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Dynamic Modeling Approach to Quantify Change Orders Impact on Labor Productivity

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DYNAMIC MODELING APPROACH TO QUANTIFY CHANGE ORDERS IMPACT ON LABOR PRODUCTIVITY

by

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ABSTRACT

In construction projects, change orders are commonly faced. These change orders, which are issued by the owner, may cause interruption to the contractor's work, resulting in damages such as loss of labor productivity, delay damages, and cost overruns which may lead to claims. The relationship between change orders and loss of labor productivity is not well understood because of the difficulty in linking the cause of the productivity loss to the change order. So, to receive compensation, the contractor needs to prove with a credible calculation that the productivity loss was a result of the change order issued by the owner.

Compared to all available productivity loss quantification methods, the "Measured Mile" approach is considered the most acceptable and popular approach in litigation. In this study, loss of labor productivity due to change orders is studied using a system dynamics method. A system dynamics model is developed using Vensim Software, validated, and utilized to quantitatively measure the impact of the change in the project scope on labor productivity.

Different road construction projects were analyzed using both methods: measured mile analysis and system dynamics model; then, the results from those two approaches were compared.

*To my **Parents,** who have been always there to support me*
*To my **Brother** and **Sisters** and their **Families***
*To all my **Friends***

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CHAPTER 1: INTRODUCTION

1.1 Background

Change orders are ordinary issues in construction projects. An increase, ranging between 5 and 10% to the project's cost due to changes is the expected norm in most construction projects (AACE 2004). Therefore, every construction contract contains a "changes clause" to delineate a process to identify and document changes (Serag et al. 2008). Each change is documented in a change order, which according to the Article 12.1.1 of AIA A201 (1977), is defined as "a written order to the contractor signed by the owner and architect, issued after execution of the contract, authorizing a change in the work or an adjustment in the contract sum or the contract time." (Serag et al. 2010).

There are many sources that can cause change orders in construction projects, according to Warhoe (2005). These sources can be classified into four broad categories: "Design deficiencies (errors and omissions), Unforeseen conditions encountered on the site, Changes in scope directed by the owner, and Criteria changes" (Warhoe 2005). The resulting changes not only disturb the work directly impacted by the changes, but they might also have indirect impact, such as loss of labor productivity, which means that a task will take longer than expected to be completed. Moreover, changes usually lead to disagreement between contractors and owners on the impact and the liability of the changes.

Considering the intricacy of establishing a causal relation between a change order and loss of productivity, this connection is not well understood. Therefore, to be entitled to compensation, the contractor needs to provide a credible estimate, proving that the loss of productivity is a result of a change order issued by the owner.

System dynamics, which are essentially deterministic, are applicable for various fields such as project management, defense analysis, and health care. System dynamics, which are used in legal cases to address matters such as delay and disruption, factor in a myriad of circumstances including interdependencies, feedbacks, time delays, and nonlinearities. Therefore, system dynamics modeling is chosen in large scale projects. In this study, it is used to quantify the impact of change orders on labor productivity.

In order to have a reasonable estimation of the change cost and make cogent project decisions, it is important to understand the types of costs that generally occur in construction projects. The main expenses that impact construction projects are fixed and variable costs.

- Fixed Costs

Fixed costs can be defined as every cost that does not depend on activity level. They are unavoidable and must be paid regardless of the level of output and the resources used. The risks associated with fixed costs are relatively low. Examples of fixed costs are overhead, insurance, rent, etc.

- Variable Costs

Variable costs are defined as the costs that change during the project's life-cycle. Examples of variable costs are equipment, fuel costs and labor rates. Labor rates are the main variable cost item in any construction project, and they determine most of the cost of any construction project. As a result, labor productivity is considered as the major factor in determining profit on a project, either by the contractors or subcontractors.

Many factors can increase labor cost, and they are divided into five main areas: schedule acceleration, changes in the scope of work, project management, project location and external characteristics. Schedule acceleration may lead to long periods of mandatory overtime; addition of second shifts, stacking of trades, and overcrowding of labors beyond the site's saturation point making it challenging to be managed or coordinated. Changes in the scope of work increase the need for rework, which adds up substantial amount of material and tasks to be re-planned and re-sequenced. Moreover, it adjoins delays, modification in the learning curve, increase in engineering errors and omissions, and adjustment of specifications. Deficiencies in the management could adversely affect the availability of the right tools, materials and equipment in the right place at the right time, the dynamics between team members and distinct crews, and the efficiency of the supervision. Project location and external conditions include physical conditions (saturated soils); logistical conditions (low-hanging power lines); environmental and legal conditions (permit requirements affecting when construction can take place); availability of skilled labor; and the local economy (AACE, 2004; Serag, 2006).

1.2 Labor Productivity

There are several different definitions for labor productivity. In an overall scope, it can be defined as the ratio of input to output. In the construction industry, it is simply the man-hours required to accomplish a given unit of work.

Productivity can be calculated using any of the following equations:

"Productivity = input ÷ Output
= Man-hours ÷ Units
= (Total man-hours) ÷ (Total units)"

In general, construction contractors are remunerated after the completion of the work, in accordance to the terms of the contract. This implies that productivity is related to project cash flow and project profitability. Thus, to achieve higher profitability, the contractor must concentrate in obtaining the highest output from the lowest input resources, striving for the highest possible productivity in a project (Dolage and Chan 2013).

When contractors experience loss in their labor productivity, it means that their profit will be directly affected. So, in construction claims, the meaning of labor productivity loss is specified to be the increase in the incurred cost experienced by the contractor due to producing less output than planned to produce per work hour of input, which means financial loss for the contractor. Loss in labor productivity can be attributed to the occurrence of certain events or factors which negatively affect the labor productivity.

1.2.1 Common Causes of Lost Productivity

In any construction project, labor productivity may decline due to numerous circumstances and events. The preponderous of variables creates a challenge in estimating the impact of changes on productivity (Klanac and Nelson 2004). Dai et al. (2009) conducted a research that identified 83 factors affecting construction labor productivity. They used 18 focus groups consisting of craft workers and their supervisors on nine job sites in the United States and investigated how craft workers consider the factors that affect their productivity, and their relative importance. “The total number of productivity influence factors in construction is enormous,” according to Herbsman and Ellis (1990) and is possibly the reason driving the difference in productivity values for the same construction item on different projects because each project has its unique conditions that affect productivity rates.

AACE (2004) has conducted a review of two publications, revealing 25 causes that cover most of the circumstances encountered on a construction project and have the potential to reduce labor productivity.

The following is a brief presentation of the main reasons for labor productivity inefficiency:

1. **Site or work area access restrictions**:
   Can lead to the following
   a. Limited access can result in the shortage of employees, materials, and equipment needed on site to work to work efficiently.
   b. Limited access to work areas can lead to delays and a time crunch for the contractor to complete work. Direct repercussions include overtime, crowding of the work area, reduction of direct supervision, and reduced integration between trades.
   c. Excessive travel time between the assembling area and working area.
2. **Site conditions:**
   Physical conditions/ logistical conditions/ environmental conditions/ legal conditions.
3. **Untimely approvals or responses:**

Productivity might halt while awaiting approval, redirection, or information when there is a delay in response time between owners, designers, and/or construction managers.

4. **Adverse or unusually severe weather conditions: heat/ cold/ wind/ rain/ snow/ humidity**

Pushing work items that are sensitive to weather conditions from good weather periods to bad weather periods may impact labor productivity.

5. **Acceleration:**

If the contractor faces schedule delay, and he is forced to speed up the project, one of the following strategies might be adopted:

Scheduled overtime:

Used frequently, instead of sporadically, overtime will cause a loss of labor productivity. This fact has been consistently documented by several studies over time. The reasons for this loss can be attributed to the following reasons:

- Fatigue. Recurrent overtime leads employees to work slower and to increase errors and accidents on site, resulting in loss in productivity.

- Increased absenteeism. Once the crew has reached its production peak, the absence of any member represents decrease in resources and, therefore, will affect productivity.

-Decreased labor morale

-Reduced supervisory effectiveness

Shift work

A study carried out by Hanna et al. (2008) shows that shift work can be both an advantage and a disadvantage to labor productivity. Small, well-organized amounts of shift work can be very effective to speed up the project. However, choosing to apply shift work can cause problems in the work coordination, as well as raise health problems for the workers.

Hire more craftsmen (overmanning)

Adding more laborers to the site beyond its saturation point can negatively affect labor productivity. This is because extra people in a given space can create obstructions. Overmanning can also lead to the following:

-Force the contractor to hire unproductive personnel due to a lack of skilled ones.

-More workers than needed supplies.

-Dilution of supervision.

-New difficulties in planning and coordinating work.

6. Out of sequence work:

Out-of-sequence work means that a series of activities are not performed the way they were planned to be, causing unplanned crew movement around the site and, consequently, loss in productivity.

7. Rework and errors:

When work in the field must be done more than due to errors, staff morale is likely to suffer resulting in loss of productivity.

8. Multiple changes and rework:

The cumulative impact of changes on the rest of the project s may impact productivity. "The need to tear out work already installed, the delays associated with changes, the need to re-plan, reschedule and re-sequence work, for example, may also cause productivity to decline (AACE 2004).

9. Learning Curve:

> At the outset of any project, there is a typical learning curve while the labor crews become familiar with the project, its location, the quality standards imposed, laydown area locations, etc. However, if the work of the project is shut down for some period of time and labor crews laid off, then when work recommences the labor crews brought back to the project may have to go through another learning curve. This is probably an unanticipated impact on labor productivity. If this happens more than once, then each time a work stoppage occurs another learning curve productivity loss impact may occur (AACE 2004).

10. Project management factors:

Poor project management can lead to:

-Failure to properly schedule and coordinate the work;

-Shortage in critical construction equipment or personnel;

-Incorrect mix of labor crews; and poor site layout.

1.3 Construction Change Orders and Construction Claims

Change orders are legal documents that adapt to “any additional work in a contract that was not included in the original contract” (Anastasopoulos, 2010). Changes in a project usually lead to disagreements between the contract parties - the owner and contractor or contractor and subcontractor - on the cost and effects of the change. “Doing changes during the performance of the work are more expensive than if the same work had been required to be performed under the original contract” (Schwartzkopf, 1995); changes usually result in an increase in construction claims between the contract parties.

1.3.1 Common Sources of Change Orders in Construction Projects

According to studies conducted by the US federal government (National Research Council 1986), the US Army Corps of Engineers, and the US Navy (Warhoe, 2005), the primary sources of change orders can be classified into four broad categories. The following is a brief explanation of each category:

1. Design deficiencies (errors and omissions):

This type of changes relates to the project plans that are either partially completed or have errors that are discovered after the initial contract has been signed. Since the traditional U.S. project delivery method is Design-Bid-Build (DBIA, 2015), which means that the contractor bids on designs that are completed prior to a contract award, the owner is the liable party for the changes that result from design deficiencies discovered by the contractor during the construction phase. Studies carried out by the US Army Corps of Engineers and US Navy show that design deficiencies account for nearly 40% of all construction changes on a design-bid-build project. Few theories explore the reasons why design deficiencies are the most common change type among construction projects. The most common theory suggests that the owners usually ask the designers to finish the design plans/drawings within an unreasonable time frame, which results in an increased chance for errors due to haste (Warhoe 2005).

2. Differing site conditions encountered on the site:

These are conditions that were not known or considered during the original design and contract. Often, these are unexpected discoveries during the build phase. (Last, 2005). This type of change is important for the contractor if he experienced an increase in the project cost and/or a delay as a result of the differing site condition. A common example is when the contractor performs earth excavation and discovers items that are not shown on the project drawings or a different soil type from that reported in the contract documents. Either of these discoveries might need special methods/techniques, which may lead the contractor to inject additional resources (time and/or money) beyond what was originally contracted.

3. Changes in scope directed by the owner:

A formal change order issued by the owner is a directed change. It is always delivered in writing and is the most controllable type of change. Compared with the first two types of changes, owner-directed changes are not frequently encountered in construction projects. In this type of change, the owner makes a modification to the project after the design is finished and the contractor had been hired. It is worth to note that this change must not be a fundamental change in the project scope, and the contractor has the right to adjust the contract's price and/or time, based on how the changes affect the costs and/or delivery schedule (Kelleher and Walters 2009).

4. Criteria changes:

Government usually has well-established standards for design and construction. This type of change occurs when the government revises its standards for design and construction, on a matter that affects the contract, which reflects a bid based on a previous version of standards. This type of change can also occur with private owner projects if they have well-established standards for design and construction (Warhoe, 2005).

1.4 Problem Statement

Change orders are very common in construction projects. Delay and loss in labor productivity are the main damages resultant from change orders. Losses in labor productivity damages resulting from change orders are highly challenging for both contractors and subcontractors to specify, prove, and account for. Owners find these factors the most difficult to comprehend and agree to. Therefore, claims about loss in labor productivity are often the most difficult to resolve. The complexity of this type of claim can be attributed to the not well understood relation between change orders and loss of labor productivity; linking of the cause of the productivity loss to the change order is difficult (Ibbs et. al.2007). For the contractor to be entitled to compensation for this type of damage, he or she needs to prove and quantify, with a credible calculation, that the productivity loss resulted from the change order issued by the owner.

> Using system dynamic modeling the causes of labor productivity loss can be identified in ways that prove liability, because system dynamics model has the ability to capture not only the quantitative effects of changes, but the softer ‘human’ effects (such as fatigue), which can play an important role in the life of any project Howick (2003).

1.5 Research Objectives

The main objective of this research is to develop a System Dynamics model that can be used to:

1. Quantitatively measure the impact of the owner changes in the project scope on labor productivity.
2. Compare the results obtained from the analysis of different road construction projects using measured mile analysis and system dynamics modeling methods.
3. Prove/deny the responsibility of change order to the occurrence of productivity loss.

