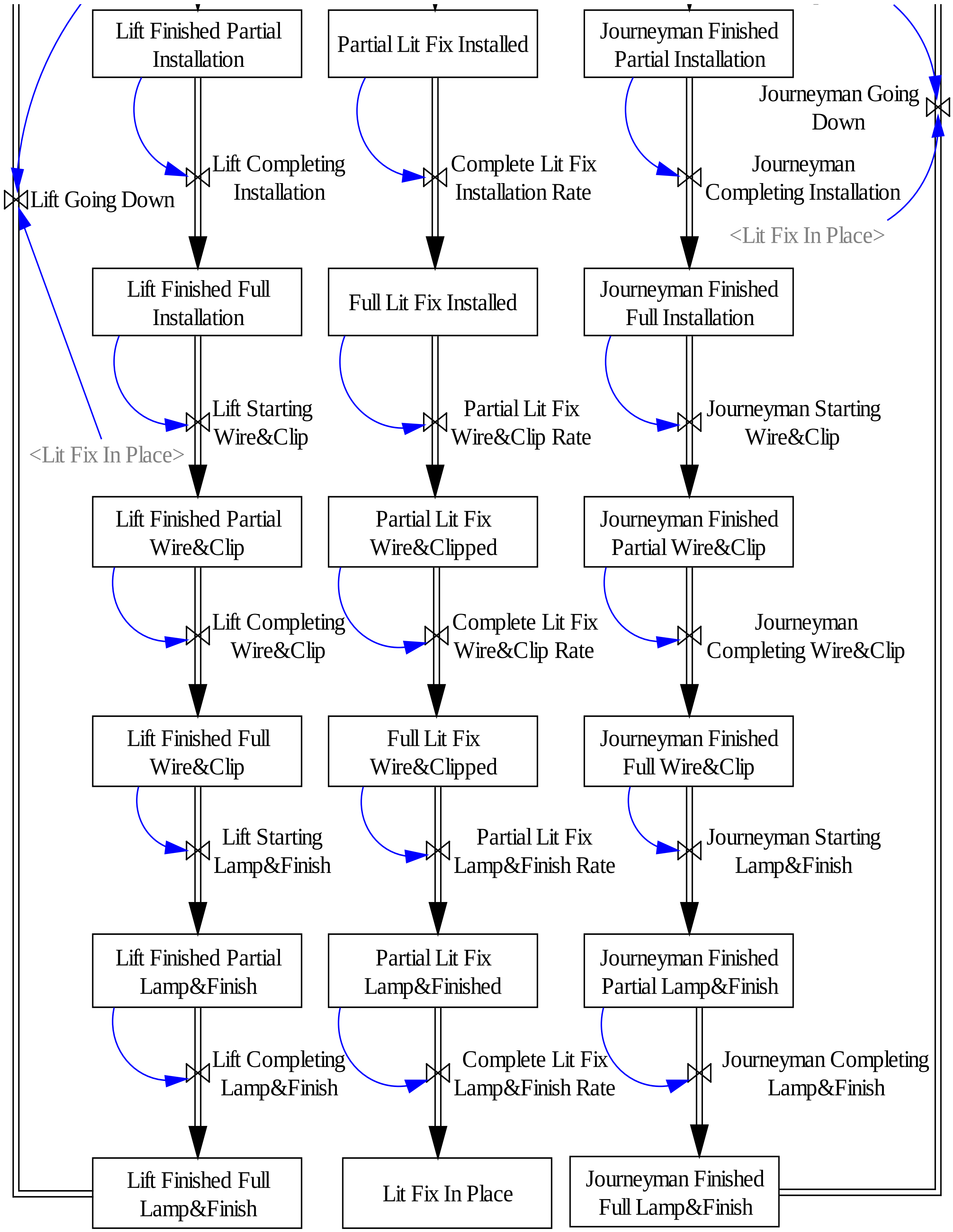


Figure 5.23: Representation of the quantitative SD model for “Base” crew case (Part B)

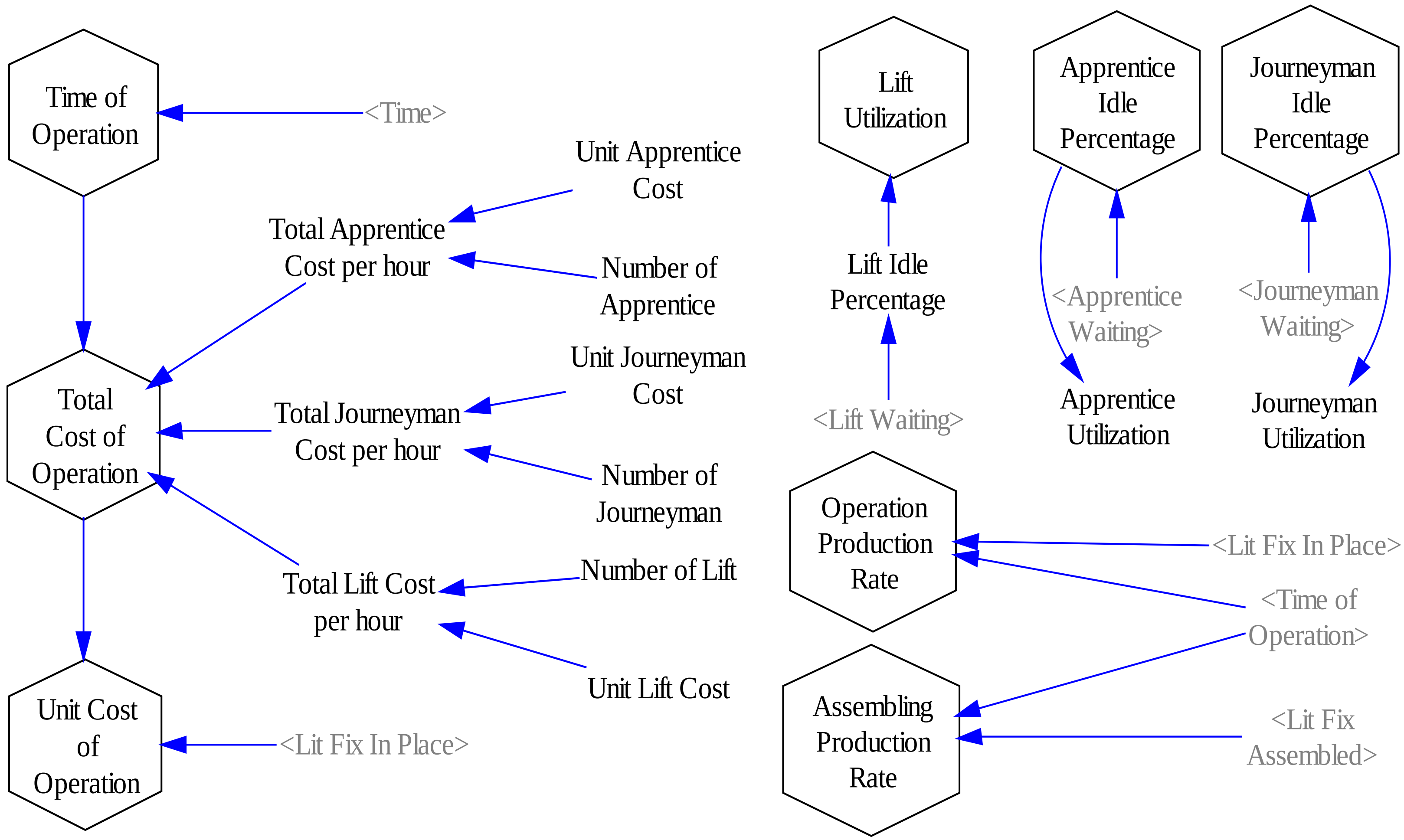


Figure 5.24: Representation of the quantitative SD model for “Base” crew case Part (C)

After modeling the three crew designs in SD, crew design characteristics and performance outcomes such as duration of operation, total cost of operation, unit cost of operation, resource utilizations, wait/idle times and production rates etc. are generated for the three quantitative SD models and compared with DES simulation results in the following Table 5.7.

Table 5.7: Comparison of DES and SD simulation results

Crew Case	DES (Stroboscope)			SD (Vensim)			Time Ratio	Cost Ratio
	Time (Hr)	Unit Cost ($)	OPR Fix/Hr	Time (hr)	Unit Cost ($)	OPR Fix/Hr		
Base	130.15	9.06	2.31	130.13	9.062	2.30	0.99984	1.0002
Improved	45.03	7.61	6.66	50.23	8.48	5.97	1.1154	1.1143
Lean	60.17	5.69	4.98	60.16	5.69	4.98	0.99983	1.0000

In order to validate the three crew design models in SD, simulation results from SD are compared with the DES results. The SD simulation results for time of operation, unit cost and operation production rates are very similar to DES simulation results.

The SD results for the “Base” and “Lean” crew cases are almost the same with less than 0.0003% variation; however some variation is present in the results for the “Improved” crew case. This could be attributed due to the complexity present in the process of the “Improved” crew case in DES. When the “Improved” crew case DES model is converted into SD certain assumptions are made in order to represent the same process and flow of entity (light fixtures) and resources (1 apprentice, 3 journeymen, and 3 lifts) that results in variation in the results.

5.5 Crew Design Analysis and Comparison

In the previous section, a well-documented construction operation focusing on the installation of light fixtures (Howell et al 1993) was modeled and simulated using DES and SD for two different crew designs (Base and Improved) having different crew size and composition. The "Base" and "Improved" crew designs are enhanced & optimized based on the lean crew design guidelines proposed in the chapter 4 to develop a "Lean" crew design. In this section, the "Lean" crew design is compared with the "Base" and "Improved" crew designs to finalize the impact of lean crew design guidelines. For the scope of this research, it was not possible to analyze and compare the crew designs based on all the proposed lean crew design characteristics. Hence, few characteristics from both the flow and work characteristics were selected to analyze and compare the three crew designs (Base, Improved and Lean).

The flow characteristics selected were: (1) motion, (2) transport, (3) waiting, (4) over-production, (5) inventory, and (6) defects. And, the work characteristics selected were: (7) crew size, (8) crew flexibility, (9) crew heterogeneity, (10) task variety, (11) task identity, and (12) support.

1) <u>MOTION</u>:

Motion is an important flow characteristic affecting crew performance in terms of non-processing time and consequently the duration and cost of work performed by a crew. Motion (number of moves) in the 3 crew designs is shown in the Table 5.8.

Table 5.8: Motion in 3 crew designs

Motion/Number of Moves (to restock 300 light fixtures)	Base	Improved	Lean
	300	20	300

In the “Improved” crew design, all three Journeymen have to go down after working on the 15 light fixtures taking a total of 20 moves to restock 300 light fixtures at the rate of 15 light fixtures at a time signifying excessive motion among all three Journeymen. The “Base” and “Lean” crew designs both take the same number of moves.

However, in the “lean” crew design, motion is restricted to the Apprentice A who is responsible for restocking unlike the “Base” crew design where Journeyman is coming down for restocking while the Apprentice is waiting towards the end. Hence, motion is best designed in the “Lean” crew leading to least duration and unit cost of work performed among the three crew designs.

2) <u>TRANSPORT</u>:

Transport is an important flow characteristic affecting crew performance in terms of non-processing time and consequently the duration and cost of work performed by a crew. Non-processing time in the 3 crew designs is shown in the Table 5.9.

Table 5.9: Non-processing time in 3 crew designs

Non-processing Time (to restock 300 light fixtures)	Base	Improved	Lean
	900 mins	300 mins	900 mins

In the “Improved” case, restocking was done for a batch size of 15 light fixtures; 3 minutes to restock, 1 minute to go up and 1 minute for the lift to come down to restock the next fixture; making it a total of 5 minutes each for 15 light fixtures requiring 20 moves to restock all the 300 fixtures. Hence a total of 300 minutes ((3*300*({3+1+1}/15)) were spent in motion and transportation of 300 light fixtures.

Whereas, a total of 900 minutes (300 moves * 3 minutes each) were spent in motion and transportation of 300 light fixtures in both the “Base” and “Lean” crew designs. However, in the “Lean” crew design, the operating time to restock was included in the assembling cycle utilizing the journeyman that was earlier utilized only one-third of the time. Hence, transportation (non-processing time) is best designed in the “Lean” crew leading to least duration and unit cost of work performed among the three crew designs.

3) WAITING:

Waiting is an important flow characteristic affecting crew performance in terms of resource utilization, non-processing time and consequently the overall crew productivity, duration and cost of work performed by a crew. Resource wait/Idle time in the 3 crew designs is shown in the Figure 5.25.

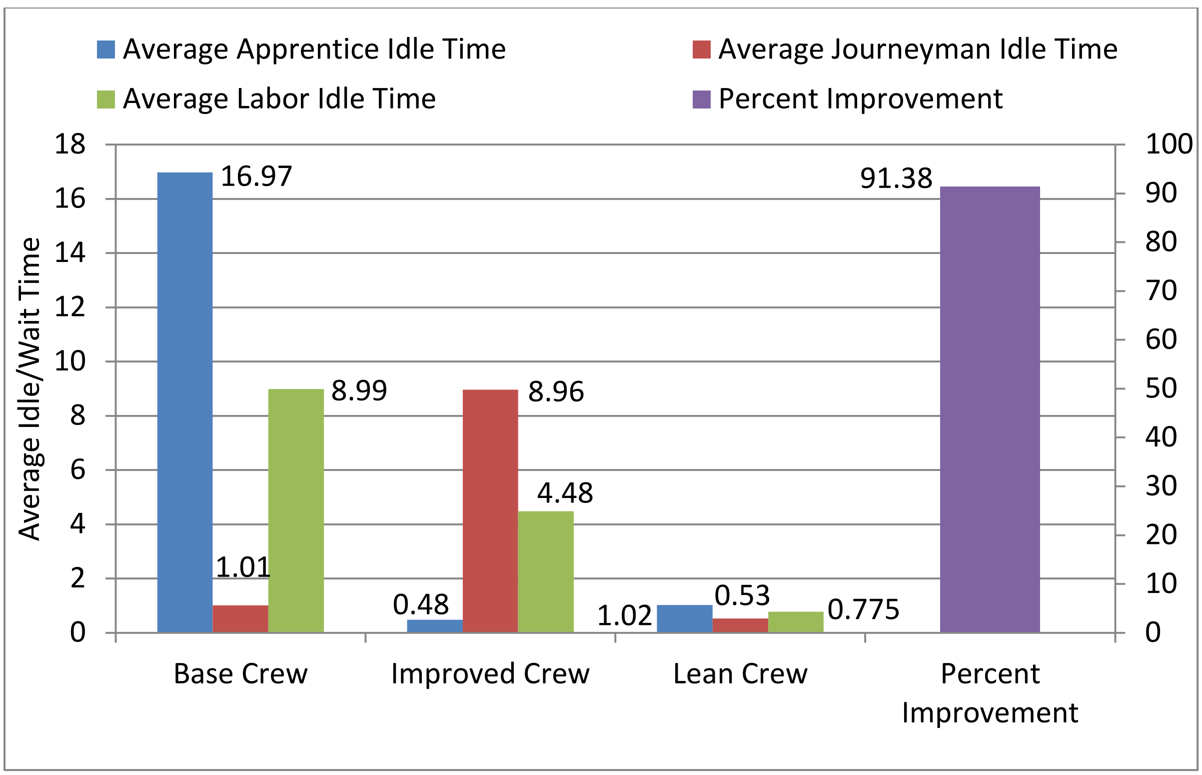


Figure 5.25: Resource Idle/Wait times in 3 crew designs

The above Figure 5.25 shows that “Lean” crew has the lowest resource idle/wait times among the three crew designs leading to decrease in the non-processing time and consequently reducing the duration and cost of work performed.

Also, the reduced idle/wait times leads to higher resource utilizations in the “Lean” crew (Figure 5.26) that in turn leads to increasing the overall crew productivity.

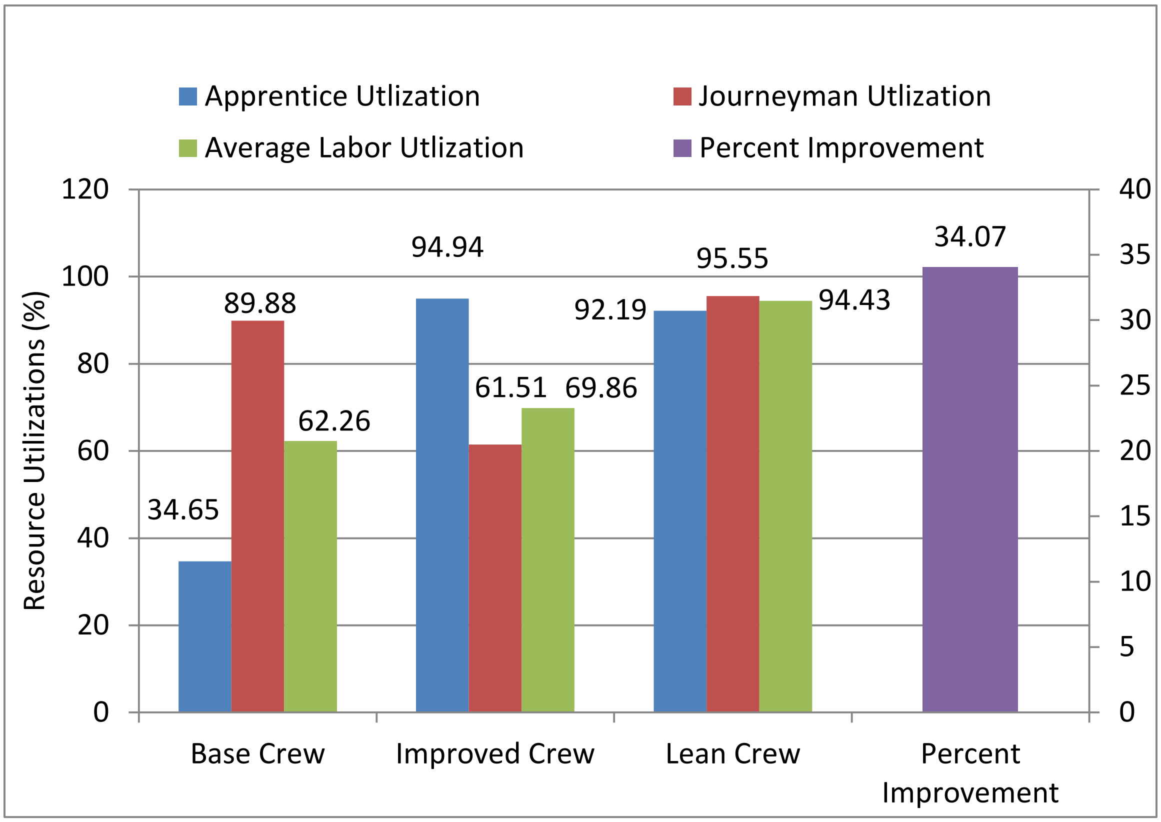


Figure 5.26: Resource Utilizations in 3 crew designs

4) <u>OVER-PRODUCTION</u>:

Over-production is an important flow characteristic affecting crew performance in terms of work-in-progress (WIP), non-uniform work load (production rates), non-continuous flow and duration and cost of work performed.

The Figure 5.27 shows that high work-in-progress (WIP) in the “Base” and “Improved” crew designs has been completely eliminated in the “Lean” crew.

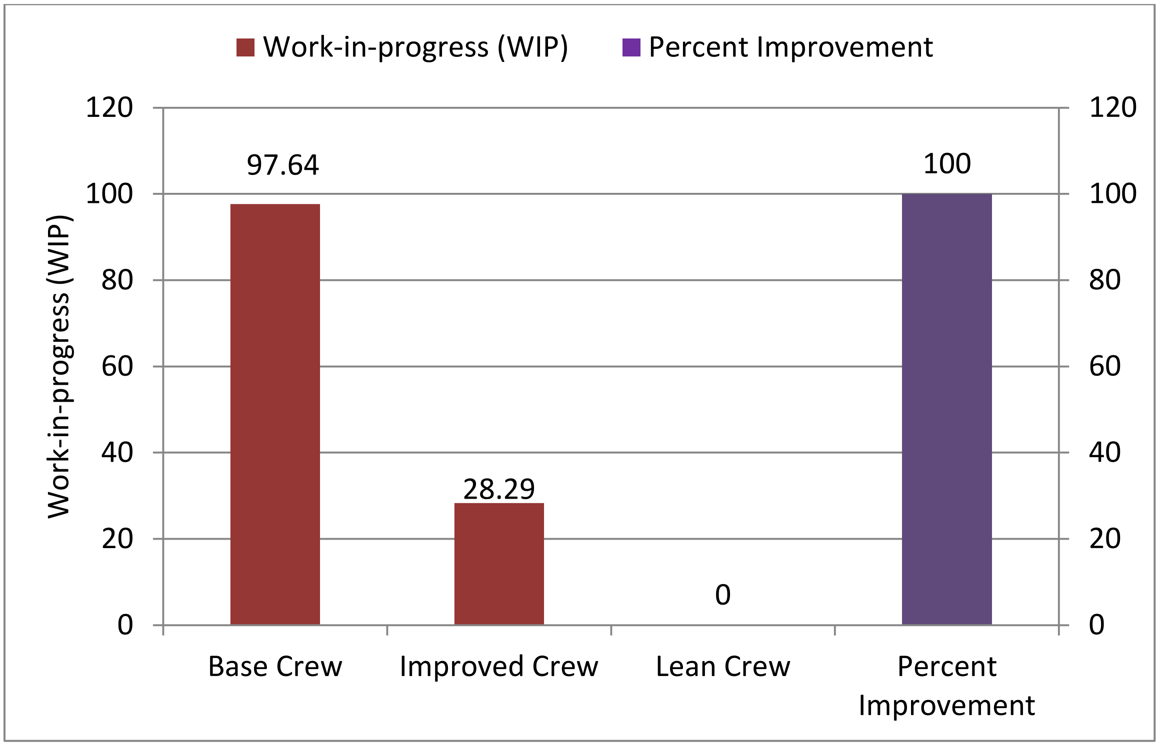


Figure 5.27: Work-in-progress (WIP) in the three crew designs

This is also evident from the assembling and installation cycle times in the three crew designs shown in the Table 5.10:

Table 5.10: Cycle times of assembling and installation activities in three crew designs

<table>
<tr><th>Activity</th><th>Task</th><th colspan="2">Base Crew</th><th colspan="2">Improved Crew</th><th colspan="2">Lean Crew</th></tr>
<tr><td>Assembling</td><td>Assemble</td><td colspan="2">9 min</td><td colspan="2">9 min</td><td>9 min</td><td rowspan="2">12 min</td></tr>
<tr><td></td><td>Restocking</td><td colspan="2">3 min</td><td colspan="2">5 min</td><td>3 min</td></tr>
<tr><td rowspan="3">Installation</td><td>Install</td><td>7 min</td><td rowspan="3">26 min</td><td>4 min</td><td rowspan="3">21 min</td><td>3.5</td><td rowspan="3">11.5 min</td></tr>
<tr><td>Wire & Clip</td><td>8.5 min</td><td>8 min</td><td>4.25</td></tr>
<tr><td>Lamp & Finish</td><td>7.5 min</td><td>4 min</td><td>3.75</td></tr>
</table>

The cycle times for assembling and installation activities in the “Lean” crew design are almost balanced and hence all the light fixtures assembled are processed and installed without having any work in progress leading to a continuous flow.

5) INVENTORY

High Inventory also leads work-in-progress. In the “Lean” crew, the batch size was reduced to only one fixture at a time from batch size of 15 fixtures in the “Improved” crew design to control the issue of over production.

The light fixtures in the “Lean” crew were only restocked by the apprentice as needed for installation unlike the “Improved” crew design where 15 light fixtures were restocked at a time. Also, reduction in the batch size along with leveling production rates of different cycles and applying pull system led to generate high operation throughput (Figure 5.28).

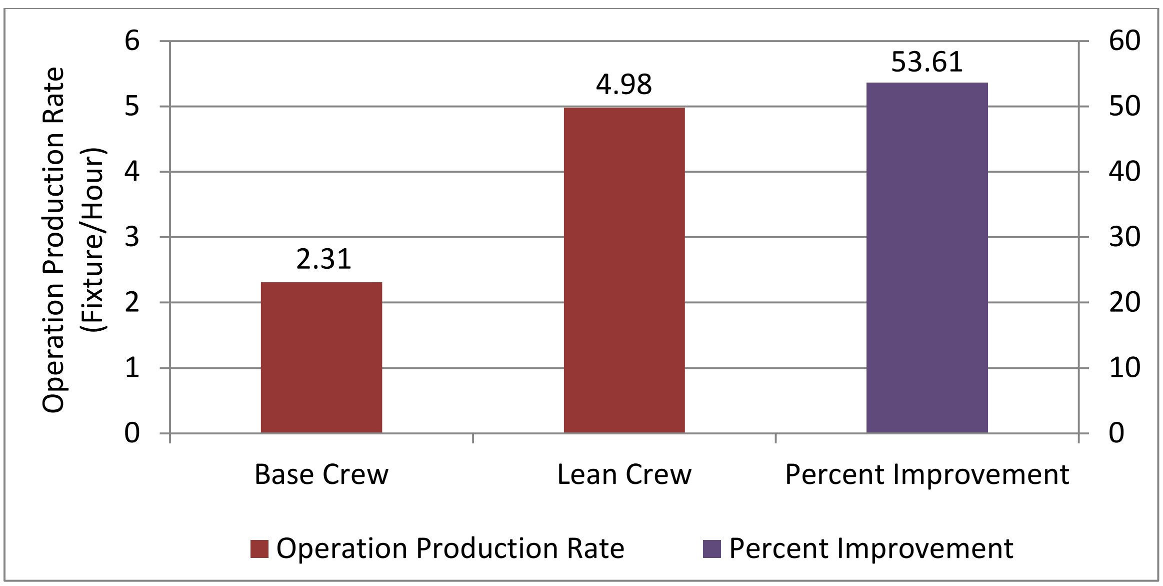


Figure 5.28: Operation production rates between Base and Lean crew design

6) DEFECTS

Defect is an important flow characteristic affecting crew performance in terms of quality, duration and cost of work performed. From the evaluation of the crew size and composition in the three crew design, it can be qualitatively inferred that due to journeyman and apprentice working together in the installation cycle, there is team work present that may reduce the number of defects that are overlooked in the earlier crew designs and improve the quality of the work performed.

7) CREW SIZE:

Crew Size is an important work characteristic affecting crew performance in terms of production capacity, satisfaction, learning, duration and cost of work performed. A reasonable increase in the size of the crew in the “Lean” crew increased the production rate of the installation cycle from 2.21 fixtures/hour (“Base” crew design) to 4.58 fixtures/hour (“Lean crew design) without increasing the cost of work performed (Figure 5.29).