1.6 Research Scope

The scope of this research will concentrate on the loss of labor productivity of road construction projects that encountered owner-directed change orders, which were issued for modification. Projects studied are 100% completed and are potential cases for claims due to the issuance of change orders. This study will examine the impact of change orders on loss of productivity; many factors encountered on the project during and after the change order will be considered.

1.7 Organization of the Research

The dissertation consists five chapters described as follows:

Chapter 1 presents an introduction to the research, highlighting the problem statement, objectives and scope of this research.

Chapter 2 reviews relevant literature from previous studies which address change orders and productivity loss.

Chapter 3 presents the methodology followed in the research. The chapter highlights data collection, problem identification, identification of causal links among model variables, explanation to the structure of the system dynamics model, model building, verification and validation of the model.

Chapter 4 presents the research results obtained from system dynamics modeling simulation and measured mile analysis, and it also contains a discussion of these results.

Chapter 5 compares and contrasts this analysis of this study with previous analyses of productivity loss quantification methods. The strengths of this project's research methods are named. Conclusions of this research and recommendation for future research complete the chapter.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Change orders are conventional issues in construction projects. For this reason, every construction contract contains a “changes clause” which describes the procedure for identifying and documenting changes (Serag et al. 2008). There are many sources that can cause change orders in construction projects. According to Warhoe (2005), these sources can be classified into four major categories, namely: “Design deficiencies (errors and omissions), Unforeseen conditions encountered on the site, Changes in scope directed by the owner and Criteria changes.” The resulting changes not only disturb the work that is directly impacted by them, but they may also have indirect impact, such as loss of labor productivity which means that the laborer will take a longer time to accomplish a certain task than he usually takes, which most of the time leads to a disagreement between the contractors and the owners on the impact and the liability of the change. The relationship between change orders and loss of labor productivity is not well understood because the link between the two instances is not evident. Yet, in order to be entitled to compensation, the contractor needs to prove with a credible calculation that the productivity loss is a result of the change order issued by the owner. Several methods were developed by the construction industry to estimate and measure the loss in labor productivity. The following section illustrates these methods with their advantages and limitations.

2.2 Methods Used to Quantify Loss in Labor Productivity

The current methods used to quantify the loss in labor productivity are divided into three main groups, based on the used input data in Nelson (2011):

1. Project Practice based method

2. Cost based method
3. Industry based method

2.2.1 Project Practice Based Method

Approaches listed under this category are the most preferred by the courts, Boards of Contract Appeals and other legal forums AACE (2004) since their calculations depend on the contemporaneous documentation of the disputed project.

2.2.1.1 Measured Mile Analysis

Compared to all available productivity loss quantification methods, measured mile is considered the most acceptable one (Ibbs and Liu 2005). The analysis in measured mile method is done by comparing the unimpacted period of the project with the impacted period; this estimates the loss in labor productivity resulting from the impact of a known series of events that affect the project (Shwartzkoph 1995).

> The basic approach is to identify an unimpacted or least impacted period of construction activity, linearly extrapolate the cumulative unimpacted hours to the end of an impacted period, and uses the difference between the projected unimpacted hours and the actual cumulated hours as the amount of damage hours (Gulezian and Samelian, 2003).

As shown in Figure 1, the first 30 observations are used as the measured mile, since they correspond to a period unimpacted by the owner-liable change, whereas the remaining 18 observations are assumed to reflect the work that was adversely affected by the owner. The projection of the measured mile leads to an estimate of 3,745 h at 100% complete; assuming that these accumulated hours would have been earned if the owner did not cause any impact, while the actual number of hours spent on the project is 4,810 h. Thus, the number of hours for which compensation would be sought is equal to 1,065 h, the difference between the measured mile prediction and the actual hours spent on the project (Gulezian and Samelian, 2003).

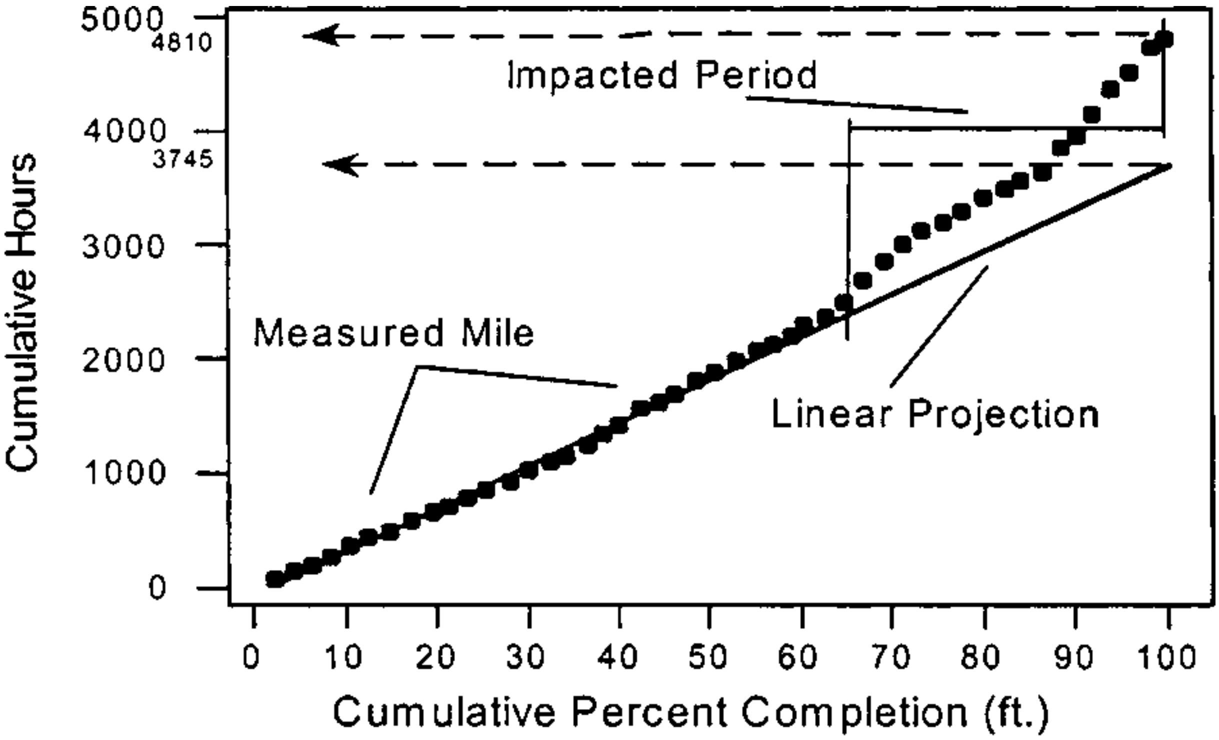


Figure 1: The Measured Mile (Gulezian and Samelian, 2003)

Measured Mile Limitations:

1. The need for the existence of a non-impacted period for the same type of work being evaluated.
2. The length of the non-impacted period should be significant compared to the impacted period.

3. Enough contemporaneous project data is needed for the analysis. Formatting of the data is also necessary to perform the analysis, so this method of analysis can be cumbersome and costly.
4. Precise recording of project documentation by the contractor.
5. Choosing the time frame for the measured mile is very subjective, which means different time frame chosen from the measured mile period might generate distinct numbers (Gulezian and Samelian, 2003).
6. All disruption during the impacted period is assumed to be due to one party.
7. This method does not produce causal logic for explaining why a change occurrence results in productivity loss.

2.2.1.2 Baseline Productivity Analysis

The baseline productivity analysis was proposed to overcome some of the limitations associated with the measured mile analysis. Similar to measured mile analysis method, baseline productivity method depends on the actual performance of the contractor in the project under analysis. In this analysis method, the main point is to define a baseline period, a period of time when the contractor performs his or her best productivity. It is not necessarily a continuous, unimpacted time frame, nor is it a purely unimpacted period; owner- and contractor-caused inefficiencies may be present throughout. Research was conducted by Thomas and Zavrski (1999) to develop the theoretical basis for the baseline productivity measurement. After analyzing a 42-project database, the main findings show that the baseline productivity depends on the complexity of the design. As the design becomes more complex, the baseline productivity worsens. Also, it shows that the baseline productivity depends on the management, craft skills and technology used.

The mechanics of the baseline method were described by Thomas in many articles, and the calculation steps are as follows:

> "1. Determine 10% of the total workdays;
>
> 2. Round the calculated number in step 1 to the next highest odd number. This number should not be less than 5. This number *n* defines the size of number of days in the baseline subset;
>
> 3. The contents of the baseline subset are selected as the *n* workdays that have the highest daily production or output;
>
> 4. For these days, make note of the daily productivity; and
>
> 5. The baseline productivity is the median of the daily productivity values in the baseline subset "(Ibbs and Liu, 2005). See figure 2.

Baseline Limitations:

1. Agree upon the definition of the baseline productivity sample.
2. The result will be a very roughly approximation of the contractor productivity.
3. In using this method, it is impossible to classify and quantify damages induced by the owner and contractor during a disputed period. This is especially true when there are multiple and/or simultaneous owner and contractor-caused disruptions, which commonly occur in real life.

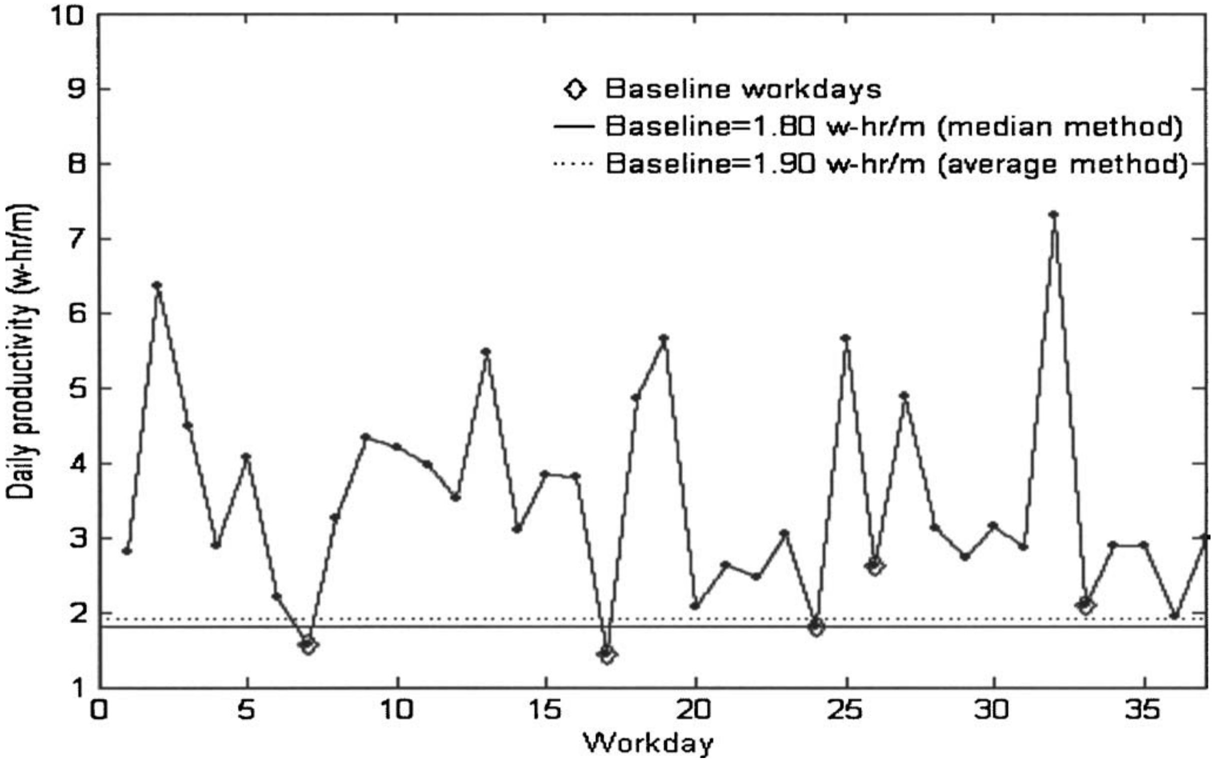


Figure 2: Baseline Productivity Calculation (Ibbs and Liu, 2005)

2.2.1.3 Earned Value Analysis

Earned value method can be used to measure productivity when there is a problem in obtaining precise data for the physical units of work installed on the project, which prevents the use of one of the most reliable methods, such as measured mile or baseline analyses. In this method, the value of payments and the unit price are used to determine the earned hours. The difference between the calculated earned hours and the actual hours expended for an impacted period can be used to compute the productivity loss experienced (Ibbs et al., 2007).

Errors can arise when using this analysis method due to uneven dollar values for different types of work (Schwartzkopf, 1995). Also, since the calculations of this analysis method are based on the percentage of the project completed and the budget, this method might not always be trustworthy. The reasons for that can be explained as follows:

1. The percent complete method lacks detail and accuracy as the physical units of work completed method used in the previous quantifying methods.
2. Results of earned value analysis can doubtful if they rely on unreasonable budget (Ibbs et al. 2007).

2.2.1.4 Comparison Studies

Conditions such as change orders might affect all aspects of a project. In these cases of holistic delay or disruption, it is necessary for a contractor to prepare an estimate of productivity loss. As there are no unimpacted periods of work activity under claim, baseline productivity cannot be calculated with the previously addressed methods. Instead, as long as there is enough data, one of the following comparison methods is the recommended practice.

Comparison studies can be classified into two types:

1. Comparable work study: There are two sub-categories of this method. One type requires that the contractor estimate productivity loss during the impacted period through analysis of an exact or similar work activity from the same project that took place during an unimpacted or significantly least impacted period. This comparable activity is selected, and its productivity is calculated. A challenge in this form of work study is determining a period of time with an analogous or similar work activity. A second type of comparable work study is to select a period comparable work in the same project from a different contractor who completed work in an unimpacted period. This type of analysis is reserved only for conditions in which data on the same work before or after a known event is

impossible to secure and when, therefore, a measured mile analysis cannot be completed.

2. Comparable project study: When comparable work studies are not possible, then it is best to use a comparable project study. Similar work activities of the project under claim and a different, documented study are compared. To be effective, this study needs to select projects with similarities in all conditions: size, magnitude, location, weather, and labor conditions (AACE 2004).

2.2.2 Cost-Based Methods

When the project lacks documentation to support calculation of productivity loss using one of the project practice-based methods, one of the cost-based methods can be used.

2.2.2.1 Total Cost Method

In this method, the contractor claims to recover its entire man-hours overrun, which can be calculated by subtracting the actual man-hours from the estimated man-hours on a given scope of work.

According to Finke (1998b), there are four prerequisites the contractor has to fulfill before he can use this method:

1. The impracticability of proving actual losses directly.
2. The reasonableness of its bid.
3. The reasonableness of its actual costs.
4. Lack of responsibility for the added costs.

Total cost method is an imprecise method. Thus, it is not usually accepted in the courts and it is not recommended for claims (Serag, 2006).

Total cost method has two major weaknesses:

1. Work has to already be performed because this method relies on data regarding actual man-hour expenditures.
2. It generates only single lump-sum disruption quantification for the relevant scope of work; thus, it will not yield activity specific results (Finke 1998b).

2.2.2.2 Modified Total Cost Method

The modified total cost method is a good alternative to the total cost method; this is especially true in claims in which changes have had a major impact. This method examines individual cost codes rather than costs of the entire project (Serag 2006).

A strength of the modified total cost method is that it considers unreasonable estimations and/or contractor inefficiencies in its calculations (Nelson 2011).

2.2.3 Industry-Based Methods

This method includes specialty industry and general industry studies.

1. Specialty industry studies are about specific topics, e.g., acceleration, learning curve, overtime, weather, etc. These studies examine matters directly related to the causation of change orders and resultant claims.
2. General industry studies are based on industry-wide manuals and/or reports.

Industry-based analysis methods can be used when there is a lack of project documentation. Also, they can be used with another method to augment supportive evidence of damages. What industry-based analysis methods gain in speed of calculation and cost savings, they lose due to lack of contextual relevance and statistical measures about the exact project in question hence other methods are preferred (Nelson 2011).

2.3 Learning Curve

Learning is the process of gaining skill or knowledge through study, instruction, or experience. In the context of the construction industry, as a task is repeated on a frequent basis, labor productivity is improved, as fewer man-hours are needed to perform a specific task (Madachy, 2007).

The learning curve is a hyperbolic curve when using arithmetic, non-logarithmic graph as shown in figure 3 and is a straight line when graphed in logarithmic from shown in figure 4.

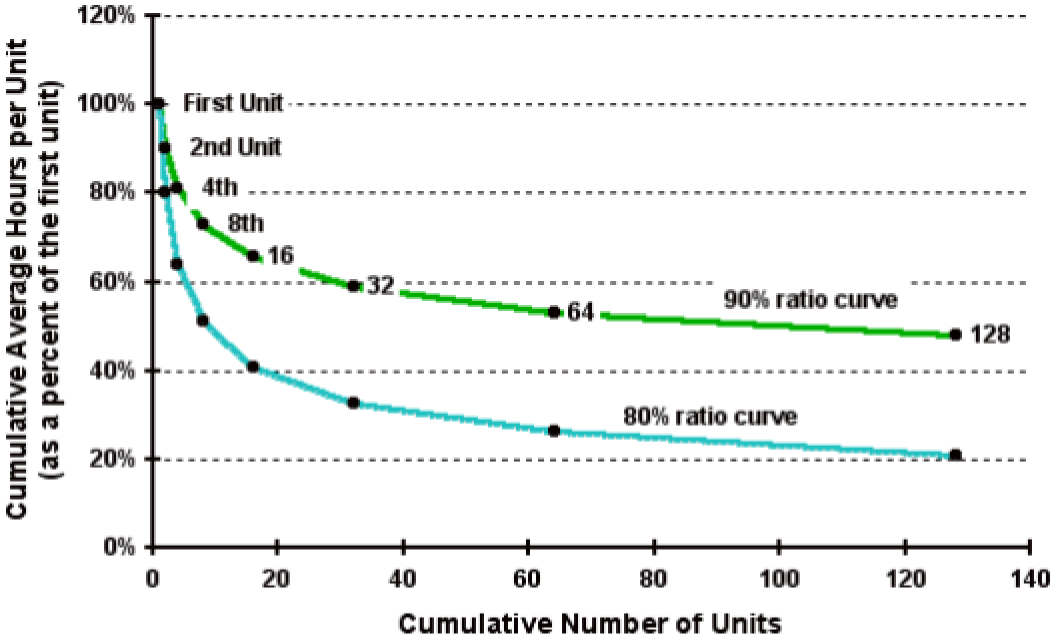


Figure 3: Learning Curve (Wideman, 1994)

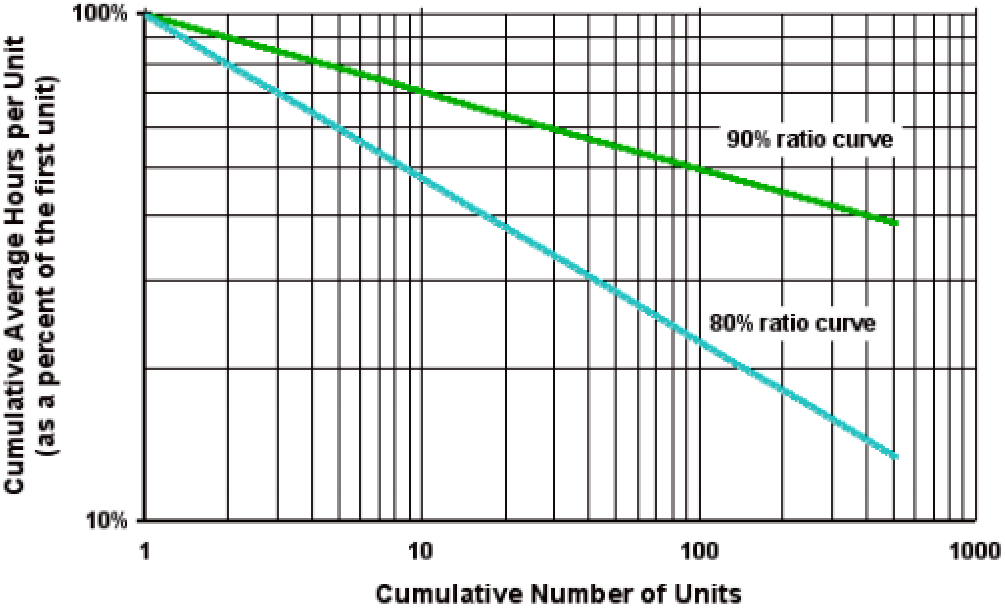


Figure 4: Straight Line Cumulative Average Learning Curve, Plotted Logarithmically (Wideman, 1994)

When expressed in mathematical formula, the man-hours needed to accomplish any particular unit in a repetitive series is (Schwartzkopf, 1995):

$Y = AX^b$

In logarithmic form:

$\text{Log } Y = \text{Log } A + b \text{ Log } X$

Where:

Y = labor hours per unit

X = Cumulative number of units

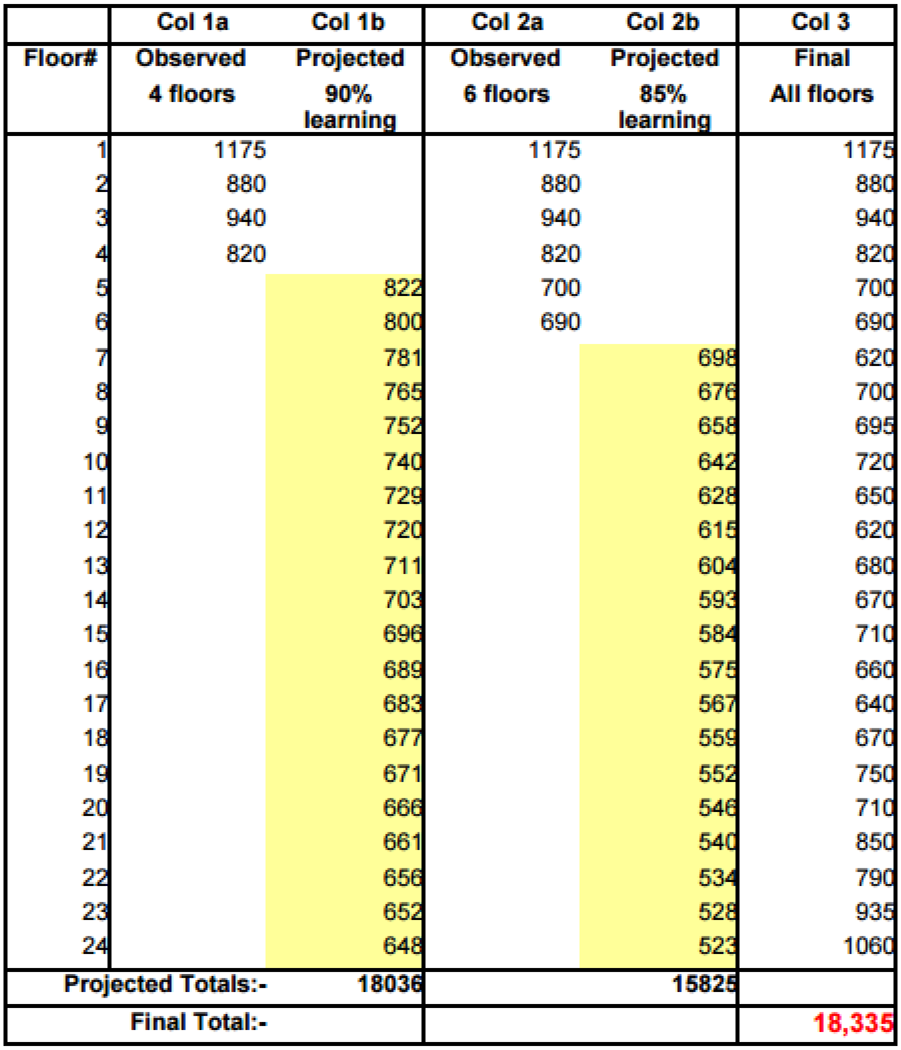
A = Labor hours to produce first unit (constant)

b = Slope of the line on log-log plot = $\log r/\log 2$.

r = the constant ration, known as the learning curve ratio**.**

In the context of the construction industry, where the work is repetitive and continuous in nature, learning curves can be used to estimate the number of labor hours needed to perform the n-th unit, as shown in Table 1. The cost as well as duration of the project can also be forecasted.

Table 1: High-Rise Repetitive Construction: Hypothetical Case (Wideman, 1994)



	Col 1a	Col 1b	Col 2a	Col 2b	Col 3
Floor#	Observed 4 floors	Projected 90% learning	Observed 6 floors	Projected 85% learning	Final All floors
1	1175		1175		1175
2	880		880		880
3	940		940		940
4	820		820		820
5		822	700		700
6		800	690		690
7		781		698	620
8		765		676	700
9		752		658	695
10		740		642	720
11		729		628	650
12		720		615	620
13		711		604	680
14		703		593	670
15		696		584	710
16		689		575	660
17		683		567	640
18		677		559	670
19		671		552	750
20		666		546	710
21		661		540	850
22		656		534	790
23		652		528	935
24		648		523	1060
Projected Totals:-		18036		15825	
Final Total:-					18,335

2.4 System Dynamics Modelling

2.4.1 What is System Dynamics

System dynamics (SD) analytical modeling is derived from Jay Forrester's work on "industrial dynamics at the Massachusetts Institute of Technology. System dynamics tends to qualitative and quantitative aspects of an identified problem. This aims to provide deeper understanding of the problem and its variables. Forrester used computer simulation to highlight the impact of time on the problem. He says, "System dynamics demonstrates how most of our own decision-making policies are the cause of the problems that we usually blame on others and how to identify policies we can follow to improve our situation".

In the context of project management, system dynamics approach a holistic view of the process of project management and reveal how most of project management decision-making policies are the cause of the problems. Emphases is on the feedback processes that take place within the project system in an attempt to improve the situation and making the correct decision as shown in Figure 5.

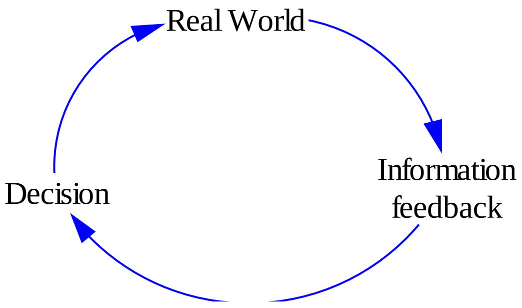


Figure 5: Learning is a Feedback Process, Feedback View (Sterman,2000)

In fact, the interactions (feedbacks) among the system components are the cause of the system complex behaviors, not the complexity of the system components themselves. Feedback loops give rise to nonlinear behavior, even if all constitutive causal relationships are linear.

Figure 6 demonstrates the cyclical nature of two or more elements which produce a feedback loop. Causality propels the cycle, so no matter which element is the starting point, all elements will contribute to the return to the starting point. For instance, in this figure, variable A will initiate a change in variable B, which will then initiate a change in variable C. Finally, to complete one cycle, a change in variable C will then create a change in variable A, and thus the loop perpetuates. This supports the understanding that a change in variable A will indirectly influence variable A and indeed that any variable in a loop will influence itself.