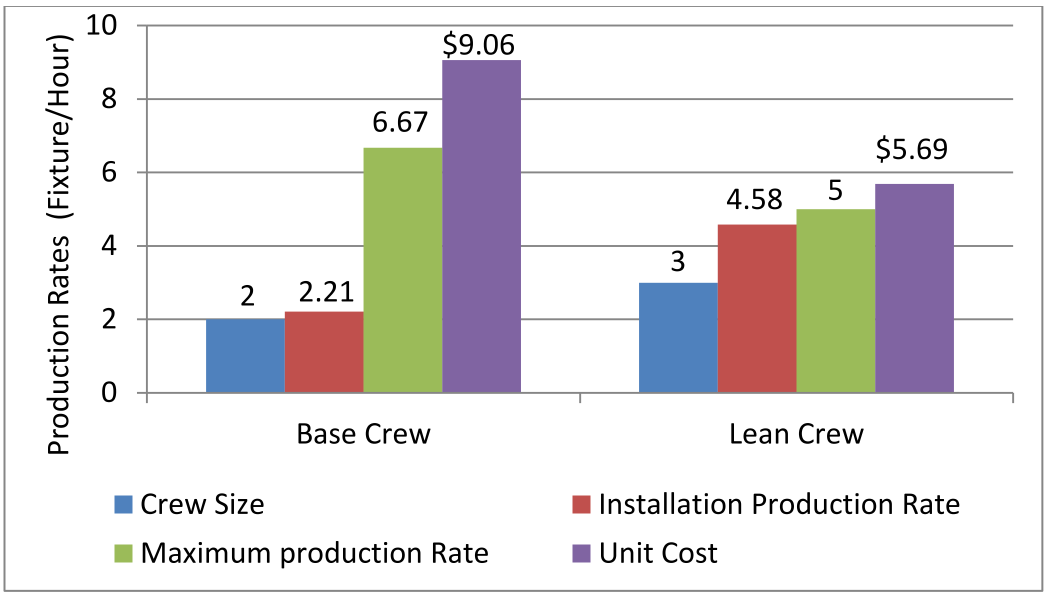


Figure 5.29: Impact of crew size on the production rates between the Base and Lean crew design

8) CREW FLEXIBILITY

Crew flexibility is an important work characteristic affecting crew performance in terms of satisfaction, learning, duration and cost of work performed. It can be qualitatively inferred that in the “Lean” crew design, the crew flexibility is higher than the other two “Base” and “Improved” crew designs with the addition of one more apprentice in the installation cycle and assigning restocking to the first apprentice.

Higher crew flexibility increases the overall crew productivity (operation production rate) by increasing the utilization and reducing the wait time for the first apprentice. Also, higher crew flexibility may lead to *satisfaction* and *learning* among the crew members arising from the feeling of helping each other in the installation cycle (journeyman and apprentice working together) and learning from the each other as a result of working together in a team.

9) CREW HETEROGENIETY

Crew heterogeneity is an important work characteristic affecting crew performance in terms of support, motivation and learning. It can be qualitatively inferred that in the "Lean" crew design, the crew heterogeneity is higher than the other two "Base" and "Improved" crew designs.

The "Lean" crew design of having the workers with different skill, knowledge and experience such as journeyman working together with the apprentice in the installation cycle, may lead to motivation in the journeyman to share his expertise and knowledge with the apprentice and consequently may lead to learning in the apprentice working together with him.

10) TASK VARIETY

Task variety is an important work characteristic affecting crew performance in terms of satisfaction and learning and pertains to the concept of job-enlargement from the STS theory. It can be qualitatively inferred that in the "Lean" crew design, the task variety is higher than the other two "Base" and "Improved" crew designs resulting from the crew design where apprentice is given the opportunity to be part of more than one task (in Lean crew design apprentice takes part in both the assembling and installation cycle).

Hence, being part of more than one task, may lead to more satisfaction in the apprentice as they would not be executing the same task/work over and over again. Also, some learning may occur in the apprentice arising from opportunity to work on a variety of tasks now.

11) TASK IDENTITY

Task identity is an important work characteristic affecting crew performance in terms of pride, satisfaction and motivation. It can be qualitatively inferred that in the “Lean” crew design, the task identity is higher than the other two “Base” and “Improved” crew designs resulting from the fact that now the apprentice is involved in executing both the assembling and installation cycles and consequently can now relate themselves with a both assembling and the installation (considered to be major part in the operation) taking ownership of the finished product. Also, increased task identity for the apprentice may also lead to higher satisfaction and motivation levels in the “Lean” crew design.

12) SUPPORT

Support is an important work characteristic affecting crew performance in terms of learning, satisfaction and motivation. It can be qualitatively inferred that in the “Lean” crew design, the support is higher than the other two “Base” and “Improved” crew designs resulting from the fact that now the apprentice and journeyman are working together providing help to each other if needed.

5.6 Chapter Summary

This chapter provided an overview of DES and SD computer simulation models with experimentation about crew interaction/design attributes in order to demonstrate how the crew design characteristics affect the performance of the crew. The simulation models are developed first using Discrete Event Simulation (DES) and then moving to System Dynamics (SD) providing the qualitative and quantitative crew design models. And, finally analysis of the simulation results took place to finalize the impact of the different crew design guidelines.

6 CONCLUSION

This research proposed lean crew design guidelines to guide the design of crews for construction operations. Discrete Event Simulation and System Dynamics models were developed to test the impact of guidelines on the crew design. The guidelines optimize both the crew and the work performed, resulting in better overall crew performance. This chapter provides an overview, contributions and conclusions of this research.

6.1 Research Overview

The overall goal of this research is to develop crew design guidelines for construction operations. The purpose of this research is achieved by conducting an extensive literature review on the existing construction models, production system theories, and crew & work design models. Research studies on "work design/team design" that have well developed theoretical and empirical foundations in Lean Production, Lean Construction, Socio-Technical System theory, Social and Organizational Psychology were investigated to identify important soft and hard factors and synthesized into lean crew design characteristics.

After, synthesizing the existing crew design and work design research into lean crew design characteristics, lean-based crew design guidelines are proposed to guide the crew design to achieve lean construction ideals of minimizing waste and maximizing value for construction operations. A Lean-based Crew Design (LbCD) Model was developed and proposed to guide the crew design process in a production setting involving initial formation of the crew, structuring of the work, execution of work/implementation (actual work/simulation model execution) and refining the crew design to maximize the crew performance based on the lean crew design guidelines.

A combination of DES and SD computer simulation models were developed in order to effectively demonstrate how the crew design characteristics affect the performance of a crew. A case study involving a well-documented construction operation from a prior research work conducted by Howell et al (1993) was selected for the purpose of modeling and simulation. The case study consists of a real time construction operation focusing on the installation of light fixtures by a construction crew. Three crew designs (Base, Improved, and Lean) with different crew size and composition were analyzed and compared to determine the impact of lean crew design guidelines on the performance of the crew.

6.2 Research Contributions

Performance of crews is very crucial to the work being executed and consequently for the overall project performance. There are numerous factors which affect the crew executing the various interconnected tasks involved in any operation. How to form or design a crew to carry out an operation in a dynamically changing construction environment is a complex task. However, despite the clear significance of crew design, only a modest scholarly interest in this area has been seen in the last two decades.

While research on the design of construction operations has come a long way, this research adds a first step in expanding it to the design of crews conducting construction operations, which will get us closer in achieving Lean Construction ideals. It benefits the construction industry by providing basis for designing crew interaction and roles during performing a construction operation.

This research aimed at contributing to the gap in the crew design research in literature by developing and proposing lean crew design characteristics and guidelines to maximize the performance of construction crews to achieve lean construction ideals. It contributes in identifying the important soft and hard factors from existing production system, crew and work design models in the construction industry affecting the performance of crews and by synthesizing the existing crew and work design approaches from lean production, lean construction, socio-technical system theory, and social and organizational psychology into lean crew design characteristics.

The lean crew design characteristics are comprised of “primary crew design characteristics”, “intermediate crew design characteristics and outcomes” and “final crew performance outcomes”. The primary work and flow characteristics that are again divided into waste, task, social and crew characteristics. The lean-based crew design guidelines are developed for maximizing joint optimization of both the crew and the work performed. They lead to better overall *crew performance* by optimizing performance indicators such as (1) *duration* of work performed; (2) *cost* of work performed; (3) *productivity*; (4) *quality* of work performed; (5) worker *satisfaction*; (6) worker *learning*; (7) worker *motivation*; (8) *pride* in work performed. In addition, simulation modeling has traditionally been carried out using discrete event simulation; however, this research ventured into the area of construction simulation by using a combination of simulation techniques such as Discrete Event Simulation and System Dynamics. In this research, three crew design model were developed and simulated using both DES and SD in order to demonstrate and analyze both the hard and soft factors affecting crew design.

DES was used to demonstrate the process and operational details of the crew design model and SD was used to develop qualitative model demonstrating the various cause-and-effect relationships and feedback among the crew design characteristics and the crew performance outcomes. And, the quantitative SD models helped in demonstrating and evaluating the pattern of behavior of various crew design characteristics and crew performance outcomes that is not possible with the use of DES.

6.3 Conclusion

6.3.1 Quantitative Findings from Case Study

In this research, DES and SD computer simulation models are used to demonstrate the use of lean-based crew design guidelines. The simulation models involved experimentation about crew interaction/design attributes in order to demonstrate how the crew design characteristics affect the performance of the crew. A well-documented construction operation focusing on the installation of light fixtures (Howell et al 1993) was modeled and simulated using DES and SD. Three crew design models were developed in order to demonstrate and analyze both the hard and soft factors affecting crew design. DES was used to demonstrate the process and operational details of the crew design model and SD was used to develop qualitative model demonstrating the various cause-and-effect relationships and feedback among the crew design characteristics and the crew performance outcomes. And, the quantitative SD models helped in demonstrating and evaluating the pattern of behavior of various crew design characteristics and crew performance outcomes that is not possible with the use of DES.

For the scope of this research, few characteristics from both the flow and work characteristics were selected to analyze and compare the three crew designs (Base, Improved and Lean) modeled and simulated in both DES and SD. Simulation analysis and comparison of the three crew design (Base, Improved and Lean) showed that the “Lean” crew design based on the lean crew design guidelines resulted in maximum performance of the crew:

1) Duration of work performed in the “Lean” crew was reduced to only 60.17 hours from 130.15 hours with 53% time savings (Figure 6.1).

2) Unit cost of work performed in the "Lean" crew was reduced to only $5.69 from $9.06 with 37.20% cost savings (Figure 6.1)

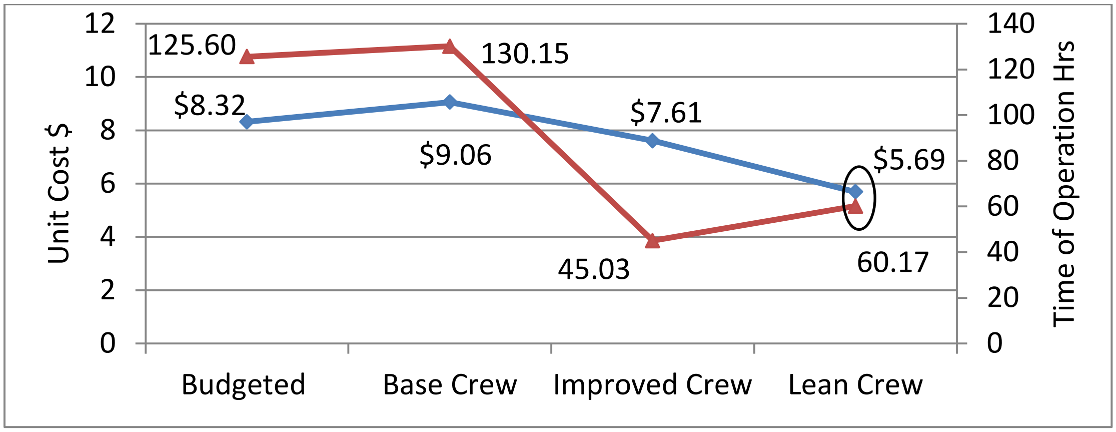


Figure 6.1: Unit Cost and Time of Operation Savings in Lean crew

3) Overall crew productivity (operation production rate) in "Lean" crew was increased to 4.98 light fixtures/hour from 2.31 light fixtures/hour with 53.61% operation production improvement (Figure 6.2).

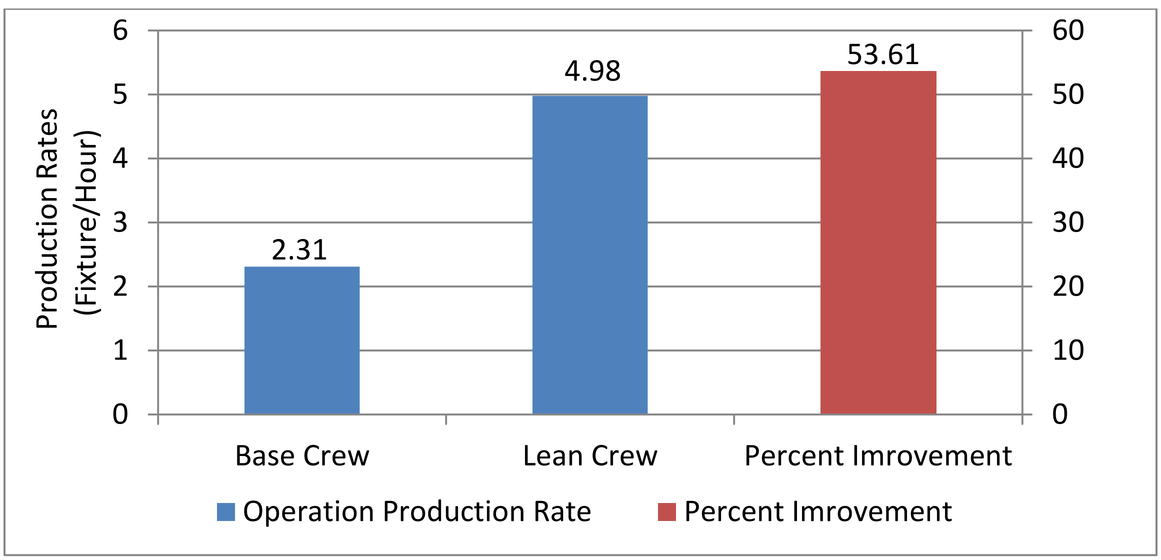


Figure 6.2: Overall Crew productivity (production rate) improvement in Lean crew

6.3.2 Qualitative Findings from Literature Review

In this research, lean crew design characteristics were developed by synthesizing the existing crew and work design approaches from lean production, lean construction, socio-technical system theory, and social and organizational psychology. These characteristics formed the basis for developing the proposed lean-based crew design guidelines.