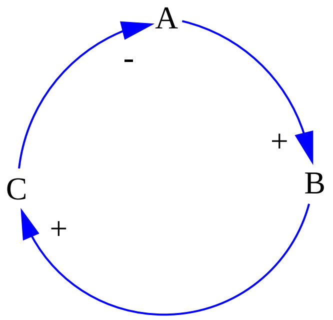


Figure 6: Causal Links and Feedback Loop (Pruyt, 2013)

All dynamics arise in any system are resulted from the interaction of just two types of feedback loops:

1. Positive (self-reinforcing) feedback loops, Figure 7, which tend to reinforce or amplify whatever is happening in the system.

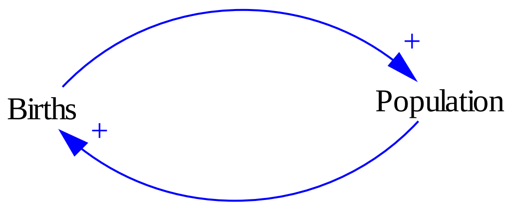


Figure 7: Positive Feedback Loop

2. Negative (self-correcting) feedback loops, Figure 8, generate balancing behavior in the system. They are sources of stability; they counteract and oppose change.

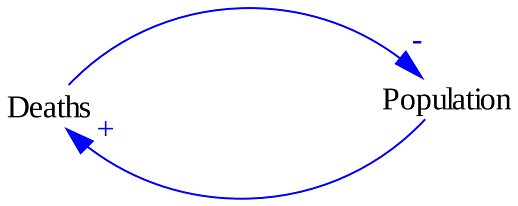


Figure 8: Negative Feedback Loop

To build a system dynamics model, there are eight steps:

1. Become acquainted with the problem:

In this step, the modeler must be familiar with the problem, looking at it from every different angle, becoming familiar with the policies proposed to fix or solve the problem, and the most important thing is asking himself whether system dynamics can help in understanding and solving the problem.

2. Dynamic problem definition:

The modeler needs to identify and articulate the issue to be addressed, check if there really a dynamic problem, and define the reference mode of the problem under study. If the reference mode cannot be drawn, this might imply the problem under study is not dynamic.

Reference mode can be defined as a set of graphs and other descriptive data showing the development of the problem over time; they are called reference modes because the modeler refers back to them throughout the modeling process since they are useful in formulating dynamic hypotheses. Figure 9 depicts common modes of behavior in dynamic systems.

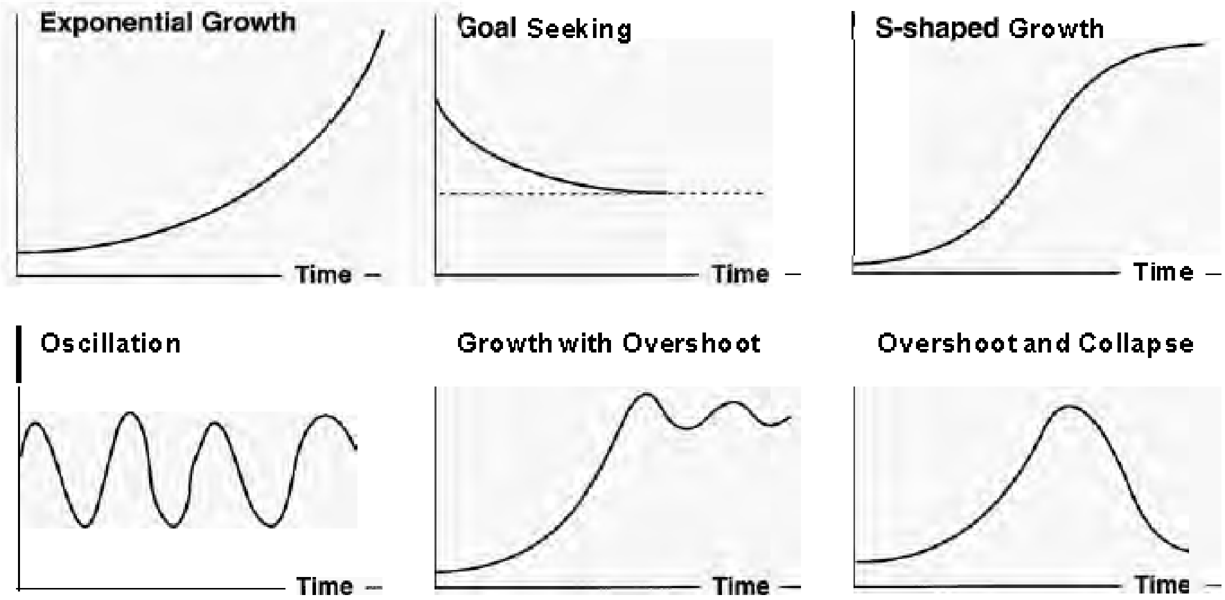


Figure 9: Common Modes of Behavior in Dynamic Systems (Sterman,2000)

3. Draw the causal loop diagram

Drawing the causal loop, Figure 10, helps in better conceptualizing the issue through listing all variables that play a potential role in the creation of the dynamics of concern, seeing the key loops in the model, and identifying the number of feedback loops that are related to the reference mode.

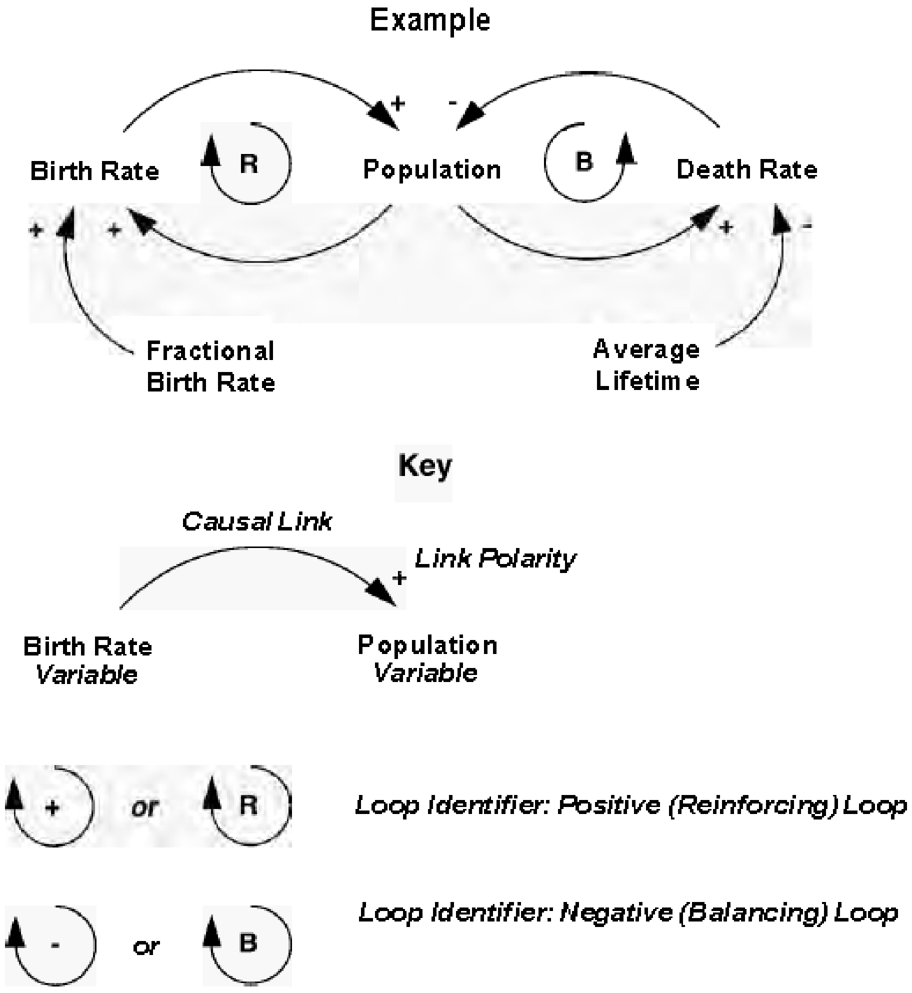


Figure 10: Causal Loop Diagram Notation (Sterman, 2000)

4. Construct the stock-and-flow diagram

After drawing the causal loop diagram, a stock-flow diagram can be built, and the underlying mathematical equations between the variables which make up the structure of the model can be added. Stocks are the representations of level variables, such as products, and flows are rates, such as products produced per day. So the stocks allow decisions to be made, and flows are changed in the system under study. Figure 11 shows a representation of a stock and flow diagram. Usually the start is with the stocks. The modeler then adds the flows and finally adds the converters to explain the flows. In this stage, the modeler needs to be sure to specify units for each variable and check for unit consistency.

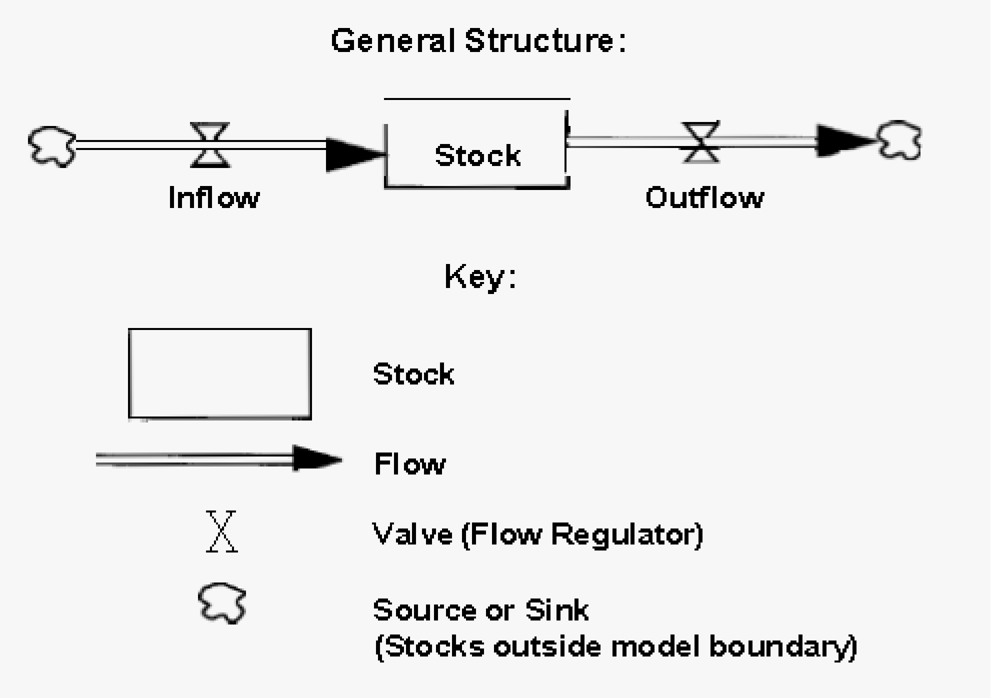


Figure 11: Stock and Flow Diagramming Notation (Sterman,2000)

5. Estimate the parameters

The modeler can take advantage of all sources of information at his disposal to estimate the model parameters. Such sources of information include the following: physical laws, controlled experiments, uncontrolled experiments, statistical information, case studies, expert judgment, stakeholder knowledge, and personal intuition.

6. Run the model to get the reference mode

This will be the first opportunity for the modeler to test the model and to check if the simulation result matches the reference mode of the problem under study. Many iterations might be needed to reach this point. For each iteration, the modeler needs to look at the variable used until he matches the reference mode.

7. Model validity and sensitivity analysis

SD validation is actually all about building confidence in the usefulness of models for the purpose at hand (Sterman, 2000). Valid models/modeling are therefore models/modeling that are believed to be useful for their intended purpose; several tests were proposed to assess the model validity as will be seen in Chapter 3. To check the sensitivity of the model results to changes in the parameters values, the modeler needs to run the model several times with variations in parameter values. After each run, he needs to check if he gets the reference model. If so, this means that he built a robust model that generates the same general pattern despite great uncertainty in parameter values.

8. Testing the impact of policies

After the modeler makes sure that he built a robust mathematical model, the model now can be used to design and evaluate structural policies to address the issue under study.

According to Sterman (1992), the main strengths of using system dynamics can be summarized as follows:

1. It is suitable for representing extremely complex systems which consist of multiple interdependent components. The reason is this method captures interdependencies so that the causal impact of changes may be traced throughout the system.

2. System dynamics, compared with all the formal modeling techniques, is the most advanced regarding proper representation, analysis, and explanation of the dynamics of complex technical and managerial systems.
3. System dynamics involves multiple feedback processes, where its System dynamics involves multiple feedback processes which aid in providing knowledge about long-term system behavior. For this reason, it is the method of choice in modeling disruption and delay since in this type of problem it is vital that the modelling approach is capable of modeling feedback.
4. More than any other formal modeling technique, a system dynamics model describes nonlinear relationships and stresses the importance of nonlinearities in model formulation.
5. System dynamics has the capability of using several sources of information since it merges two individual aspects: quantitative and qualitative. Therefore, it has the potentiality to increase the recognition of an identified problem. Moreover, this model helps to improve the understanding of the problem's foundation and the existing relationship between pertinent variables, in order to form the guidelines for decision rules, organizational structures, goals, and other administrative dimensions of the system.
6. System Dynamics is able to model external events, managerial actions taken because of these events and the consequences of these actions.

2.4.2 The Use of System Dynamics in Construction Claims and Project Management

System dynamics, which is essentially deterministic, has been applied in many different fields of study, including project management, defense analysis, and health care. It has been used in litigation to explain complex effects, such as delay and disruption. System dynamics is useful to deal with the dynamics' complexity created by the interdependencies, feedbacks, time delays, and nonlinearities in large scale projects.

There are limited publications that address the use of system dynamics modeling in disruption and delay claims.

Cooper (1980) led the development and application of a computer simulation model to resolve a $500 million Ingalls shipbuilding claim against the US Navy. Using a system dynamics model, the analyst diagnosed the causes of cost and schedule overruns on two multibillion dollar shipbuilding programs and quantified the costs of disruption resulting from delays and design changes under the Navy's responsibility. In an out-of-court agreement, the Navy consented to pay $447 million of the claim; the SD model was the source for between $200-300 million of the settlement.

After the settlement, Ingalls shipbuilding extended the model to aid strategic decisions making in managing its shipyard operations. Managers consider it as a valuable tool to appraise the outcomes of alternative policies in bidding and marketing, contract management, program work schedule, resources management, and cost anticipation. Additionally, the system dynamics model proved to be a required technique to avoid contractor's claims.

A case study was undertaken by Williams et al. (1995) to show the effects of delays and in-development product enhancements on manufacturing development project, which are frequently highly paralleled and time-constrained. The project consisted of the design and short-run manufacture of a specialized vehicle, involving considerable leading-edge development. The project was very time constrained, and there was a highly parallel design stage, as well as a degree of concurrent engineering, with vehicle manufacture starting before the end of the design stage.

The majority of the claims regarded product changes requested by the purchaser. The remaining claims were due to delay and disruption triggered by the events from the direct claim, added to others caused by approval of documentation, for instance.

Cognitive mapping was used by the analysts to reveal key vicious circles, particularly the positive relationship between cross-relations, between concurrent activities, and activity duration, which under time constraints caused activities to become more parallel and, hence, increased the cross-relations as shown in Figure 12.

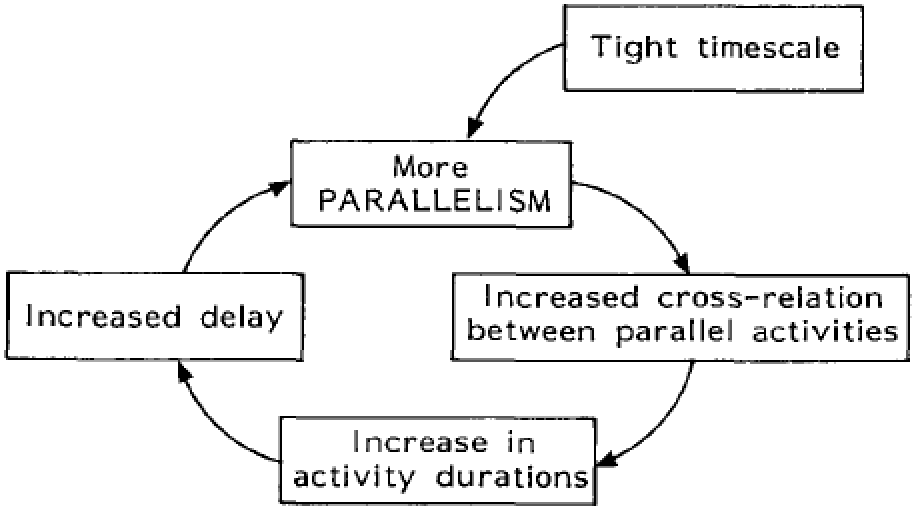


Figure 12: Key Feedback Loop (Williams et al., 1995)

To quantify feedback effects, a system dynamics was used to model the vicious circles and explain the level of delay and disruption faced in the project. It was noted that the totality of the effects was wider than the sum of the individual effects, since they added up to one another.

Ackerman et al. (1997) highlight the importance of mixing more than one qualitative and quantitative modeling method to improve the quality of the claim. The authors participated in preparing the claim case for one of the megaprojects associated with the construction of the channel tunnel link project between England and France. For the costs of disruption and delays, they prepared a sustainable and quantified model of the impact of “disruption and delay” upon the megaproject.

The major causes of disruption and delay were: 1) the extended and additional requirements, particularly with respect to safety, that directly increased design and manufacturing time, and also had extensive ramifications for other parts of the project. 2) The approval of design documents was often delayed.

The client, contractor, intended to use the model to support a claim for extra costs attributable to the actions of their customers that disrupted work on the project. The client expected that the analyst will rely on computer simulation using system dynamics for two reasons: 1) it was successfully used in similar cases in the United States. 2) The client’s lawyers believed that a system dynamics modeling approach would be more transparent to a judge than discrete-event simulation modeling.

To construct the system dynamics model, they needed to understand how the different parts of the project affected each other, and what sustainable data existed that would enable them to quantify the model in a valid manner.

To do this, they 1) used “cognitive mapping” to model each of the individual views of the many senior project managers and wove them into a single qualitative model, group map, using a software tool, COPE. 2) Constructed an intermediate model, Influence diagram, which showed the relationship between variables by extracting primary feedback loops and variables (exogenous and endogenous) from the group map. 3) Built a system dynamics model based on the resulting influence diagram, and the group map was used to clarify the precise meaning of elements in the system dynamics model. The overall mixed approach used is shown in Figure 13.

The SD model had to be built in such a way that it could respond to a large number of possible scenarios for agreed liability in court. The model was expected to demonstrate the same general patterns of behavior as the real system, and the model had only to be complex enough to meet this objective.

They found that the largest number of feedback loops occurred in the design phase of the megaproject, while others occurred in the “methods engineering” (pre-manufacture planning), manufacturing, and testing-and-commissioning stages.

After the analyst developed the SD model that provided the basis for a disruption-and-delay claim, it became relatively opaque for two reasons. 1) The size of the SD model, as it incorporated around 350 variables making it difficult to understand, especially for those not familiar with the project or the underlying process. 2) The software package, Stella, they used to build the model can look extremely chaotic, unless the labels attached to the elements of the model are kept short, but this brevity results in obscure naming conventions that occasionally confuse even the members of the modeling team. To overcome this problem, they used the group map with its fuller descriptions and elaborated material to illustrate the meaning and context of any of the variables. So, by cycling between different modeling methods, which can be related, they achieved benefits that cannot be attained through a staged process that does not permit continuous interaction.

Soft and hard modeling methods can be used to complement one another.

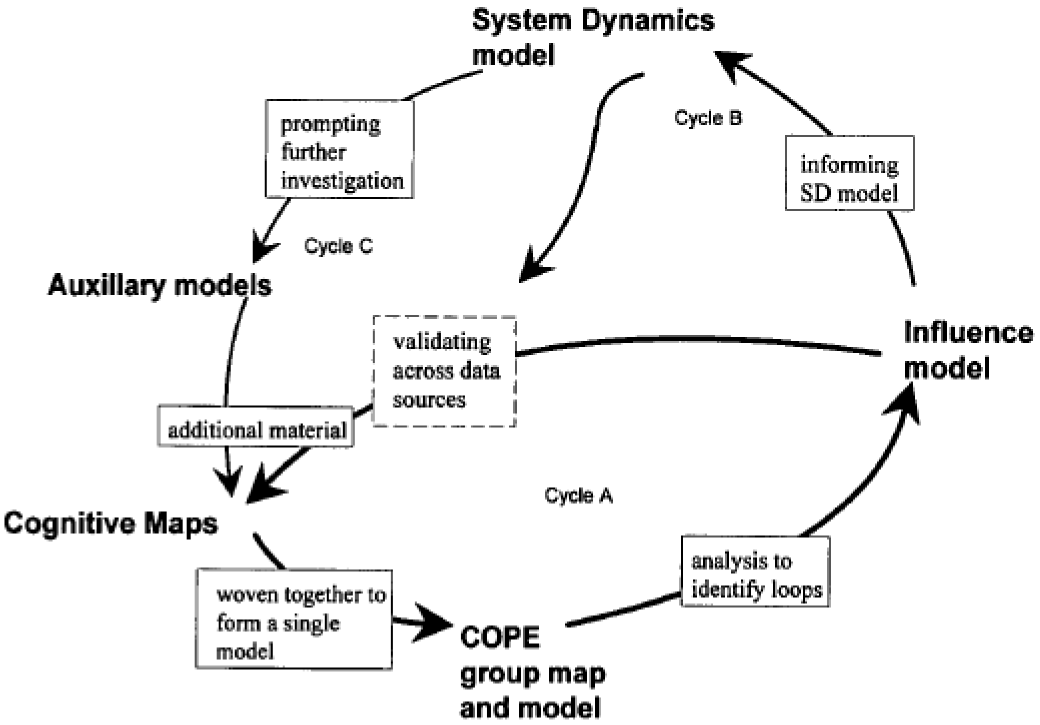


Figure 13: Cyclical Process Used in Modeling Delay and Disruption (Ackerman et al., 1997)

Williams et al. (2003) presented a systematic approach using causal loop diagrams and system dynamics to format delay and disruption claims documents. According to Williams et al. (2003), claim documents must include the following four parts:

1. Identify the disruptive triggers for the case under study.
2. Build qualitative model for the case, depending on the interacting effects of the triggers identified in part 1.
3. Transformation of the qualitative model in part 2 into a computer simulation model, i.e. a "quantitative model."
4. Explore different scenarios using the quantitative part of the claim document.

Thus, by following the proposed approach, three main elements required in any delay and disruption claims will be available in the claim document: namely, proof of causality, proof of accountability, and a quantum for the claim.

Howick (2003) explored the question of whethersystem dynamics is actually a suitable modeling approach to take when analyzing disruption and delay (D&D) for litigation. She explored this question by considering whether SD is capable of meeting the modeling purposes of analyzing D&D for litigation. The investigations have shown the following:

- It is imperative that SD models external events and their outcomes, such as D&D.
- SD models might not be sufficiently clear to model D&D if taken out of context. Nevertheless, when combined with qualitative models, such as cause maps and influence diagrams, SD models provide a translucent link between the events and outcomes. As a result, SD can be a suitable tool to verify causality and responsibility in the analysis of D&D for litigation.

- In the attempt to capture detailed operational issues of project management, the SD models can show deficiencies. Nonetheless, when combined with other tools, it constitutes a great support to deal with the drawbacks of using SD to analyze D&D for litigation.
- The litigation process comprises a wide variety of audiences, which may represent a considerable number of challenges for the modeler. Above all, it is worth mentioning the issues with the level of understanding for distinct audiences about the SD model.

The process above mentioned highlights the importance of understanding the limitations of SD use, so the modeler is prepared to advise about the suitability of SD as a modeling approach in supporting specific claims for compensation.

Howick (2005) discussed the nature of reactions to the System Dynamics model used to corroborate claims in litigation audiences discussing compensation for time and cost overruns on large and complex projects. In such situations, the process involves many different parties meaning that the model is exposed to a variety of audiences: lawyers, members from the plaintiff’s and defendant’s organizations, expert modelers, arbitrators and judges. Each of the audiences will have different objectives in mind when examining the model. A litigation process, constitutes a challenge for the modeler, who should build a tool capable of satisfying a number of different needs from assorted audiences. The challenge ranges from being sufficiently detailed to pass the scrutiny of a modeling expert, to being easily understood by a judge who may have no modelling expertise. It requires from the modeler the understanding on how the different audiences will react to the models. When using SD models to support a claim for compensation, the model can only prove successful if its audience is convinced that it adequately represents reality; otherwise, it will be rejected.

Rodrigues and Bowers (1995) proposed a holistic project management methodology which would incorporate traditional and system dynamics approaches. To do so, they discussed the features and purposes of both approaches.

The focus of traditional project management has been slanted inappropriately on the project work. Expansion of the scope to include more variables and interactions is important. System dynamics developed as an alternative which would address more factors in the analysis of a project.

The objectives of traditional project management and of system dynamics modeling is distinct, so they are complementary. While traditional models do not address complex strategic issues well, system dynamics modeling does and therefore is a supportive corollary to traditional methods. SD analysis can provide insights that traditional modeling would overlook. Meanwhile, the complexity of SD modeling hampers an understanding of day-to-day details in the project management. In this area of concern, traditional methods are stronger than SD methods.

Rodrigues and Bowers (1995) hence suggested that integrating the two methodologies would give more accurate analysis. This is especially true because of the different perspectives on estimating in each of the two forms.

Chapman (1998) conducted a research that focused on the impact of changes of key project personnel during the design stage of a construction project on design production. A system dynamics model of the design process is proposed and explores the causes behind the loss in design productivity resulting from staff changes. Figure 14 illustrates the feedback loop of loss of staff. Based on the model, the author explained the resulting productivity loss from staff changes by the following reasons:"

1. New staff hired to an ongoing project has to go through a learning curve to become familiar with the project details.
2. New staff hired to an ongoing project takes time to reach the level of work rate of the departed and existing team members.
3. The work rate of the existing team members reduces because they have to break off from their normal duties to train new team members or assist them to become familiar with the project.
4. Voluminous and complex nature of project information makes it difficult to be passed in totality from one individual to the next, even if the new team member has a handover period and/or a debriefing from the departing team member.
5. A project may commence with a tight time constraint with little or no tolerance in staff costs, if the project sponsor has set the completion date as the highest priority. In such situations, schedule pressure may place a strain on staff morale, and if staff losses occur, the design organization has considerable difficulty in recovering." (Chapman, 1998)

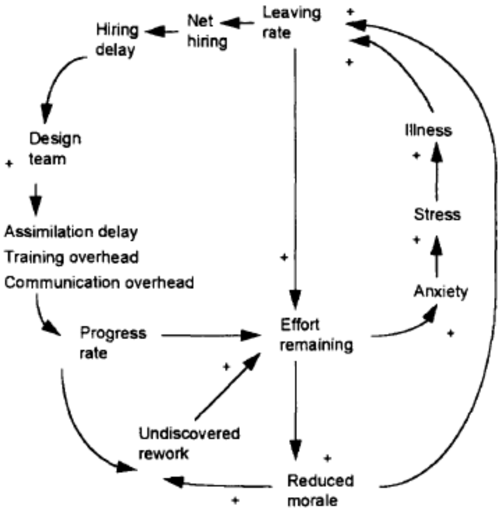


Figure 14: Feedback Loop of Loss of Staff (Chapman, 1998)

Howick and Eden (2001) investigated disruption and delay that resulted from client demand for earlier project delivery in an attempt to help managers and contractors in deciding whether to go for incentives for early delivery or not. To accomplish this task, a system dynamics model, based upon a large model, was developed to represent the complexity of a claim for disruption and delay in relation to a specific mega-project was used. The impact of compressed delivery date on disruption and delay was assessed in relation to two specific and typical options: namely, pressure and overtime.