The lean crew design guidelines were used to refine the "Base" and "Improved" crew designs from the light fixture case study and crew performance was qualitatively evaluated in terms of: *quality* of work performed, worker *satisfaction,* worker *learning,* worker *motivation, pride* in work performed. Based on the extensive literature review and the lean crew design guidelines, qualitative comparisons of the three crew designs (Base, Improved and Lean) indicate that the crew performance (*quality* of work performed, worker *satisfaction,* worker *learning,* worker *motivation, pride* in work performed) is potentially improved in lean crew design compared to the base and improved crew designs (discussed in detail in the crew design analysis and comparison section in chapter 5).

In the opinion of the author, application of lean crew design guidelines would result in maximizing the performance of the Lean crew in the following way:

1) Quality of work performed in the lean crew design would be improved due to reduction in overburden and task interdependence compared to the base and improved crew designs, where there is high overburden on the journeyman installing the fixtures alone.
2) Worker satisfaction in the lean crew design would be improved due to higher crew flexibility, crew heterogeneity and increased support with the addition of an apprentice to install the light fixtures along with the journeyman. Also with the addition of an apprentice for installation activity, task variety and task identity are increased in the lean

crew design compared to the base and improved crew design where apprentice is only assembling the fixtures with limited task variety, crew flexibility and crew heterogeneity.

3) Worker learning in the lean crew design would be improved due to higher crew flexibility, crew heterogeneity, coordination and task variety where worker learning is encouraged between the apprentice and the journeyman working together compared to the base and improved crew designs.

4) Worker motivation in the lean crew design would be improved due to higher crew heterogeneity, coordination and task identity among the crew compared to the base and improved crew designs.

5) Pride in the work performed in the lean crew design would be improved due to increased task identity with the apprentice now taking pride in executing a significant part of the operation such as installation of light fixtures compared to the base and improved crew designs where the apprentice is only assembling the light fixtures having very limited pride.

APPENDICES

Appendix A: DES "Base" Crew Model Formulation and Simulation Results.

The input and output parameters used to formulate the discrete event simulation "Base" model are shown below:

1. AprntcCost = Cost of 1 Apprentice per Hour = $6
2. JrnymnCost = Cost of 1 Apprentice per Hour = $13.4
3. LftCost = Cost of 1 Lift per Hour = $1.5
4. AprntcNumb = Number of Apprentice in Crew = AprntcWt.CurCount
5. JrnymnNumb = Number of Journeyman in Crew = JrnymnWt.CurCount
6. TOO = Time of Operation in Hours = SimTime/60
7. AprntcUtlizR = Apprentice Utilization in % (Resource) = (1-(AprntcWtQ/AprntcNumb))*100
8. AprntcUtlizT = Apprentice Utilization in % (Time) = (1-(JrnymnWtQ/JrnymnNumb))*100
9. JrnymnUtlizR = Journeyman Utilization in % (Resource) =((Restocking.AveDur+LftGoinUp.AveDur+Install.AveDur)/((LftGoinUpWt.AveWait+JrnymnWt.AveWait) +(Restocking.AveDur+LftGoinUp.AveDur+Install.AveDur)))*100
10. JrnymnUtlizT = Journeyman Utilization in % (Time) =((Restocking.AveDur+LftGoinUp.AveDur+Install.AveDur)/((LftGoinUpWt.AveWait+JrnymnWt.AveWait) +(Restocking.AveDur+LftGoinUp.AveDur+Install.AveDur)))*100
11. LftUtlizR = Lift Utilization in in % (Resource) = (1- ((LftDwnWt.AveCount+LftGoinUpWt.AveCount)/LftNumb))*100
12. LiftUtlizT = Lift Utilization in % (Time)

=(Restocking.AveDur+LftGoinUp.AveDur+Install.AveDur+LftGoinDwn.AveDur)/((LftGoinUpWt.AveWait+LftDwnWt.AveWait)+(Restocking.AveDur+LftGoinUp.AveDur+Install.AveDur+LftGoinDwn.AveDur)))*100

13. TotalCost = Total Cost of the Operation ($)

    =TOO*((AprntcCost*AprntcNumb) +(JrnymnCost*JrnymnNumb)+(LftCost*LftNumb))

14. UnitCost = Unit Cost of the Operation ($)

    = TotalCost/LitFixInPlcQ

Please note:

The discrete event simulation results for the "Base" model are uploaded online and can be accessed at the following website:

https://docs.google.com/file/d/0BxrMYHbElFuNNkhCdi1JdmRQdEk/edit

Appendix B: DES "Improved" Crew Model Formulation and Simulation Results.

The input and output parameters used to formulate the discrete event simulation "Improved" model are shown below:

1. AprntcCost = Cost of 1 Apprentice per Hour = $6
2. JrnymnCost = Cost of 1 Apprentice per Hour = $13.4
3. LftACost = Cost of Lift A per Hour= $1.5
4. LftBCost = Cost of Lift B per Hour= $1.5
5. LftCCost = Cost of Lift C per Hour= $1.5
6. JrnymnANumb = Number of Journeyman A in Crew = JrnymnAWt.CurCount
7. JrnymnBNumb = Number of Journeyman B in Crew = JrnymnBWt.CurCount
8. JrnymnCNumb = Number of Journeyman C in Crew = JrnymnCWt.CurCount
9. AprntcNumb = Number of Apprentice in Crew = AprntcWt.CurCount
10. LitFixInPlcQ = Total Number of Light Fixtures in Place = LitFixInPlc.CurCount

11. AprntcWtQ = Average Content of Apprentice in Queue = AprntcWt.AveCount
12. JrnymnAWtQ = Average Content of Journeyman A in Queue = JrnymnAWt.AveCount
13. JrnymnBWtQ = Average Content of Journeyman B in Queue = JrnymnBWt.AveCount
14. JrnymnCWtQ = Average Content of Journeyman C in Queue = JrnymnCWt.AveCount
15. LftAUpWtQ = Average Content of Lift A Up in Queue = LftAUpWt.AveCount
16. LftADwnWtQ = Average Content of Lift A Down in Queue = LftADwnWt.AveCount
17. LftAGoinUpWtQ = Average Content of Lift A GoingUp in Queue = LftAGoinUpWt.AveCount
18. LftAGoinDwnWtQ = Average Content of Lift A Going Down in Queue = LftAGoinDwnWt.AveCount
19. LftBUpWtQ = Average Content of Lift B Up in Queue = LftBUpWt.AveCount
20. LftBDwnWtQ = Average Content of Lift B Down in Queue = LftBDwnWt.AveCount
21. LftBGoinUpWtQ = Average Content of Lift B GoingUp in Queue = LftBGoinUpWt.AveCount
22. LftBGoinDwnWtQ = Average Content of Lift B Going Down in Queue = LftBGoinDwnWt.AveCount
23. LftCUpWtQ = Average Content of Lift C Up in Queue = LftCUpWt.AveCount
24. LftCDwnWtQ = Average Content of Lift C Down in Queue = LftCDwnWt.AveCount
25. LftCGoinUpWtQ = Average Content of Lift C GoingUp in Queue = LftCGoinUpWt.AveCount
26. LftCGoinDwnWtQ = Average Content of Lift C Going Down in Queue = LftCGoinDwnWt.AveCount
27. AssmblD = Average Duration of Assemble = Assemble.AveDur

28. JrnymnARestckD = Average Duration of Restocking by Journeyman A

= JrnymnARestck.AveDur

29. JrnymnBRestckD = Average Duration of Restocking by Journeyman B

= JrnymnARestck.AveDur

30. JrnymnCRestckD = Average Duration of Restocking by Journeyman C

= JrnymnCRestck.AveDur

31. InstallD = Average Duration of Installation = Install.AveDur

32. WirnClipD = Average Duration of Wire and Clipping = WirnClip.AveDur

33. LmpnFnsD = Average Duration of Lamp and Finish = LmpnFns.AveDur

34. LftAGoinDwnD = Average Duration of of Lift A Going Down = LftAGoinDwn.AveDur

35. LftAGoinUpD = Average Duration of of Lift A Going Up = LftAGoinUp.AveDur

36. LftBGoinDwnD = Average Duration of of Lift B Going Down = LftBGoinDwn.AveDur

37. LftBGoinUpD = Average Duration of Lift B Going Up = LftBGoinUp.AveDur

38. LftCGoinDwnD = Average Duration of of Lift C Going Down

39. LftCGoinUpD = Average Duration of Lift C Going Up = LftCGoinUp.AveDur

40. JrnymnAWtD = Average Duration of Journeman A in Queue = JrnymnAWt.AveWait

41. JrnymnBWtD = Average Duration of Journeman B in Queue = JrnymnBWt.AveWait

42. JrnymnCWtD = Average Duration of Journeman C in Queue = JrnymnCWt.AveWait

43. AprntcWtD = Average Duration of Apprentice in Queue = AprntcWt.AveWait

44. LftAUpWtD = Average Duration of Lift A Up in Queue = LftAUpWt.AveWait

45. LftADwnWtD = Average Duration of Lift A Down in Queue = LftADwnWt.AveWait

46. LftAGoinUpWtD = Average Duration of Lift A Going Up in Queue = LftAGoinUpWt.AveWait

47. LftAGoinDwnWtD = Average Duration of Lift A Going Down in Queue
= LftAGoinDwnWt.AveWait
48. LftBUpWtD = Average Duration of Lift B Up in Queue =LftBUpWt.AveWait
49. LftBDwnWtD = Average Duration of Lift B Down in Queue = LftBDwnWt.AveWait
50. LftBGoinUpWtD = Average Duration of Lift B Going Up in Queue = LftBGoinUpWt.AveWait
51. LftBGoinDwnWtD = Average Duration of Lift B Going Down in Queue
= LftBGoinDwnWt.AveWait
52. LftCUpWtD = Average Duration of Lift C Up in Queue = LftCUpWt.AveWait
53. LftCDwnWtD = Average Duration of Lift C Down in Queue = LftCDwnWt.AveWait
54. LftCGoinUpWt = DAverage Duration of Lift C Going Up in Queue = LftCGoinUpWt.AveWait
55. LftCGoinDwnWtD = Average Duration of Lift C Going Down in Queue
= LftCGoinDwnWt.AveWait
56. AprntcUtlizR = Apprentice Utilization in % (Resource) = (1-(AprntcWtQ/AprntcNumb))*100
57. AprntcUtlizT = Apprentice Utilization in % (Time) = ((AssmblD)/(AprntcWtD+AssmblD))*100
58. JrnymnAUtlizR = Journeyman A Utilization in % (Resource)
= (1-(JrnymnAWtQ/JrnymnANumb))*100
59. JrnymnAUtlizT = Journeyman A Utilization in % (Time)
=(JrnymnARestckD+LftAGoinUpD+InstallD)/((LftAGoinUpWtD+LftAUpWtD+JrnymnAWtD)+(JrnymnARestckD+LftAGoinUpWtD+InstallD)))*100

60. JrnymnBUtlizR = Journeyman B Utilization in % (Resource)

= (1-(JrnymnBWtQ/JrnymnBNumb))*100

61. JrnymnBUtlizT = Journeyman B Utilization in % (Time)

=((JrnymnBRestckD+LftBGoinUpD+WirnClipD)/((LftBGoinUpWtD+LftBUpWtD+JrnymnBWtD)+(JrnymnBRestckD+LftBGoinUpD+WirnClipD)))*100

62. JrnymnCUtlizR = Journeyman C Utilization in % (Resource)

= (1(1-(JrnymnCWtQ/JrnymnCNumb))*100

63. JrnymnCUtlizT = Journeyman C Utilization in % (Time)

=((JrnymnCRestckD+LftCGoinUpD+WirnClipD)/((LftCGoinUpWtD+LftCUpWtD+JrnymnCWtD)+(JrnymnCRestckD+LftCGoinUpD+LmpnFnsD)))*100

64. LftAUtlizR = Lift A Utilization in %(Resource)

= (1-((LftADwnWtQ+LftAGoinUpWtQ+LftAUpWtQ)/1))*100

65. LftAUtlizT = Lift A Utilization in %(Time)

=((JrnymnARestckD+LftAGoinUpD+InstallD+LftAGoinDwnD)/((LftADwnWtD+LftAGoinUpWtD+LftAUpWtD)+(JrnymnARestckD+LftAGoinUpD+InstallD+LftAGoinDwnD)))*100

66. LftBUtlizR = Lift B Utilizationin in %(Resource)

= (1-((LftBDwnWtQ+LftBGoinUpWtQ+LftBUpWtQ)/1))*100

67. LftBUtlizT = Lift B Utilizationin in %(Time)

=((JrnymnBRestckD+LftBGoinUpD+WirnClipD+LftBGoinDwnD)/((LftBDwnWtD+LftBGoinUpWtD+LftBUpWtD)+(JrnymnBRestckD+LftBGoinUpD+WirnClipD+LftBGoinDwnD)))*100