The findings show that employing overtime and/or managerial pressure to a compressed delivery date can have negative side effects to an otherwise well-planned project. Increased fatigue and decreased morale will likely harm both productivity and quality of work. This will then loop and cause further disruption and delay. This again would cycle because the delay would cause greater strain on the system.

Therefore, managers need to use caution when choosing acceleration methods of overtime or pressure. The ramifications can be more costly than originally considered, and, once the loop begins, the trajectory is difficulty to repair. Analysis is crucial to consider D&D and the advantages and disadvantages of potential incentives and acceleration. It can be concluded that bonuses would need to be significant if the advantages are to outweigh the disadvantages of utilizing these techniques.

Love et al. (2002) used system dynamics methodology to study and investigate the impact of change and rework on project management system performance, which, being a dynamic system, is subjected to both attended and unattended dynamics. The authors looked at how specific dynamics (e.g., purchaser changes, design freezing, and information management, building regulations, consultant fees, communications, coordination and integration of the project team, and training and skill development) can help or hinder a construction project management system. They used both a case study and SD modeling to reveal that there are ways to “maximize the effect of positive dynamics, and minimize the effect of negative ones.”

The work of Love et al. (2002) emphasizes the usefulness of monitoring project dynamics and developing appropriate responses efficiently to changes within the system of the project. A formal method to prepare responses to unattended dynamics is seen as a needed solution to the problems revealed in the case studies. Without such a method, problems will persist; contractors and clients alike will be dissatisfied.

Cooper et al. (2004) proposed the use of heuristics by project managers and estimators as a way to enable them to better estimate disruption impacts. The heuristics proposed by the authors is based on a simulation of system dynamic model of a representative design build project. Using system dynamic modeling approach, they developed a model that represents the mechanisms by which project disruption occurs, as shown in Figure 15. They started the model with typical values for (a) the potential strength of productivity affecting factors, and (b) the relative scheduling of design and built activity.

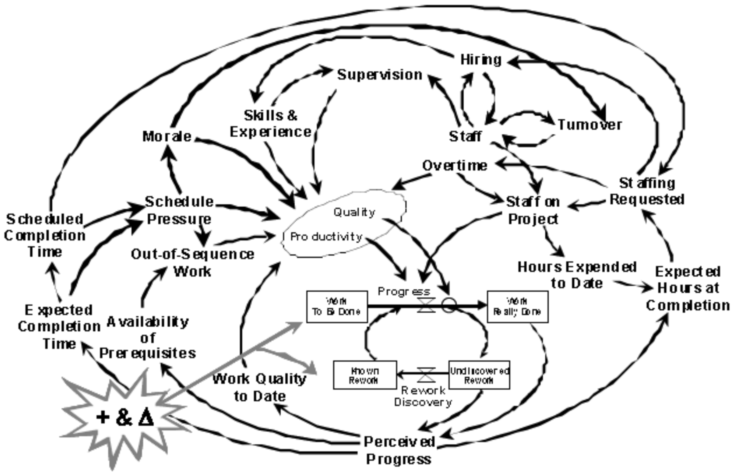


Figure 15: Model Used by Cooper et al. (2004)

In order to generate the heuristic guidelines that enable project managers to customize an estimate of disruption impacts to their project conditions, they tested hundreds of variations and combinations of different numerical values of four key factors:

- Magnitude of changes
- Timing of changes
- Build overlap with design schedule
- Build schedule duration

Eden et al. (2005) compared two approaches: the “measured mile” and system dynamics simulation modeling that are often used in the forensic analysis of failed projects to analyze the reasons behind project cost overruns.

The comparison reveals the following problems associated with measured mile approach:

- It supposes the presence of an unimpacted beginning to the project;
- It assumes that the entire difference between observed values and predictions is claimable though, in reality, the contractor might be liable for some or all of the difference;
- It lacks causal logic about the extra work that might be precipitated by disruption and delay;
- It relies on a linear extrapolation of the measure mile to estimate future progress.

On the other hand, the systems dynamics modeling approach:

- Shows causality through the use of causal loop diagrams in building the simulation model;
- Permits statistical validation of causal logic between the modeling and actual data at any desired point in the project;
- Directly addresses both constructive acceleration and management’s actions made in effort of project compression;
- Accounts for disruption and delay for which the contractor is liable;
- Includes nonlinearities which emerge in real projects.

The study concludes that despite the popularity of the measured mile approach in litigation, its results can be untrustworthy in cases where disruptions and delays are a substantial part of the explanation for project late delivery and costs overruns.

Ibbs et al. (2007) created a causal loop diagram that can be used when changes happened in a construction project to clarify the interactions of changes, disruptions, loss of productivity, and the causing party.

Alvanchi et al. (2012) developed a system dynamics model that could be used by the work manager to estimate, with a reasonable degree of precision, the expected productivity in many different construction jobs under different arrangements of a working hour.

Ibbs and Liu (2005) describe how to create a system dynamic model and show how it can be used to show the link between acceleration, disruption and delay, and productivity loss with a simple example, as shown in Figure 16. The values derived in the analysis are strictly hypothetical. In the paper, they mentioned the importance of accurately estimating the coefficient that quantified the correlation between two adjacent schedule activities, as well as the sensitivity of the coefficients.

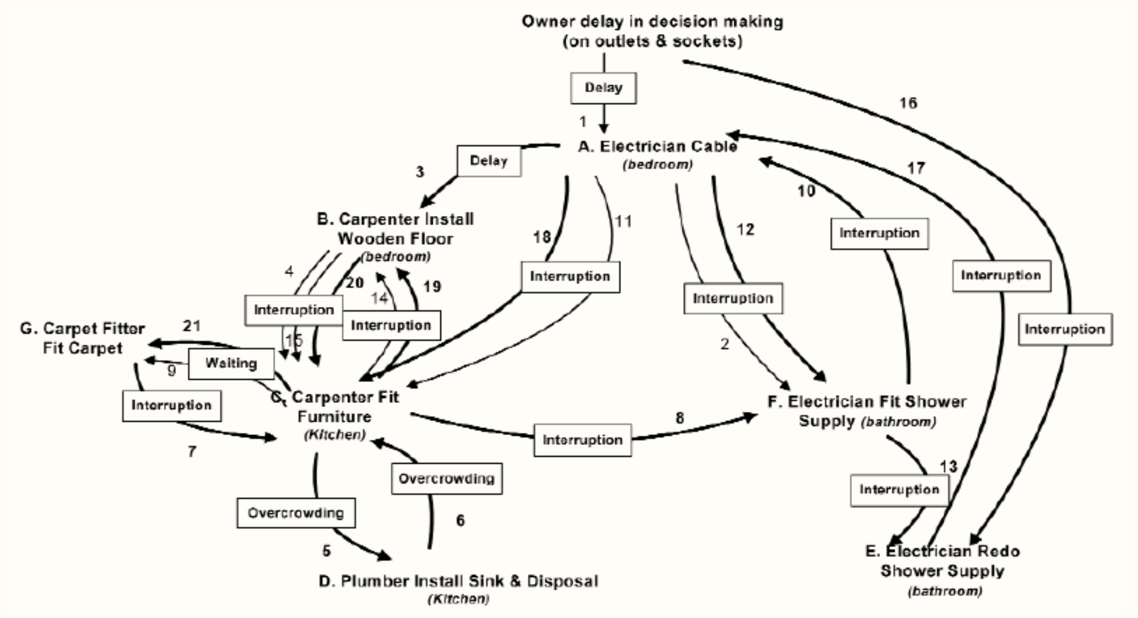


Figure 16: The System Dynamic Model for Disruption and Delay Analysis (Ibbs and Liu, 2005)

Love et al. (2011) studied the dynamics of rework and the issues related to their happening in complex hydrocarbon (oil and gas) projects. They built a general causal loop diagram that could be used by the managers to provide them with a better understanding of the interrelationships between factors that contributed to rework; thus, rework prevention might be in the future projects.

Boateng et al. (2012) used system dynamics modeling approach to derive a hypothesized model of social and environmental risk. The cited model, assembled in conformity with British Standards for risk management, aimed at creating a universal tool to manage risks in megaproject development. It was organized in five steps: risk management planning, risk identification, qualitative and quantitative risk analysis, risk response planning, and risk monitoring and control.

Considering that design errors are widespread, most design and construction companies fail to measure the errors made by them, which leads to a lower familiarity with the procedures that undermine project performance. Han et al. (2013) developed a system dynamics model to capture the dynamics of design errors which lead to rework and/or design changes. They systematically assessed negative impacts, such as schedule delays and cost overruns in design and construction projects. They systematically assessed negative impacts, such as schedule delays and cost overruns in design and construction projects, with the understanding that these impacts are reciprocal and looped in relationship.

Han et al. (2013) applied the model to a university building project and revealed that design errors are a main contribution to significant schedule delays. This is in spite of the efforts of construction managers to make timely deliveries of projects through methods of acceleration. Their analysis confirmed that design errors significantly increase pressure when they are discovered during the construction phase.

Additionally, the case study revealed that schedule pressure spreads the negative impact of design errors to many other construction activities, even including those not directly impacted by the errors.

The case study proved that construction managers tend to be optimistically biased in estimating the recovery of delayed schedules, and it results in underestimation of the negative impacts of hidden design errors and schedule pressure. The developed model was proven to be a more objective and comprehensive tool to assess the impact of hidden errors and schedule pressure. To conclude, the case study confirmed that the model developed could assess more accurately the often underestimated negative impact of design errors. Therefore, the developed model can help managers to understand clearly the dynamics of design errors, while recovering delayed schedule more effectively.

Nasirzadeh and Nojedehi (2013) developed a System Dynamic model to represent the effect of different inter-related influencing factors that affect labor productivity, which then can be used by the project manager to find the origin of productivity loss. Therefore, the project manager can assess the effect of different solutions to improve labor productivity.

To construct the model, the authors first identified the factors that affect labor productivity. Then, by using the cause and effect feedback loops, they constructed the qualitative model. Finally, the mathematical equations that defined the inter-relationships that existed between different factors were determined and the quantitative model was built. They also conducted sensitivity analysis to assess the impact of different factors on labor productivity.

The developed model was employed in a housing project to evaluate its performance. The case example consisted of 600 m^3 of poured concrete. Although the proposed model might provide the decision makers with valuable information, the authors mentioned the need to use more sample projects to validate the outputs of the model.

CHAPTER 3: METHODOLOGY

3.1 Background

The objective of this study is to quantify the effect of change orders on labor productivity in road construction projects using System Dynamics modeling approach and to compare the results obtained with the ones obtained through measured mile analysis, which is considered the most acceptable productivity loss quantification method in litigation. The study can be applied to construction projects that faced change orders and, as a result of these changes, the contractor's performance was affected. The proposed model can be used to determine the main sources that result in labor productivity loss on a certain type of task.

3.2 Data Collection

The first and most important step is to determine the projects' criteria under study. The key projects' criteria are:

- Projects Type: Heavy Construction (Road Projects).
- Owner Type: Public Owners.
- Projects are 100% completed.
- Projects encountered change orders.
- Data Source: Daily Work Reports, Contract Documents, Changes & Inspection Reports.

3.3 Data Preparation

After data is collected from the projects, the next step is to prepare the data to start building the model.

Several reasons are behind the issuance of change orders in roadway construction projects; such reasons include design errors, unforeseen site condition, and plan modifications where the contractor encountered productivity loss. In these cases, the contractor tries to pass the full blame of productivity loss due to change orders to the owner.

There are several factors referred to the contractor part in addition to the change orders issuance can affect labor productivity due to changes such as accident on site by the contractor's resources, and material problems. Through the data extracting and preparation stage, it observed that the contractor was working inefficiently even prior to the issuance of change orders. This study will focus on measuring the loss of the productivity for road projects. The productivity measure will be expressed as man-hours per unit installed.

The initial contractor productivity for the particular type of work under study that will used to start the model will be measured as the best productivity achieved by the contractor along the work period. This value is the same as to the measured mile approach as discussed in Chapter 2.

Labor productivity levels for both impacted and unimpacted periods are derived from project records as daily work reports which lists the contractors who are present, and for how long, for a particular day and for a particular contract, man-hours, and how many persons worked, and the quantities of items installed on a job on a given day. It was avoided to use the bid hours since it might not reflect the actual productivity rates on site. This comparison is considered fair for the contractor and owner since it relies on data obtained during actual contract performance.

The level of aggregation of the data used in the model stock and flow is appropriate in terms of what was being measured: man-hours, productivity, and work really done over a period of time. In construction projects, work is performed on a daily basis, while the performance reviews and work inspection is performed on a monthly basis. Based on that, the data was configured to show results on a weekly basis, the man- hours are summed up weekly while the quantities installed were divided to a weekly performance instead of monthly one.

The researcher used Florida Automated Weather Network, FAWN, website and from the archived weather data he reported the temperature values during the project periods based on the project site and the particular days of work.

3.4 Problem Identification

Change orders often arise in most construction projects, and these changes may cause loss of labor productivity. Consequently, it will lead to increase in the man-hours needed to complete the project scope, resulting in increase of the project’s cost. However, the relationship between change orders and labor productivity is not well understood. This research emphasizes the analysis of the impact of change orders on labor productivity, quantifying productivity loss and linking this loss to their causes.

3.5 Reference Mode

Work really done over the project period is selected as the reference mode to illustrate the multi-dimensional patterns of behavior for this system arising through the nonlinear interaction of the subsystems with one another. It also used in the validation of the system dynamics model.

Actual quantities installed are commonly observed and an easily recorded reference mode of behavior as shown in Figure 17. Over the project time, the mode of behavior in the dynamic system is goal seeking. The system generates goal-seeking trend because of the interaction of the positive and negative loops that are non-linear within its subsystems.

The problem is dynamic and complex because the reference mode varies over time, is affected by many factors in the system, and is affected by the feedback loops in the system. Some of the factors that affect the reference mode are the amount and timing of change orders, weekly worked hours, number of labors on site, labors productivity, overtime hours, rework, fatigue, labor crowding, temperature, etc.

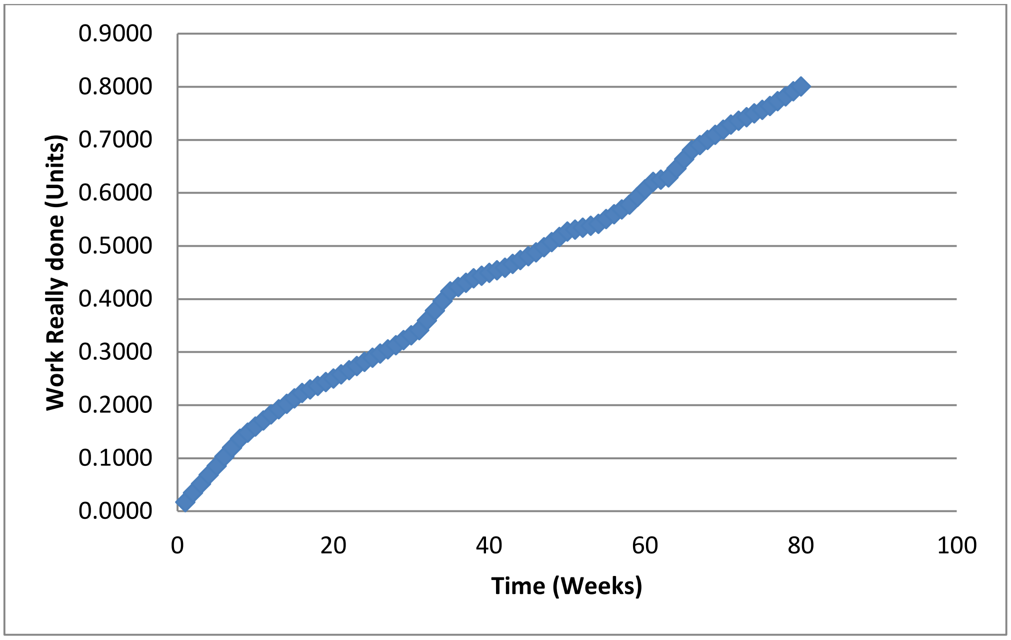


Figure 17: Work Really Done Trend Over Project Time

3.6 Identification of Parameters

The main parameters contributing to our problem were identified before the construction of causal loop diagram (CLD). The model boundary that is showing up the parameters used in the system dynamic model and used to study the subsystem’s feedbacks are listed in Table 1. This table summarizes the scope of the model by presenting the most important endogenous variables which are the dynamic variables involved in the feedback loops of the system so they enable us to explore the patterns of behavior created by the rule among them and discover how the behavior might change if those rules are altered. The model also contained several exogenous variables whose values are not directly affected by the system. The table also listed the excluded variables which intentionally omitted during the model building in order to provide the user with an important notation as whether this model is appropriate for their purpose or not

Table 2: Model Boundary – Endogenous and Exogenous Variables

Endogenous variables	Exogenous variables	Excluded variables
Available time	Average daily workers on site	Resource availability
Desired completion rate	Baseline productivity	Safety on site
Desired workforce	Fatigue onset time	
Effect of learning on productivity	Labors on site	
Fatigue	Learning rate	
Man-hours	Maximum workweek	
Maximum completion rate	Scope change	
Productivity	Standard workweek	
Remaining work	Target delivery time	

Endogenous variables	Exogenous variables	Excluded variables
Scheduled overtime	Temperature	
Work being done	Time for inspection and discovered error	
Work really done	Work to do	
Workweek		

Table 3: Model Boundary- Overview of Variables

Parameter	Description	Type	Units
Available time	The remaining time budget before reaching project deadline	Endogenous	Weeks
Average daily workers on site	Number of laborers on site	Exogenous	Laborers
Baseline productivity	Contractor best productivity	Exogenous	Labor* Hours/unit
Desired completion rate	Desired work rate to deliver project on time	Endogenous	Units/week
Desired workforce	Desired number of laborers to deliver project on time	Endogenous	Laborers
Fatigue	Workers' physical fatigue	Endogenous	-
Labors on site	Number of available laborers on site	Exogenous	Laborers
Man-hours	man-hours spent each week	Endogenous	Labor* Hours /week

Parameter	Description	Type	Units
Maximum completion rate	Work To Do/minimum delivery delay	Endogenous	Units/week
Maximum workweek	Maximum hours/week, depends on the organization’s policy	Exogenous	Hours/week
Productivity	Actual labor hours spent to produce one unit	Endogenous	Labor*hours/unit
Rework due to changes	Amount of units needed rework due to change order	Endogenous	Units/week
Rework due to contractor’s errors	Amount of units needed rework due to contractor’s error	Endogenous	Units/week
Scheduled overtime	Scheduled overtime hours per week to deliver project on time	Endogenous	Hours/week
Scope change	Amount of added/deleted units from the project scope	Exogenous	Units/week
Time for inspection and discovered error	Time needed to inspect work and discover errors	Exogenous	Weeks
Work being done	Rate of the work execution over time	Endogenous	Units/week
Work really done	Total number of accomplished units	Endogenous	Units
Work to do	Total number of units not accomplished yet	Exogenous	Units
Workweek	Adjusted standard workweek by the effect of overtime	Endogenous	Hours/week

3.7 System Conceptualization

After the determining the parameters used in modeling, the causal loop diagram (CLD) is constructed to better understanding of the system structure. Based on cause-effect relationships among parameters, the causal (feedback) loops are determined to outline the relationships among system variables which are not necessarily linear but circular chains of cause and effect, as shown in Figure 18, which displays five causal loops, three of them balancing loops, and the others reinforcing loops. An explanation of the defined loops is presented below. A positive sign indicates reinforcing impact, and a negative sign indicates balancing impact.

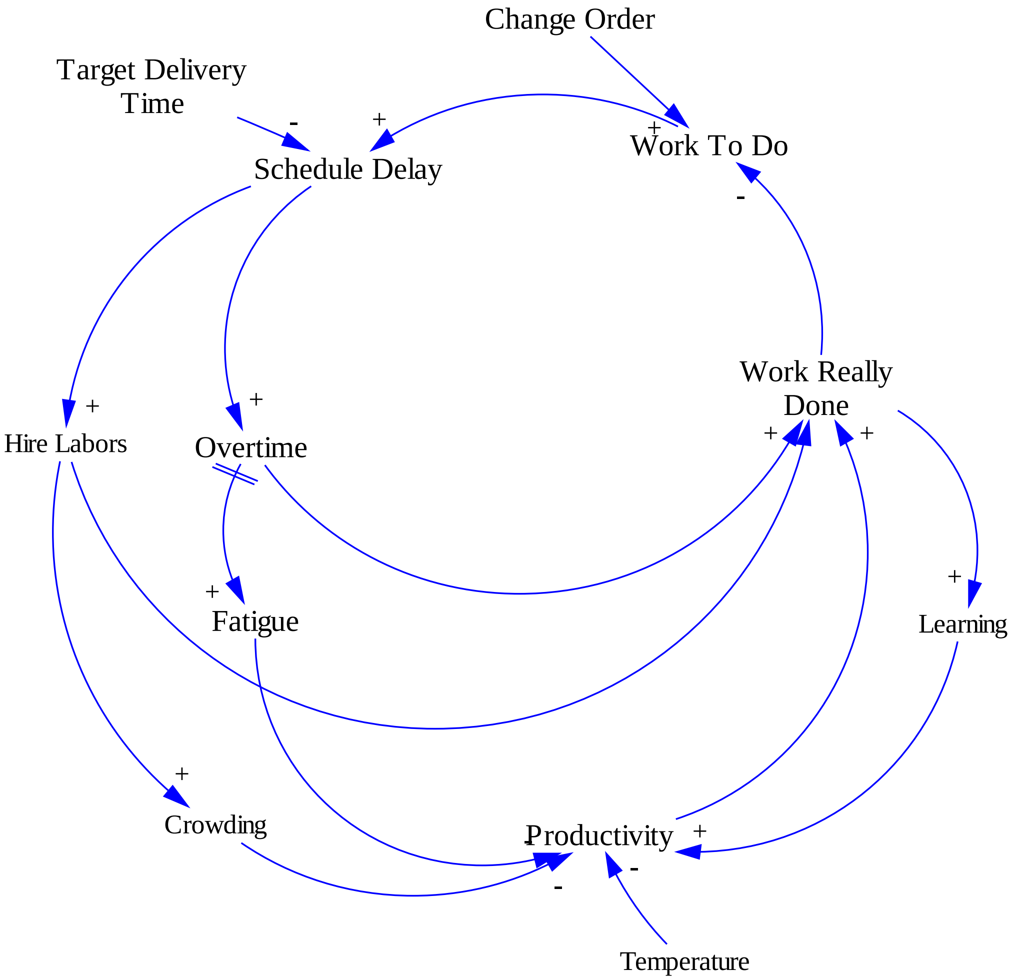


Figure 18: Causal Loop Diagram of Labor Productivity

1. Work To Do →+ Schedule Delay →+Overtime →+ Work Done →- Work To Do (Balancing – 1)
2. Work To Do →+ Schedule Delay →+ Overtime →+ Fatigue →- Productivity →+ Work Done → Work To Do (Reinforcing – 1)
3. Work To Do →+ Schedule Delay →+ Hire Labors →+ Crowding →- Productivity →+ Work Done → Work To Do (Reinforcing – 2)
4. Work Done →+ Learning →+ Productivity → Work Done (Balancing – 2)
5. Work To Do →+ Hire labors →+ Work Done →- Work To Do (Balancing –3)

Once a change order is issued, the number of units needed to accomplish the project is changed, and some finished work might need to rework because of the change order that also increased the number of items needed to accomplish. To avoid delay in the project, and based on the targeted delivery time, the contractor might use one of the work acceleration techniques, e.g., putting the available workers on overtime, meaning an increased number of working hours per day, to strive for an increase in the number of items accomplished per day (balancing loop). Too much overtime for successive weeks will cause fatigue to the workers, resulting in productivity loss, and therefore, decreasing the number of accomplished units per week (reinforcing loop). The contractor might choose to hire more labors to increase the number of items accomplished per day (balancing loop). Too many labors onsite lead to overcrowding, implying that the available space per labor to work efficiently decreases and will generate productivity loss and consequent decrease in the number of accomplished units per day (reinforcing loop). As the number of items finished increases, the labor learning effect increases. This will lead to the reduction of time required to complete the activity, resulting in increase of labor productivity, which means increasing the number of accomplished units per day (balancing loop).

3.8 Model Formulation

Based on highly established and validated models like those created by Alvanchi et al. (2012), Chang et al. (2007), Han et al. (2013), Nasirzadeh and Nojedehi (2013), Sterman and Oliva (2010), Warhoe (2013) and Lisse (2013); a system dynamics model, Stock-Flow diagram (SFD), was developed. The stock and flow diagram is presented in Figure 19.

When the contractor wins the bid he has to do a certain amount of work as specified in the bid documents “Work To Do.” During the simulation, this amount of work will flow through “Work Being Done” towards the “Work Really Done” stock, at a prescribed work rate depending on the contractor’s best productivity. When the project owner issued change orders that add work items to the project scope, it is hypothesized that the productivity can be impacted. Factors such as scope change, temperature, labor crowding, overtime, fatigue, and learning effects create feedback loops that affect the contractor productivity, as well as the work rate flow, as shown in Figure 19. This model studies the effect of these different factors on productivity, labor hours needed to finish and deliver the project on time, as well as on the rate of work really done.