68. LftCUtlizR = Lift C Utilizationin in %(Resource)

= (1-((LftCDwnWtQ+LftCGoinUpWtQ+LftCUpWtQ)/1))*100

69. TotalCostTotal = Cost of the Operation ($)

=TOO*((AprntcCost*AprntcNumb)+(JrnymnACost*1)+(JrnymnBCost*1)+(JrnymnCCost*1)+(LftACost*1)+(LftBCost*1)+(LftCCost*1))

70. UnitCost = Unit Cost of the Operation ($) = TotalCost/LitFixInPlcQ

Please note:

The discrete event simulation results for the "Improved" model are uploaded online and can be accessed at the following website:

https://docs.google.com/open?id=0BxrMYHbElFuNRnhtVklSeTE4UVE

Appendix C: DES "Lean" Crew Model Formulation and Simulation Results

The input and output parameters used to formulate the discrete event simulation "Lean" model are shown below:

1. AprntcACost = Cost of 1 Apprentice per Hour = $6
2. JrnymnACost = Cost of Journeyman A per Hour = $13.4
3. AprntcBCost = Cost of Apprentice B per Hour = $6
4. LftACost = Cost of Lift A per Hour= $1.5
5. LftBCost = Cost of Lift B per Hour= $1.5
6. TOO = Time of Operation in Hours = SimTime/60
7. AprntcANumb = Number of Apprentice in Crew = AprntcAWt.CurCount
8. AprntcBNumb = Number of Apprentice B in Crew = AprntcBWt.CurCount
9. JrnymnANumb = Number of Journeyman A in Crew = JrnymnAWt.CurCount
10. LftANumb = Number of Lift A = LftADwnWt.CurCount
11. LftBNumb = Number of Lift B = LftBWt.CurCount

12. LitFixInPlcQ = Total Number of Light Fixtures in Place = LitFixInPlc.CurCount
13. AprntcBWtQ = Average Content of Apprentice B in Queue = AprntcBWt.AveCount
14. AprntcAWtQ = Average Content of Apprentice A in Queue = AprntcAWt.AveCount
15. JrnymnAWtQ = Average Content of Journeyman A in Queue = JrnymnAWt.AveCount
16. LftAUpWtQ = Average Content of Lift A Up in Queue = LftAUpWt.AveCount
17. LftADwnWtQ = Average Content of Lift A Down in Queue = LftADwnWt.AveCount
18. LftAGoinUpWtQ = Average Content of Lift A GoingUp in Queue = LftAGoinUpWt.AveCount
19. LftBWtQ = Average Content of Lift B in Queue = LftBWt.AveCount
20. LftAGoinUpDur = Average Duration of of Lift A Going Up = LftAGoinUp.AveDur
21. LftAGoinDwnDur = Average Duration of of Lift A going Down = LftAGoinDwn.AveDur
22. RestockDur = Average Duration of Restocking = Restocking.AveDur
23. InstallDur = Average Duration of Installation = Install.AveDur
24. WirenClipDur = Average Duration of Wire and Clipping = WirenClip.AveDur
25. LampnFinishDur = Average Duration of Lamp and Finish = LampnFinish.AveDur
26. AprntcAWtDur = Average Duration of Aprntc A in Queue = AprntcAWt.AveWait
27. JrnymnAWtDur = Average Duration of Journeman A in Queue = JrnymnAWt.AveWait
28. AprntcBWtDur = Average Duration of Apprentice B in Queue = AprntcBWt.AveWait
29. LftAUpWtDur = Average Duration of Lift A Up in Queue = LftAUpWt.AveWait
30. LftADwnWtDur = Average Duration of Lift A Down in Queue = LftADwnWt.AveWait
31. LftAGoinUpWtDur = Average Duration of Lift A Going Up in Queue = LftAGoinUpWt.AveWait
32. LftBWtDur = Average Duration of Lift B in Queue = LftBWt.AveWait

33. AprntcBUtlizR = Apprentice B Utilization in % (Resource) = (1-(AprntcBWtQ/AprntcBNumb))*100
34. AprntcBUtlizT = Apprentice B Utilization in % (Time) =((InstallDur+WirenClipDur+LampnFinishDur)/((AprntcBWtDur)+(InstallDur+WirenClipDur+LampnFinishDur)))*100
35. AprntcAUtlizR = Apprentice A Utilization in % (Resource) (1-(AprntcAWtQ/AprntcANumb))*100
36. AprntcAUtlizT = Apprentice A Utilization in % (Time) =((AssmblDur+RestockDur+LftAGoinUpDur+LftAGoinDwnDur)/((AprntcAWtDur+LftAUpWtDur+LftAGoinUpWtDur)+(AssmblDur+RestockDur+LftAGoinUpDur+LftAGoinDwnDur)))*100
37. JrnymnAUtlizR = Journeyman A Utilization in % (Resource) =(1-(JrnymnAWtQ/JrnymnANumb))*100
38. JrnymnAUtlizT = Journeyman A Utilization in % (Time) =((InstallDur+WirenClipDur+LampnFinishDur)/((JrnymnAWtDur)+(InstallDur+WirenClipDur+LampnFinishDur)))*100
39. JrnymnAUtlizT = Journeyman A Utilization in % (Time) =((InstallDur+WirenClipDur+LampnFinishDur)/((JrnymnAWtDur)+(InstallDur+WirenClipDur+LampnFinishDur)))*100
40. LftAUtlizRES = Lift A Utilizationin in %(Resource) =(1-((LftAUpWtQ+LftADwnWtQ+LftAGoinUpWtQ)/LftANumb))*100
41. LftAUtlizTIM = Lift A Utilizationin in %(Time)

=((RestockDur+LftAGoinUpDur+LftAGoinDwnDur)/((LftAUpWtDur+LftADwnWtDur+LftAGoinDwnDur)+(RestockDur+LftAGoinUpDur+LftAGoinDwnDur)))*100

42. LftBUtlizRES = Lift B Utilizationin in %(Resource) = (1-(LftBWtQ/LftBNumb))*100

43. LftBUtlizTIM = Lift B Utilizationin in %(Time) =((InstallDur+WirenClipDur+LampnFinishDur)/((LftBWtDur)+(InstallDur+WirenClipDur+LampnFinishDur)))*100

44. TotalCost = Total Cost of the Operation ($) =TOO*((AprntcACost*AprntcANumb)+(AprntcBCost*AprntcBNumb)+(JrnymnACost*JrnymnANumb)+(LftACost*LftANumb)+(LftBCost*LftBNumb))

45. UnitCost = Unit Cost of the Operation ($) = TotalCost/LitFixInPlcQ

Please note:

The discrete event simulation results for the “Lean” model are uploaded online and can be accessed at the following website:

https://docs.google.com/file/d/0BxrMYHbElFuNRFhEWW9tOVRaRTQ/edit

Appendix D: SD “Base” Crew Model Formulation

The mathematical equations used to formulate the system dynamics “Base” model are shown below:

(01) Apprentice Assembling=
IF THEN ELSE(Apprentice Waiting>=1/9:AND:Lit Fix Waiting>=1/9 , 1/9 , 0)
Units: (labor/Minute)

(02) Apprentice Finished Assembling= INTEG (
+Apprentice Assembling-Apprentice Returning,
0)
Units: labor

(03) Apprentice Idle Percentage=
IF THEN ELSE(Apprentice Waiting=1:OR:Apprentice Waiting=1/9, Apprentice Waiting

*100 , 0)
Units: **undefined**

(04) Apprentice Returning=
IF THEN ELSE(Apprentice Finished Assembling=1, 1 , 0)
Units: labor/Minute

(05) Apprentice Utilization=
100-Apprentice Idle Percentage
Units: **undefined**

(06) Apprentice Waiting= INTEG (
+Apprentice Returning-Apprentice Assembling ,
1)
Units: labor

(07) Assembling Production Rate=
ZIDZ(Lit Fix Assembled, Time of Operation)
Units: **undefined**

(08) Complete Lit Fix Installation Rate=
IF THEN ELSE(Partial Lit Fix Installed>=1, 1 , 0)
Units: light fixture/Minute

(09) "Complete Lit Fix Lamp&Finish Rate"=
IF THEN ELSE("Partial Lit Fix Lamp&Finished">=1, 1 , 0)
Units: light fixture/Minute

(10) "Complete Lit Fix Wire&Clip Rate"=
IF THEN ELSE("Partial Lit Fix Wire&Clipped">=1, 1 , 0)
Units: light fixture/Minute

(11) FINAL TIME = 7900
Units: Minute
The final time for the simulation.

(12) Full Lit Fix Installed= INTEG (
+Complete Lit Fix Installation Rate-"Partial Lit Fix Wire&Clip Rate",
0)
Units: light fixture

(13) "Full Lit Fix Wire&Clipped"= INTEG (
+"Complete Lit Fix Wire&Clip Rate"-"Partial Lit Fix Lamp&Finish Rate",
0)
Units: light fixture

(14) INITIAL TIME = 0
Units: Minute
The initial time for the simulation.

(15) Journeyman Completing Installation=
IF THEN ELSE(Journeyman Finished Partial Installation>=1, 1 , 0)
Units: labor/Minute

(16) "Journeyman Completing Lamp&Finish"=
IF THEN ELSE("Journeyman Finished Partial Lamp&Finish">=1, 1 , 0)
Units: labor/Minute

(17) "Journeyman Completing Wire&Clip"=
IF THEN ELSE("Journeyman Finished Partial Wire&Clip">=1, 1 , 0)
Units: labor/Minute

(18) Journeyman Finished Full Installation= INTEG (
+Journeyman Completing Installation-"Journeyman Starting Wire&Clip",
0)
Units: labor

(19) "Journeyman Finished Full Lamp&Finish"= INTEG (
+"Journeyman Completing Lamp&Finish"-Journeyman Going Down,
0)
Units: labor

(20) "Journeyman Finished Full Wire&Clip"= INTEG (
+"Journeyman Completing Wire&Clip"-"Journeyman Starting Lamp&Finish",
0)
Units: labor

(21) Journeyman Finished Partial Installation= INTEG (
+Journeyman Starting Installation-Journeyman Completing Installation,
0)
Units: labor

(22) "Journeyman Finished Partial Lamp&Finish"= INTEG (
+"Journeyman Starting Lamp&Finish"-"Journeyman Completing Lamp&Finish",
0)
Units: labor

(23) "Journeyman Finished Partial Wire&Clip"= INTEG (
+"Journeyman Starting Wire&Clip"-"Journeyman Completing Wire&Clip",
0)
Units: labor

(24) Journeyman Finished Restocking= INTEG (
+Journeyman Restocking-Journeyman Going Up,
0)
Units: labor

(25) Journeyman Going Down=
IF THEN ELSE("Journeyman Finished Full Lamp&Finish">=1:AND:Lit Fix In Place
>=1, 1 , 0)
Units: labor/Minute

(26) Journeyman Going Up=
IF THEN ELSE(Journeyman Finished Restocking>0:AND:Journeyman Finished Restocking
<=1, 1 , 0)
Units: labor/Minute

(27) Journeyman Idle Percentage=
IF THEN ELSE(Journeyman Waiting=1, Journeyman Waiting*100 , 0)
Units: **undefined**

(28) Journeyman Restocking=
IF THEN ELSE(Journeyman Waiting>=1:AND:Lit Fix Assembled>=1, 1 , 0)
Units: labor/Minute

(29) Journeyman Starting Installation=
IF THEN ELSE(Journeyman Up>0:AND:Journeyman Up<=1, 1/6 , 0)
Units: labor/Minute

(30) "Journeyman Starting Lamp&Finish"=
IF THEN ELSE("Journeyman Finished Full Wire&Clip">0:AND:"Journeyman Finished Full Wire&Clip"
<=1, 1/6 , 0)
Units: labor/Minute

(31) "Journeyman Starting Wire&Clip"=
IF THEN ELSE(Journeyman Finished Full Installation>0:AND:Journeyman Finished Full Installation
<=1, 1/8 , 0)
Units: labor/Minute

(32) Journeyman Up= INTEG (
+Journeyman Going Up-Journeyman Starting Installation,
0)
Units: labor

(33) Journeyman Utilization=
100-Journeyman Idle Percentage
Units: **undefined**

(34) Journeyman Waiting= INTEG (
+Journeyman Going Down-Journeyman Restocking,
1)
Units: labor

(35) Lift Completing Installation=
IF THEN ELSE(Lift Finished Partial Installation>=1, 1 , 0)
Units: labor/Minute

(36) "Lift Completing Lamp&Finish"=
IF THEN ELSE("Lift Finished Partial Lamp&Finish">=1, 1 , 0)
Units: labor/Minute

(37) "Lift Completing Wire&Clip"=
IF THEN ELSE("Lift Finished Partial Wire&Clip">=1, 1 , 0)
Units: labor/Minute

(38) Lift Finished Full Installation= INTEG (
+Lift Completing Installation-"Lift Starting Wire&Clip",
0)
Units: labor

(39) "Lift Finished Full Lamp&Finish"= INTEG (
+"Lift Completing Lamp&Finish"-Lift Going Down,
0)
Units: labor

(40) "Lift Finished Full Wire&Clip"= INTEG (
+"Lift Completing Wire&Clip"-"Lift Starting Lamp&Finish",
0)
Units: labor

(41) Lift Finished Partial Installation= INTEG (
+Lift Starting Installation-Lift Completing Installation,
0)
Units: labor

(42) "Lift Finished Partial Lamp&Finish"= INTEG (
+"Lift Starting Lamp&Finish"-"Lift Completing Lamp&Finish",
0)
Units: labor

(43) "Lift Finished Partial Wire&Clip"= INTEG (
+"Lift Starting Wire&Clip"-"Lift Completing Wire&Clip",
0)
Units: labor

(44) Lift Finished Restocking= INTEG (
+Lift Restocking-Lift Going Up,
0)
Units: labor

(45) Lift Going Down=
IF THEN ELSE("Lift Finished Full Lamp&Finish">=1:AND:Lit Fix In Place>=1,
1 , 0)
Units: labor/Minute

(46) Lift Going Up=
IF THEN ELSE(Lift Finished Restocking>0:AND:Lift Finished Restocking<=1,
1 , 0)
Units: labor/Minute

(47) Lift Idle Percentage=
IF THEN ELSE(Lift Waiting<=1/9:OR:Lift Waiting>=8/9, Lift Waiting*100 , 0
)
Units: **undefined**

(48) Lift Restocking=
IF THEN ELSE(Lift Waiting>=1:AND:Lit Fix Assembled>=1, 1 , 0)
Units: labor/Minute

(49) Lift Starting Installation=
IF THEN ELSE(Lift Up>0:AND:Lift Up<=1, 1/6 , 0)
Units: labor/Minute

(50) "Lift Starting Lamp&Finish"=
IF THEN ELSE("Lift Finished Full Wire&Clip">0:AND:"Lift Finished Full Wire&Clip"
<=1, 1/6 , 0)
Units: labor/Minute

(51) "Lift Starting Wire&Clip"=
IF THEN ELSE(Lift Finished Full Installation>0:AND:Lift Finished Full Installation
<=1, 1/8 , 0)
Units: labor/Minute

(52) Lift Up= INTEG (

+Lift Going Up-Lift Starting Installation,
0)
Units: labor

(53) Lift Utilization=
100-Lift Idle Percentage
Units: **undefined**

(54) Lift Waiting= INTEG (
+Lift Going Down-Lift Restocking,
1)
Units: labor

(55) Lit Fix Assembled= INTEG (
+Lit Fix Assembling Rate-Lit Fix Restocking Rate,
0.0001)
Units: light fixture

(56) Lit Fix Assembling Rate=
IF THEN ELSE(Lit Fix Waiting>=1/9:AND:Apprentice Waiting>=1/9, 1/9 , 0)
Units: light fixture/Minute

(57) Lit Fix Going Up Rate=
IF THEN ELSE(Lit Fix Restocked>0:AND:Lit Fix Restocked<=1, 1 , 0)
Units: light fixture/Minute

(58) Lit Fix In Place= INTEG (
+"Complete Lit Fix Lamp&Finish Rate",
0.1111)
Units: light fixture

(59) Lit Fix Restocked= INTEG (
+Lit Fix Restocking Rate-Lit Fix Going Up Rate,
0)
Units: light fixture

(60) Lit Fix Restocking Rate=
IF THEN ELSE(Lit Fix Assembled>=1:AND:Lift Waiting>=1:AND:Journeyman
Waiting
>=1, 1 , 0)
Units: light fixture/Minute

(61) Lit Fix Up= INTEG (
+Lit Fix Going Up Rate-Partial Lit Fix Installation Rate,
0)
Units: light fixture

(62) Lit Fix Waiting= INTEG (
-Lit Fix Assembling Rate,
330)
Units: light fixture

(63) Number of Apprentice=
1
Units: labor

(64) Number of Journeyman=
1
Units: labor

(65) Number of Lift=
1
Units: labor

(66) Operation Production Rate=
ZIDZ(Lit Fix In Place, Time of Operation)
Units: **undefined**

(67) "OPR-APR Ratio"=
ZIDZ(Operation Production Rate, Assembling Production Rate)
Units: **undefined**

(68) Partial Lit Fix Installation Rate=
IF THEN ELSE(Lit Fix Up>0:AND:Lit Fix Up<=1, 1/6 , 0)
Units: light fixture/Minute

(69) Partial Lit Fix Installed= INTEG (
+Partial Lit Fix Installation Rate-Complete Lit Fix Installation Rate,
0)
Units: light fixture

(70) "Partial Lit Fix Lamp&Finish Rate"=
IF THEN ELSE("Full Lit Fix Wire&Clipped">0:AND:"Full Lit Fix Wire&Clipped"
<=1, 1/6 , 0)
Units: light fixture/Minute

(71) "Partial Lit Fix Lamp&Finished"= INTEG (
+"Partial Lit Fix Lamp&Finish Rate"-"Complete Lit Fix Lamp&Finish Rate",
0)
Units: light fixture

(72) "Partial Lit Fix Wire&Clip Rate"=
IF THEN ELSE(Full Lit Fix Installed>0:AND:Full Lit Fix Installed<=1, 1/8
, 0)
Units: light fixture/Minute

(73) "Partial Lit Fix Wire&Clipped"= INTEG (
+"Partial Lit Fix Wire&Clip Rate"-"Complete Lit Fix Wire&Clip Rate",
0)
Units: light fixture

(74) SAVEPER =
TIME STEP
Units: Minute [0,?]
The frequency with which output is stored.

(75) Time of Operation=
Time/60
Units: hours

(76) TIME STEP = 1
Units: Minute [0,?]
The time step for the simulation.

(77) Total Apprentice Cost per hour=
Number of Apprentice*Unit Apprentice Cost
Units: dollars/hour

(78) Total Cost of Operation=
Time of Operation*(Total Apprentice Cost per hour+Total Journeyman Cost per hour
+Total Lift Cost per hour)
Units: dollars

(79) Total Journeyman Cost per hour=
Number of Journeyman*Unit Journeyman Cost
Units: dollars/hour

(80) Total Lift Cost per hour=
Number of Lift*Unit Lift Cost
Units: dollars/hour

(81) Unit Apprentice Cost=
6
Units: dollars/(labor*hour)

(82) Unit Cost of Operation=

Total Cost of Operation/Lit Fix In Place
Units: dollars/light fixture

(83) Unit Journeyman Cost=
13.4
Units: dollars/(labor*hour)

(84) Unit Lift Cost=
1.5
Units: dollars/(labor*hour)

The complete system dynamics model for the "Base" case is uploaded online and can be accessed at the following website:

https://docs.google.com/open?id=0BxrMYHbElFuNUUdUX1F6WGE3Y3M

Appendix E: SD "Improved" Crew Model Formulation

The mathematical equations used to formulate the system dynamics "Improved" model are shown below:

Model mathematical equations:

(001) "1st Half Lit Fix Restocked"= INTEG (
+"1st Half Lit Fix Restocking Rate"-"2nd Half Lit Fix Restocking Rate",
0)
Units: light fixture

(002) "1st Half Lit Fix Restocking Rate"=
IF THEN ELSE(Lit Fix Assembled>=15:AND:Lift A
Waiting>=1:AND:Journeyman A Waiting
>=1, 15 , 0)
Units: light fixture/Minute

(003) "2nd Half Light Fix Restocked"= INTEG (
+"2nd Half Lit Fix Restocking Rate"-Complete Lit Fix Restocking Rate,
0)
Units: light fixture

(004) "2nd Half Lit Fix Restocking Rate"=
IF THEN ELSE("1st Half Lit Fix Restocked">=15, 15 , 0)
Units: light fixture/Minute

(005) Apprentice Assembling=
IF THEN ELSE(Apprentice Waiting>=1/9:AND:Lit Fix Waiting>=1/9 , 1/9 , 0

)
Units: labor/Minute

(006) Apprentice Finished Assembling= INTEG (
+Apprentice Assembling-Apprentice Returning,
0)
Units: labor

(007) Apprentice Idle Percentage=
IF THEN ELSE(Apprentice Waiting<=1/9:OR:Apprentice Waiting>=8/9,
Apprentice Waiting
*100 , 0)
Units: **undefined**

(008) Apprentice Returning=
IF THEN ELSE(Apprentice Finished Assembling=1, 1 , 0)
Units: labor/Minute

(009) Apprentice Utilization=
100-Apprentice Idle Percentage
Units: **undefined**

(010) Apprentice Waiting= INTEG (
+Apprentice Returning-Apprentice Assembling ,
1)
Units: labor

(011) Assembling Cycle Production Rate=
ZIDZ(Lit Fix Assembled , Time of Operation)
Units: **undefined**

(012) Complete Lit Fix Installation Rate=
IF THEN ELSE(Partial Lit Fix Installed>=1, 1 , 0)
Units: light fixture/Minute

(013) "Complete Lit Fix Lamp&Finish Rate"=
IF THEN ELSE("Partial Lit Fix Lamp&Finished">=1, 1 , 0)
Units: light fixture/Minute

(014) Complete Lit Fix Restocking Rate=
IF THEN ELSE("2nd Half Light Fix Restocked">=15, 15 , 0)
Units: light fixture/Minute

(015) "Complete Lit Fix Wire&Clip Rate"=
IF THEN ELSE("Partial Lit Fix Wire&Clipped">=1, 1 , 0)
Units: light fixture/Minute

(016) FINAL TIME = 4000
Units: Minute
The final time for the simulation.

(017) Full Lit Fix In Place= INTEG (
+"Complete Lit Fix Lamp&Finish Rate",
0)
Units: light fixture

(018) Full Lit Fix Installed= INTEG (
+Complete Lit Fix Installation Rate-"Partial Lit Fix Wire&Clip Rate",
0)
Units: light fixture

(019) Full Lit Fix Restocked= INTEG (
+Complete Lit Fix Restocking Rate-Lit Fix Going Up Rate,
0)
Units: light fixture

(020) "Full Lit Fix Wire&Clipped"= INTEG (
+"Complete Lit Fix Wire&Clip Rate"-"Partial Lit Fix Lamp&Finish Rate",
0)
Units: light fixture

(021) INITIAL TIME = 0
Units: Minute
The initial time for the simulation.

(022) Journeyman A Completing Installation=
IF THEN ELSE(Journeyman A Finished Partial Installation>=1, 1 , 0)
Units: labor/Minute

(023) Journeyman A Completing Restock=
IF THEN ELSE(Journeyman A Finished 2nd Half Restock>=1, 1 , 0)
Units: labor/Minute

(024) Journeyman A Finished 2nd Half Restock= INTEG (
+Journeyman A Starting 2nd Half Restock-Journeyman A Completing Restock,
0)
Units: labor

(025) Journeyman A Finished Full Installation= INTEG (
+Journeyman A Completing Installation-Journeyman Going Down,
0)
Units: labor

(026) Journeyman A Finished Full Restock= INTEG (
+Journeyman A Completing Restock-Journeyman A Going Up,
0)
Units: labor

(027) Journeyman A Finished Partial Installation= INTEG (
+Journeyman A Starting Installation-Journeyman A Completing Installation,
0)
Units: labor

(028) Journeyman A Finished Partial Restocking= INTEG (
+Journeyman A Starting 1st Half Restock-Journeyman A Starting 2nd Half
Restock
,
0)
Units: labor

(029) Journeyman A Going Up=
IF THEN ELSE(Journeyman A Finished Full Restock>=1, 1 , 0)
Units: labor/Minute

(030) Journeyman A Idle Percentage=
IF THEN ELSE(Journeyman A Waiting=1, Journeyman A Waiting*100 , 0)
Units: **undefined**

(031) Journeyman A Starting 1st Half Restock=
IF THEN ELSE(Journeyman A Waiting>=1:AND:Lit Fix Assembled>=15, 1 , 0)
Units: labor/Minute

(032) Journeyman A Starting 2nd Half Restock=
IF THEN ELSE(Journeyman A Finished Partial Restocking>=1, 1 , 0)
Units: labor/Minute

(033) Journeyman A Starting Installation=
IF THEN ELSE(Journeyman A Up>0:AND:Journeyman A Up<=1, 1/59 , 0)
Units: labor/Minute

(034) Journeyman A Up= INTEG (
+Journeyman A Going Up-Journeyman A Starting Installation,
0)
Units: labor

(035) Journeyman A Utilization=
100-Journeyman A Idle Percentage
Units: **undefined**

(036) Journeyman A Waiting= INTEG (
+Journeyman Going Down-Journeyman A Starting 1st Half Restock,
1)
Units: labor

(037) Journeyman B Completing Restock=
IF THEN ELSE(Journeyman B Finished 2nd Half Restock>=1, 1 , 0)
Units: labor/Minute

(038) "Journeyman B Completing Wire&Clip"=
IF THEN ELSE("Journeyman B Finished Partial Wire&Clip">=1, 1 , 0)
Units: labor/Minute

(039) Journeyman B Finished 2nd Half Restock= INTEG (
+Journeyman B Starting 2nd Half Restock-Journeyman B Completing Restock,
0)
Units: labor

(040) Journeyman B Finished Full Restock= INTEG (
+Journeyman B Completing Restock-Journeyman B Going Up,
0)
Units: labor

(041) "Journeyman B Finished Full Wire&Clip"= INTEG (
+"Journeyman B Completing Wire&Clip"-Journeyman B Going Down,
0)
Units: labor

(042) Journeyman B Finished Partial Restocking= INTEG (
+Journeyman B Starting 1st Half Restock-Journeyman B Starting 2nd Half
Restock
,
0)
Units: labor

(043) "Journeyman B Finished Partial Wire&Clip"= INTEG (
+"Journeyman B Starting Wire&Clip"-"Journeyman B Completing Wire&Clip",
0)
Units: labor

(044) Journeyman B Going Down=
IF THEN ELSE("Journeyman B Finished Full Wire&Clip">=1, 1 , 0)
Units: labor/Minute

(045) Journeyman B Going Up=

IF THEN ELSE(Journeyman B Finished Full Restock>=1, 1 , 0)
Units: labor/Minute

(046) Journeyman B Idle Percentage=
IF THEN ELSE(Journeyman B Waiting=1, Journeyman B Waiting*100 , 0)
Units: **undefined**

(047) Journeyman B Starting 1st Half Restock=
IF THEN ELSE(Journeyman B Waiting>=1, 1 , 0)
Units: labor/Minute

(048) Journeyman B Starting 2nd Half Restock=
IF THEN ELSE(Journeyman B Finished Partial Restocking>=1, 1 , 0)
Units: labor/Minute

(049) "Journeyman B Starting Wire&Clip"=
IF THEN ELSE(Journeyman B Up>0:AND:Journeyman B Up<=1, 1/59 , 0)
Units: labor/Minute

(050) Journeyman B Up= INTEG (
+Journeyman B Going Up-"Journeyman B Starting Wire&Clip",
0)
Units: labor

(051) Journeyman B Utilization=
100-Journeyman B Idle Percentage
Units: **undefined**

(052) Journeyman B Waiting= INTEG (
+Journeyman B Going Down-Journeyman B Starting 1st Half Restock,
1)
Units: labor

(053) "Journeyman C Completing Lamp&Finish"=
IF THEN ELSE("Journeyman C Finished Partial Lamp&Finish">=1, 1 , 0)
Units: labor/Minute

(054) Journeyman C Completing Restock=
IF THEN ELSE(Journeyman C Finished 2nd Half Restock>=1, 1 , 0)
Units: labor/Minute

(055) Journeyman C Finished 2nd Half Restock= INTEG (
+Journeyman C Starting 2nd Half Restock-Journeyman C Completing Restock,
0)
Units: labor

(056) "Journeyman C Finished Full Lamp&Finish"= INTEG (
+"Journeyman C Completing Lamp&Finish"-Journeyman C Going Down,
0)
Units: labor

(057) Journeyman C Finished Full Restock= INTEG (
+Journeyman C Completing Restock-Journeyman C Going Up,
0)
Units: labor

(058) "Journeyman C Finished Partial Lamp&Finish"= INTEG (
+"Journeyman C Starting Lamp&Finish"-"Journeyman C Completing Lamp&Finish"
,
0)
Units: labor

(059) Journeyman C Finished Partial Restocking= INTEG (
+Journeyman C Starting 1st Half Restock-Journeyman C Starting 2nd Half Restock
,
0)
Units: labor

(060) Journeyman C Going Down=
IF THEN ELSE("Journeyman C Finished Full Lamp&Finish">=1, 1 , 0)
Units: labor/Minute

(061) Journeyman C Going Up=
IF THEN ELSE(Journeyman C Finished Full Restock>=1, 1 , 0)
Units: labor/Minute

(062) Journeyman C idle Percentage=
IF THEN ELSE(Journeyman C Waiting=1, Journeyman C Waiting*100 , 0)
Units: **undefined**

(063) Journeyman C Starting 1st Half Restock=
IF THEN ELSE(Journeyman C Waiting>=1, 1 , 0)
Units: labor/Minute

(064) Journeyman C Starting 2nd Half Restock=
IF THEN ELSE(Journeyman C Finished Partial Restocking>=1, 1 , 0)
Units: labor/Minute

(065) "Journeyman C Starting Lamp&Finish"=
IF THEN ELSE(Journeyman C Up>0:AND:Journeyman C Up<=1, 1/59 , 0)

Units: labor/Minute

(066) Journeyman C Up= INTEG (
+Journeyman C Going Up-"Journeyman C Starting Lamp&Finish",
0)
Units: labor

(067) Journeyman C Utilization=
100-Journeyman C idle Percentage
Units: **undefined**

(068) Journeyman C Waiting= INTEG (
+Journeyman C Going Down-Journeyman C Starting 1st Half Restock,
1)
Units: labor

(069) Journeyman Going Down=
IF THEN ELSE(Journeyman A Finished Full Installation>=1:AND:Full Lit Fix
Installed
>=1, 1 , 0)
Units: labor/Minute

(070) Lift A Completing Installation=
IF THEN ELSE(Lift A Finished Partial Installation>=1, 1 , 0)
Units: labor/Minute

(071) Lift A Completing Restock=
IF THEN ELSE(Lift A Finished 2nd Half Restock>=1, 1 , 0)
Units: labor/Minute

(072) Lift A Finished 1st Half Restock= INTEG (
+Lift A Starting 1st Half Restock-Lift A Starting 2nd Half Restock,
0)
Units: labor

(073) Lift A Finished 2nd Half Restock= INTEG (
+Lift A Starting 2nd Half Restock-Lift A Completing Restock,
0)
Units: labor

(074) Lift A Finished Full Installation= INTEG (
+Lift A Completing Installation-Lift A Going Down,
0)
Units: labor

(075) Lift A Finished Full Restock= INTEG (

+Lift A Completing Restock-Lift A Going Up,
0)
Units: labor

(076) Lift A Finished Partial Installation= INTEG (
+Lift A Starting Installation-Lift A Completing Installation,
0)
Units: labor

(077) Lift A Going Down=
IF THEN ELSE(Lift A Finished Full Installation>=1:AND:Full Lit Fix Installed >=1, 1 , 0)
Units: labor/Minute

(078) Lift A Going Up=
IF THEN ELSE(Lift A Finished Full Restock>=1, 1 , 0)
Units: labor/Minute

(079) Lift A Idle Percentage=
IF THEN ELSE(Lift A Waiting=1, Lift A Waiting*100 , 0)
Units: **undefined**

(080) Lift A Starting 1st Half Restock=
IF THEN ELSE(Lift A Waiting>=1:AND:Lit Fix Assembled>=15, 1 , 0)
Units: labor/Minute

(081) Lift A Starting 2nd Half Restock=
IF THEN ELSE(Lift A Finished 1st Half Restock>=1, 1 , 0)
Units: labor/Minute

(082) Lift A Starting Installation=
IF THEN ELSE(Lift A Up>0:AND:Lift A Up<=1, 1/59 , 0)
Units: labor/Minute

(083) Lift A Up= INTEG (
+Lift A Going Up-Lift A Starting Installation,
0)
Units: labor

(084) Lift A Utilization=
100-Lift A Idle Percentage
Units: **undefined**

(085) Lift A Waiting= INTEG (
+Lift A Going Down-Lift A Starting 1st Half Restock,
1)

Units: labor

(086) Lift B Completing Restock=
IF THEN ELSE(Lift B Finished 2nd Half Restock>=1, 1 , 0)
Units: labor/Minute

(087) "Lift B Completing Wire&Clip"=
IF THEN ELSE("Lift B Finished Partial Wire&Clip">=1, 1 , 0)
Units: labor/Minute

(088) Lift B Finished 1st Half Restock= INTEG (
+Lift B Starting 1st Half Restock-Lift B Starting 2nd Half Restock,
0)
Units: labor

(089) Lift B Finished 2nd Half Restock= INTEG (
+Lift B Starting 2nd Half Restock-Lift B Completing Restock,
0)
Units: labor

(090) Lift B Finished Full Restock= INTEG (
+Lift B Completing Restock-Lift B Going Up,
0)
Units: labor

(091) "Lift B Finished Full Wire&Clip"= INTEG (
+"Lift B Completing Wire&Clip"-Lift B Going Down,
0)
Units: labor

(092) "Lift B Finished Partial Wire&Clip"= INTEG (
+"Lift B Starting Wire&Clip"-"Lift B Completing Wire&Clip",
0)
Units: labor

(093) Lift B Going Down=
IF THEN ELSE("Lift B Finished Full Wire&Clip">=1, 1 , 0)
Units: labor/Minute

(094) Lift B Going Up=
IF THEN ELSE(Lift B Finished Full Restock>=1, 1 , 0)
Units: labor/Minute

(095) Lift B Idle Percentage=
IF THEN ELSE(Lift B Waiting=1, Lift B Waiting*100 , 0)
Units: **undefined**

(096) Lift B Starting 1st Half Restock=
IF THEN ELSE(Lift B Waiting>=1, 1 , 0)
Units: labor/Minute

(097) Lift B Starting 2nd Half Restock=
IF THEN ELSE(Lift B Finished 1st Half Restock>=1, 1 , 0)
Units: labor/Minute

(098) "Lift B Starting Wire&Clip"=
IF THEN ELSE(Lift B Up>0:AND:Lift B Up<=1, 1/59 , 0)
Units: labor/Minute

(099) Lift B Up= INTEG (
+Lift B Going Up-"Lift B Starting Wire&Clip",
0)
Units: labor

(100) Lift B Utilization=
100-Lift B Idle Percentage
Units: **undefined**

(101) Lift B Waiting= INTEG (
+Lift B Going Down-Lift B Starting 1st Half Restock,
1)
Units: labor

(102) "Lift C Completing Lamp&Finish"=
IF THEN ELSE("Lift C Finished Partial Lamp&Finish">=1, 1 , 0)
Units: labor/Minute

(103) Lift C Completing Restock=
IF THEN ELSE(Lift C Finished 2nd Half Restock>=1, 1 , 0)
Units: labor/Minute

(104) Lift C Finished 1st Half Restock= INTEG (
+Lift C Starting 1st Half Restock-Lift C Starting 2nd Half Restock,
0)
Units: labor

(105) Lift C Finished 2nd Half Restock= INTEG (
+Lift C Starting 2nd Half Restock-Lift C Completing Restock,
0)
Units: labor

(106) "Lift C Finished Full Lamp&Finish"= INTEG (

+"Lift C Completing Lamp&Finish"-Lift C Going Down,
0)
Units: labor

(107) Lift C Finished Full Restock= INTEG (
+Lift C Completing Restock-Lift C Going Up,
0)
Units: labor

(108) "Lift C Finished Partial Lamp&Finish"= INTEG (
+"Lift C Starting Lamp&Finish"-"Lift C Completing Lamp&Finish",
0)
Units: labor

(109) Lift C Going Down=
IF THEN ELSE("Lift C Finished Full Lamp&Finish">=1, 1 , 0)
Units: labor/Minute

(110) Lift C Going Up=
IF THEN ELSE(Lift C Finished Full Restock>=1, 1 , 0)
Units: labor/Minute

(111) Lift C Idle Percentage=
IF THEN ELSE(Lift C Waiting=1, Lift C Waiting*100 , 0)
Units: **undefined**

(112) Lift C Starting 1st Half Restock=
IF THEN ELSE(Lift C Waiting>=1, 1 , 0)
Units: labor/Minute

(113) Lift C Starting 2nd Half Restock=
IF THEN ELSE(Lift C Finished 1st Half Restock>=1, 1 , 0)
Units: labor/Minute

(114) "Lift C Starting Lamp&Finish"=
IF THEN ELSE(Lift C Up>0:AND:Lift C Up<=1, 1/59 , 0)
Units: labor/Minute

(115) Lift C Up= INTEG (
+Lift C Going Up-"Lift C Starting Lamp&Finish",
0)
Units: labor

(116) Lift C Utilization=
100-Lift C Idle Percentage
Units: **undefined**

(117) Lift C Waiting= INTEG (
+Lift C Going Down-Lift C Starting 1st Half Restock,
1)
Units: labor

(118) Lit Fix Assembled= INTEG (
+Lit Fix Assembling Rate-"1st Half Lit Fix Restocking Rate",
15)
Units: light fixture

(119) Lit Fix Assembling Rate=
IF THEN ELSE(Lit Fix Waiting>=1/9:AND:Apprentice Waiting>=1/9, 1/9 , 0)
Units: light fixture/Minute

(120) Lit Fix Going Up Rate=
IF THEN ELSE(Full Lit Fix Restocked>=15, 15 , 0)
Units: light fixture/Minute

(121) Lit Fix Up= INTEG (
+Lit Fix Going Up Rate-Partial Lit Fix Installation Rate,
0)
Units: light fixture

(122) Lit Fix Waiting= INTEG (
-Lit Fix Assembling Rate,
330)
Units: light fixture

(123) Number of Apprentice=
1
Units: labor

(124) Number of Journeyman=
3
Units: labor

(125) Number of Lift=
3
Units: labor

(126) Operation Production Rate=
ZIDZ(Full Lit Fix In Place, Time of Operation)
Units: **undefined**

(127) Partial Lit Fix Installation Rate=

IF THEN ELSE(Lit Fix Up>0:AND:Lit Fix Up<=15, 1/3 , 0)
Units: light fixture/Minute

(128) Partial Lit Fix Installed= INTEG (
+Partial Lit Fix Installation Rate-Complete Lit Fix Installation Rate,
0)
Units: light fixture

(129) "Partial Lit Fix Lamp&Finish Rate"=
IF THEN ELSE("Full Lit Fix Wire&Clipped">0:AND:Journeyman C
Up>0:AND:Lift C Up
>0, 1/3 , 0)
Units: light fixture/Minute

(130) "Partial Lit Fix Lamp&Finished"= INTEG (
+"Partial Lit Fix Lamp&Finish Rate"-"Complete Lit Fix Lamp&Finish Rate",
0)
Units: light fixture

(131) "Partial Lit Fix Wire&Clip Rate"=
IF THEN ELSE(Full Lit Fix Installed>0:AND:Journeyman B Up>0:AND:Lift B
Up
>0, 1/7 , 0)
Units: light fixture/Minute

(132) "Partial Lit Fix Wire&Clipped"= INTEG (
+"Partial Lit Fix Wire&Clip Rate"-"Complete Lit Fix Wire&Clip Rate",
0)
Units: light fixture

(133) SAVEPER =
TIME STEP
Units: Minute [0,?]
The frequency with which output is stored.

(134) Time of Operation=
Time/60
Units: hours

(135) TIME STEP = 1
Units: Minute [0,?]
The time step for the simulation.

(136) Total Apprentice Cost per hour=
Number of Apprentice*Unit Apprentice Cost
Units: dollars/hour

(137) Total Cost of Operation=
Time of Operation*(Total Apprentice Cost per hour+Total Journeyman Cost per hour
+Total Lift Cost per hour)
Units: dollars

(138) Total Journeyman Cost per hour=
Number of Journeyman*Unit Journeyman Cost
Units: dollars/hour

(139) Total Lift Cost per hour=
Number of Lift*Unit Lift Cost
Units: dollars/hour

(140) Unit Apprentice Cost=
6
Units: dollars/(labor*hour)

(141) Unit Cost of Operation=
ZIDZ(Total Cost of Operation, Full Lit Fix In Place)
Units: dollars/light fixture

(142) Unit Journeyman Cost=
13.4
Units: dollars/(labor*hour)

(143) Unit Lift Cost=
1.5
Units: dollars/(labor*hour)

The complete system dynamics model for the “Improved” case is uploaded online and can be accessed at the following website:

https://docs.google.com/open?id=0BxrMYHbElFuNSHJiZXozTDU2eUk

Appendix F: SD “Lean” Crew Model Formulation

The mathematical equations used to formulate the system dynamics “Lean” model are shown below:

<u>Model mathematical equations:</u>

(01) Apprentice Assembling=

IF THEN ELSE(Apprentice Waiting>=1/9:AND:Lit Fix Waiting>=1/9 , 1/9 , 0)
Units: (labor/Minute)

(02) Apprentice Finished Assembling= INTEG (
+Apprentice Assembling-Apprentice Returning,
0)
Units: labor

(03) Apprentice Idle Percentage=
IF THEN ELSE(Apprentice Waiting=1:OR:Apprentice Waiting=1/9, Apprentice Waiting
*100 , 0)
Units: **undefined**

(04) Apprentice Returning=
IF THEN ELSE(Apprentice Finished Assembling=1, 1 , 0)
Units: labor/Minute

(05) Apprentice Utilization=
100-Apprentice Idle Percentage
Units: **undefined**

(06) Apprentice Waiting= INTEG (
+Apprentice Returning-Apprentice Assembling ,
1)
Units: labor

(07) Assembling Production Rate=
ZIDZ(Lit Fix Assembled, Time of Operation)
Units: **undefined**

(08) Complete Lit Fix Installation Rate=
IF THEN ELSE(Partial Lit Fix Installed>=1, 1 , 0)
Units: light fixture/Minute

(09) "Complete Lit Fix Lamp&Finish Rate"=
IF THEN ELSE("Partial Lit Fix Lamp&Finished">=1, 1 , 0)
Units: light fixture/Minute

(10) "Complete Lit Fix Wire&Clip Rate"=
IF THEN ELSE("Partial Lit Fix Wire&Clipped">=1, 1 , 0)
Units: light fixture/Minute

(11) FINAL TIME = 7900
Units: Minute

The final time for the simulation.

(12) Full Lit Fix Installed= INTEG (
+Complete Lit Fix Installation Rate-"Partial Lit Fix Wire&Clip Rate",
0)
Units: light fixture

(13) "Full Lit Fix Wire&Clipped"= INTEG (
+"Complete Lit Fix Wire&Clip Rate"-"Partial Lit Fix Lamp&Finish Rate",
0)
Units: light fixture

(14) INITIAL TIME = 0
Units: Minute
The initial time for the simulation.

(15) Journeyman Completing Installation=
IF THEN ELSE(Journeyman Finished Partial Installation>=1, 1 , 0)
Units: labor/Minute

(16) "Journeyman Completing Lamp&Finish"=
IF THEN ELSE("Journeyman Finished Partial Lamp&Finish">=1, 1 , 0)
Units: labor/Minute

(17) "Journeyman Completing Wire&Clip"=
IF THEN ELSE("Journeyman Finished Partial Wire&Clip">=1, 1 , 0)
Units: labor/Minute

(18) Journeyman Finished Full Installation= INTEG (
+Journeyman Completing Installation-"Journeyman Starting Wire&Clip",
0)
Units: labor

(19) "Journeyman Finished Full Lamp&Finish"= INTEG (
+"Journeyman Completing Lamp&Finish"-Journeyman Going Down,
0)
Units: labor

(20) "Journeyman Finished Full Wire&Clip"= INTEG (
+"Journeyman Completing Wire&Clip"-"Journeyman Starting Lamp&Finish",
0)
Units: labor

(21) Journeyman Finished Partial Installation= INTEG (
+Journeyman Starting Installation-Journeyman Completing Installation,
0)

Units: labor

(22) "Journeyman Finished Partial Lamp&Finish"= INTEG (
+"Journeyman Starting Lamp&Finish"-"Journeyman Completing Lamp&Finish",
0)
Units: labor

(23) "Journeyman Finished Partial Wire&Clip"= INTEG (
+"Journeyman Starting Wire&Clip"-"Journeyman Completing Wire&Clip",
0)
Units: labor

(24) Journeyman Finished Restocking= INTEG (
+Journeyman Restocking-Journeyman Going Up,
0)
Units: labor

(25) Journeyman Going Down=
IF THEN ELSE("Journeyman Finished Full Lamp&Finish">=1:AND:Lit Fix In Place
>=1, 1 , 0)
Units: labor/Minute

(26) Journeyman Going Up=
IF THEN ELSE(Journeyman Finished Restocking>0:AND:Journeyman Finished Restocking
<=1, 1 , 0)
Units: labor/Minute

(27) Journeyman Idle Percentage=
IF THEN ELSE(Journeyman Waiting=1, Journeyman Waiting*100 , 0)
Units: **undefined**

(28) Journeyman Restocking=
IF THEN ELSE(Journeyman Waiting>=1:AND:Lit Fix Assembled>=1, 1 , 0)
Units: labor/Minute

(29) Journeyman Starting Installation=
IF THEN ELSE(Journeyman Up>0:AND:Journeyman Up<=1, 1/6 , 0)
Units: labor/Minute

(30) "Journeyman Starting Lamp&Finish"=
IF THEN ELSE("Journeyman Finished Full Wire&Clip">0:AND:"Journeyman Finished Full Wire&Clip"
<=1, 1/6 , 0)
Units: labor/Minute

(31) "Journeyman Starting Wire&Clip"=
IF THEN ELSE(Journeyman Finished Full Installation>0:AND:Journeyman Finished Full Installation
<=1, 1/8 , 0)
Units: labor/Minute

(32) Journeyman Up= INTEG (
+Journeyman Going Up-Journeyman Starting Installation,
0)
Units: labor

(33) Journeyman Utilization=
100-Journeyman Idle Percentage
Units: **undefined**

(34) Journeyman Waiting= INTEG (
+Journeyman Going Down-Journeyman Restocking,
1)
Units: labor

(35) Lift Completing Installation=
IF THEN ELSE(Lift Finished Partial Installation>=1, 1 , 0)
Units: labor/Minute

(36) "Lift Completing Lamp&Finish"=
IF THEN ELSE("Lift Finished Partial Lamp&Finish">=1, 1 , 0)
Units: labor/Minute

(37) "Lift Completing Wire&Clip"=
IF THEN ELSE("Lift Finished Partial Wire&Clip">=1, 1 , 0)
Units: labor/Minute

(38) Lift Finished Full Installation= INTEG (
+Lift Completing Installation-"Lift Starting Wire&Clip",
0)
Units: labor

(39) "Lift Finished Full Lamp&Finish"= INTEG (
+"Lift Completing Lamp&Finish"-Lift Going Down,
0)
Units: labor

(40) "Lift Finished Full Wire&Clip"= INTEG (
+"Lift Completing Wire&Clip"-"Lift Starting Lamp&Finish",
0)

Units: labor

(41) Lift Finished Partial Installation= INTEG (
+Lift Starting Installation-Lift Completing Installation,
0)
Units: labor

(42) "Lift Finished Partial Lamp&Finish"= INTEG (
+"Lift Starting Lamp&Finish"-"Lift Completing Lamp&Finish",
0)
Units: labor

(43) "Lift Finished Partial Wire&Clip"= INTEG (
+"Lift Starting Wire&Clip"-"Lift Completing Wire&Clip",
0)
Units: labor

(44) Lift Finished Restocking= INTEG (
+Lift Restocking-Lift Going Up,
0)
Units: labor

(45) Lift Going Down=
IF THEN ELSE("Lift Finished Full Lamp&Finish">=1:AND:Lit Fix In Place>=1,
1 , 0)
Units: labor/Minute

(46) Lift Going Up=
IF THEN ELSE(Lift Finished Restocking>0:AND:Lift Finished Restocking<=1,
1 , 0)
Units: labor/Minute

(47) Lift Idle Percentage=
IF THEN ELSE(Lift Waiting<=1/9:OR:Lift Waiting>=8/9, Lift Waiting*100 , 0
)
Units: **undefined**

(48) Lift Restocking=
IF THEN ELSE(Lift Waiting>=1:AND:Lit Fix Assembled>=1, 1 , 0)
Units: labor/Minute

(49) Lift Starting Installation=
IF THEN ELSE(Lift Up>0:AND:Lift Up<=1, 1/6 , 0)
Units: labor/Minute

(50) "Lift Starting Lamp&Finish"=
IF THEN ELSE("Lift Finished Full Wire&Clip">0:AND:"Lift Finished Full Wire&Clip"
<=1, 1/6 , 0)
Units: labor/Minute

(51) "Lift Starting Wire&Clip"=
IF THEN ELSE(Lift Finished Full Installation>0:AND:Lift Finished Full Installation
<=1, 1/8 , 0)
Units: labor/Minute

(52) Lift Up= INTEG (
+Lift Going Up-Lift Starting Installation,
0)
Units: labor

(53) Lift Utilization=
100-Lift Idle Percentage
Units: **undefined**

(54) Lift Waiting= INTEG (
+Lift Going Down-Lift Restocking,
1)
Units: labor

(55) Lit Fix Assembled= INTEG (
+Lit Fix Assembling Rate-Lit Fix Restocking Rate,
0.0001)
Units: light fixture

(56) Lit Fix Assembling Rate=
IF THEN ELSE(Lit Fix Waiting>=1/9:AND:Apprentice Waiting>=1/9, 1/9 , 0)
Units: light fixture/Minute

(57) Lit Fix Going Up Rate=
IF THEN ELSE(Lit Fix Restocked>0:AND:Lit Fix Restocked<=1, 1 , 0)
Units: light fixture/Minute

(58) Lit Fix In Place= INTEG (
+"Complete Lit Fix Lamp&Finish Rate",
0.1111)
Units: light fixture

(59) Lit Fix Restocked= INTEG (
+Lit Fix Restocking Rate-Lit Fix Going Up Rate,

0)
Units: light fixture

(60) Lit Fix Restocking Rate=
IF THEN ELSE(Lit Fix Assembled>=1:AND:Lift Waiting>=1:AND:Journeyman Waiting
>=1, 1 , 0)
Units: light fixture/Minute

(61) Lit Fix Up= INTEG (
+Lit Fix Going Up Rate-Partial Lit Fix Installation Rate,
0)
Units: light fixture

(62) Lit Fix Waiting= INTEG (
-Lit Fix Assembling Rate,
330)
Units: light fixture

(63) Number of Apprentice=
1
Units: labor

(64) Number of Journeyman=
1
Units: labor

(65) Number of Lift=
1
Units: labor

(66) Operation Production Rate=
ZIDZ(Lit Fix In Place, Time of Operation)
Units: **undefined**

(67) Partial Lit Fix Installation Rate=
IF THEN ELSE(Lit Fix Up>0:AND:Lit Fix Up<=1, 1/6 , 0)
Units: light fixture/Minute

(68) Partial Lit Fix Installed= INTEG (
+Partial Lit Fix Installation Rate-Complete Lit Fix Installation Rate,
0)
Units: light fixture

(69) "Partial Lit Fix Lamp&Finish Rate"=

IF THEN ELSE("Full Lit Fix Wire&Clipped">0:AND:"Full Lit Fix Wire&Clipped"
<=1, 1/6 , 0)
Units: light fixture/Minute

(70) "Partial Lit Fix Lamp&Finished"= INTEG (
+"Partial Lit Fix Lamp&Finish Rate"-"Complete Lit Fix Lamp&Finish Rate",
0)
Units: light fixture

(71) "Partial Lit Fix Wire&Clip Rate"=
IF THEN ELSE(Full Lit Fix Installed>0:AND:Full Lit Fix Installed<=1, 1/8
, 0)
Units: light fixture/Minute

(72) "Partial Lit Fix Wire&Clipped"= INTEG (
+"Partial Lit Fix Wire&Clip Rate"-"Complete Lit Fix Wire&Clip Rate",
0)
Units: light fixture

(73) SAVEPER =
TIME STEP
Units: Minute [0,?]
The frequency with which output is stored.

(74) Time of Operation=
Time/60
Units: hours

(75) TIME STEP = 1
Units: Minute [0,?]
The time step for the simulation.

(76) Total Apprentice Cost per hour=
Number of Apprentice*Unit Apprentice Cost
Units: dollars/hour

(77) Total Cost of Operation=
Time of Operation*(Total Apprentice Cost per hour+Total Journeyman Cost per hour
+Total Lift Cost per hour)
Units: dollars

(78) Total Journeyman Cost per hour=
Number of Journeyman*Unit Journeyman Cost
Units: dollars/hour

(79) Total Lift Cost per hour=
Number of Lift*Unit Lift Cost
Units: dollars/hour

(80) Unit Apprentice Cost=
6
Units: dollars/(labor*hour)

(81) Unit Cost of Operation=
Total Cost of Operation/Lit Fix In Place
Units: dollars/light fixture

(82) Unit Journeyman Cost=
13.4
Units: dollars/(labor*hour)

(83) Unit Lift Cost=
1.5
Units: dollars/(labor*hour)

The complete system dynamics model for the “Lean” case is uploaded online and can be accessed at the following website:

https://docs.google.com/file/d/0BxrMYHbElFuNbzgtU3g2cjJ2dFE/edit

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