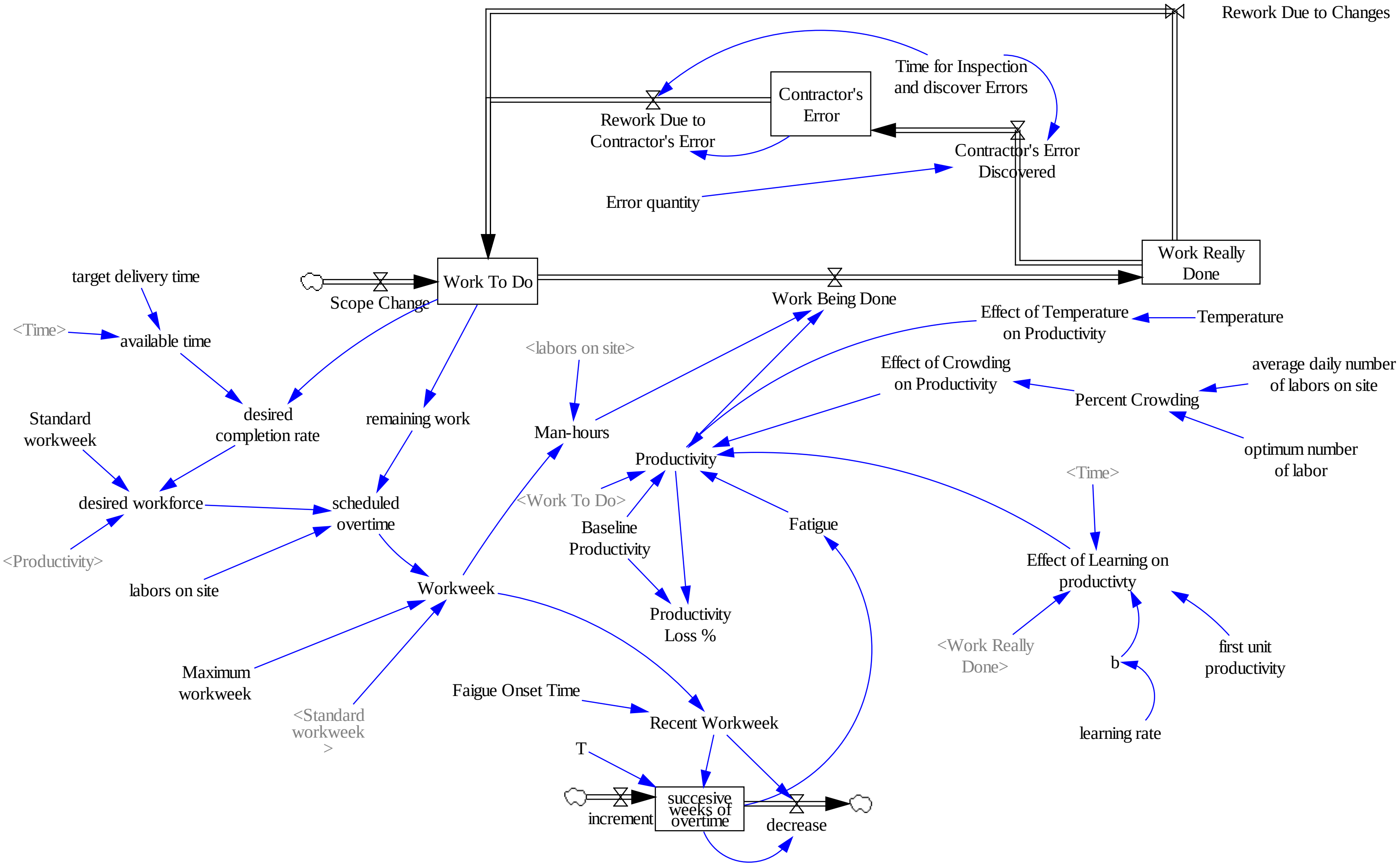


Figure 19: Stock and Flow Diagram

3.9 Model Verification

Model testing is a critical step in modeling process to ensure that the model is correctly implemented according to the conceptual model. During verification process, errors are revealed and fixed, so the modeler creates the best available model to study the case in the question, in addition to understanding the model limitations.

This section presents the process used to verify and test the suitability of the model for its specific purpose, build confidence in the simulation model, discover flaws, fix it, and improve the model so it can be used usefully. According to Sterman (2000), five tests were applied to verify the system dynamics model.

3.9.1 Boundary Adequacy

According to Sterman (2000), the boundary adequacy test answers the following questions:

1. Are the important concepts for addressing the problem endogenous to the model?

This question asked whether the data that has been input into the model generating the output or is the model generating the output? When the input parameters are modified, can they be clearly seen that the model is generating the output? The major endogenous and exogenous variables used in the model are summarized in Table 1. All major variables (productivity, work really done, overtime, fatigue, crowding, and learning) are generated endogenously, whereas scope change, work to do, temperature, and hiring of laborers are the exogenous variables. All the variables used are based on concepts that have been existing and used in the construction industry for years.

2. Does the behavior of the model change significantly when boundary assumptions are relaxed?

For the purpose of the model in this study, the behavior of the model changes as would be expected when the boundary assumptions are relaxed. Increasing or decreasing the boundary assumptions will create a cause-and-effect chain that will impact other aspects of the model. For example, if the overtime boundary is relaxed, the fatigue impact on labor will be affected; therefore, labor productivity and the amount of work really done will be affected.

3.9.2 Structure Verification

A basic and important test in the verification process is “structure verification.” “Structure assessment tests ask whether the model is consistent with knowledge of the real system relevant to the purpose” (Sterman 2000). The cause-and-effect relationships among variables are represented by a causal loop diagram, as shown in Figure 18. Once a change order is issued, the number of units needed to accomplish the project is changed and some finished work might need to be reworked. To avoid delay in the project, and based on the target delivery time, the contractor might schedule work acceleration, i.e., putting the available workers on overtime, which means increasing the number of working hours per day and increasing the number of items accomplished per day. Too much overtime for successive weeks will cause fatigue to the workers, resulting in productivity loss and further decrease in the number of accomplished units per week. The contractor might choose to hire more laborers, which will increase the number of items accomplished per day. Too many laborers onsite, however, will lead to overcrowding which means the available space per laborer to work efficiently decreases. This results in productivity loss and a decrease in the number of accomplished units per day. As the number of items finished increases, the labor learning curve is increased and results in a reduction of the time to complete a similar activity. This increases labor productivity and, consequently, increases the number of accomplished units per day.

3.9.3 Dimensional Consistency

The model developed in this study was created using a well-known system dynamics software package called “Vensim”. The software has a built-in function that notifies the user if there are any inconsistencies with dimension. Additionally, each mathematical equation used to formulate the stock-flow diagram is tested by the researcher to confirm that the measurement units of the used variables and constants are dimensionally consistent.

The following are two of these equations with their dimensional consistency analyses:

- $desired\ workforce = \frac{desired\ completion\ rate * contractor\ productivity}{standard\ workweek}$

This equation describes that the required number of workers (desired workforce) to deliver the project on time depends on the required completion rate, actual contractor productivity, and the standard working hours per week (standard workweek). Therefore, the dimensional analysis for this equation is:

$$worker = \frac{\frac{unit}{week} * \frac{labor * hour}{unit}}{\frac{hour}{week}} = worker$$

Thus, the equation is dimensionally consistent.

-$Work\ Being\ Done = \frac{Man\text{–}hours}{productivity}$

This equation describes the number of units accomplished per week (work being done), as dependent on the number of hours spent by the laborers per week (man-hours) and actual labor hours spent to produce one unit of work (productivity). The dimensional analysis for this equation is:

$$\frac{unit}{week} = \frac{labor * \frac{hour}{week}}{\frac{labor * hour}{unit}} = \frac{unit}{week}$$

Thus the equation is dimensionally consistent.

3.9.4 Parameter Verification

According to Sterman (2000), the parameter verification test answers the following questions:

1. Are the parameter values consistent with relevant descriptive and numerical knowledge of the system?

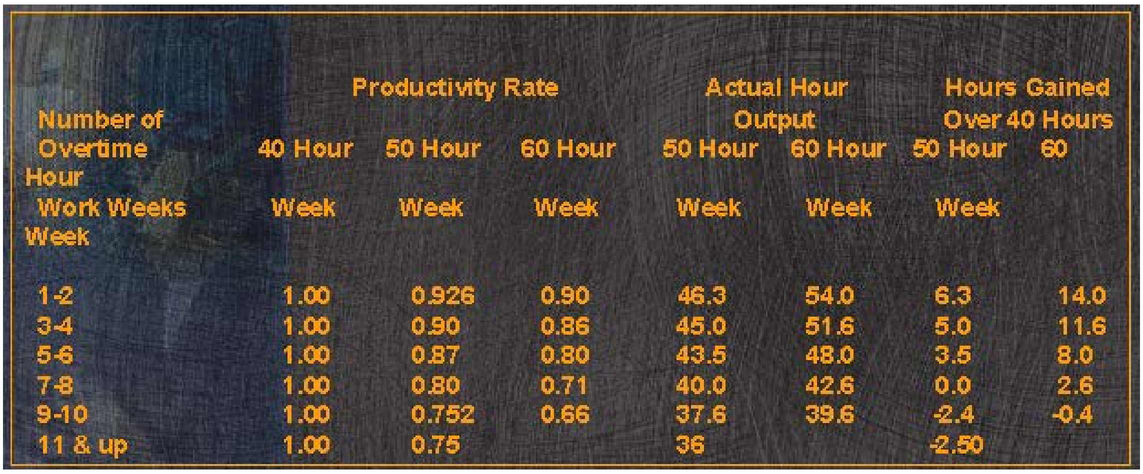
All parameters values used in model building of the causal loop diagram and stock and flow diagram are consistent with the knowledge of construction industry. The values given to the parameters of this model are based on the existing project data and existing knowledge found in published papers and research. The following is an illustration for some of the parameters used and their values.

Acceleration techniques are used to increase the productive labor-hour on a job. These techniques include overtime, overmanning and trade stacking, and shift work, all of which are used by the contractor to complete work earlier than scheduled, to overcome delay in project schedule due to changes, or to make up for a material delay. Although each one of these acceleration techniques will increase the daily production on a job, it is not true that doubling the amount of hours, or doubling the worker-power will double the output. There is an inherent loss of labor productivity with each of these acceleration techniques.

- Overtime:

The simplest way to accelerate a project is to increase man-hours with the use of overtime. This adaptable technique retains the original number of workers who are already familiar with the project. It also maintains the original sequence so that there are not new needs for coordinating multiple trades and workers within a specific area. Overtime has two main variations: (1) spot overtime and (2) scheduled or extended overtime. The former is used to address unexpected changes or to complete work that is time-sensitive. The latter is offered as an incentive to attractive labor or in effort to complete a project earlier than would be done with the standard workweek.

Overtime is commonly selected for acceleration when the impact of a change is not fully known. Other techniques should be considered, however, because overtime is costly. Part of this cost is because workers typically receive remuneration at 1.5 times the standard wage. An additional reason for the cost is that hourly productivity does not increase and in fact declines due to physical fatigue. Figure 20 shows loss of productivity due to overtime and how it varies with the duration that overtime is used.



Number of Overtime Hour Work Weeks Week	Productivity Rate			Actual Hour Output		Hours Gained Over 40 Hours	
	40 Hour Week	50 Hour Week	60 Hour Week	50 Hour Week	60 Hour Week	50 Hour Week	60
1-2	1.00	0.926	0.90	46.3	54.0	6.3	14.0
3-4	1.00	0.90	0.86	45.0	51.6	5.0	11.6
5-6	1.00	0.87	0.80	43.5	48.0	3.5	8.0
7-8	1.00	0.80	0.71	40.0	42.6	0.0	2.6
9-10	1.00	0.752	0.66	37.6	39.6	-2.4	-0.4
11 & up	1.00	0.75		36		-2.50	

Figure 20: Scheduled Overtime Productivity Decreases (Hanna, 2008)

- Overmanning:

Overmanning means increasing the number of workers within the same trade on a project. Using overmanning, the contractor can achieve a higher production rate without the fatigue issue that is inherent with overtime, yet. Labor congestion and a decreasing in supervision will lead to a decrease in labor productivity. Figure 21 shows the loss of productivity due to overmanning.

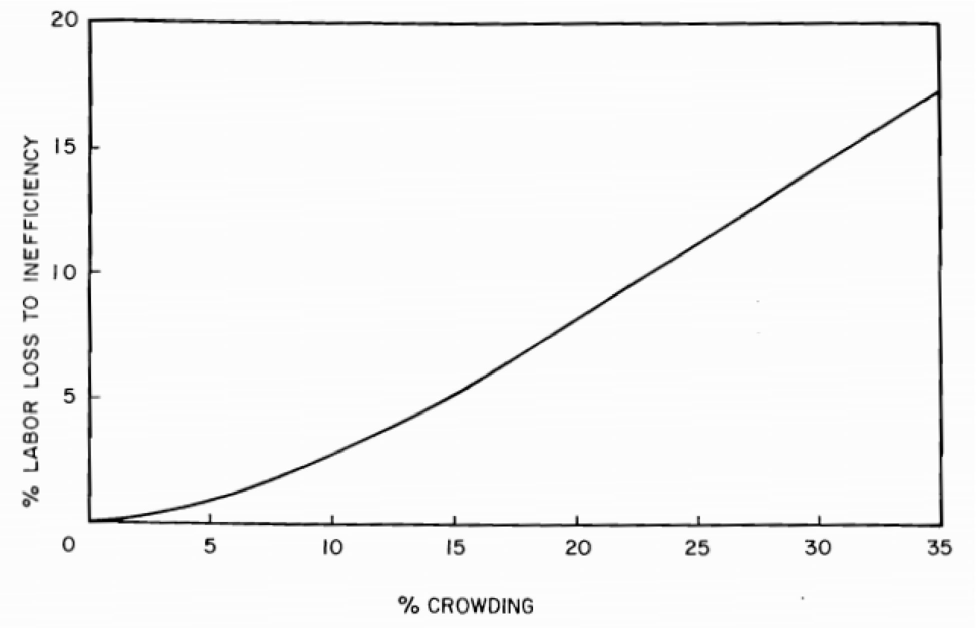


Figure 21: Effect of Crowding on Labor efficiency (U.S. Army Corps of Engineers, 1979)

- Temperature

A study done by W. F. Fox to explore the effect of temperature on labor productivity reports that “there is a critical hand surface temperature (HST) below which performance is significantly affected and above which there are few effects. He states, “for tactile sensitivity, the critical HST in near 8^{o} C (46^{o} F). For manual dexterity the critical HST is somewhat higher between 12^{o} C (54^{o} F) and 16^{o} C (61^{o} F)” (Schwartzkopf, 1995). Figure 22 shows labor efficiency as a function of temperature.

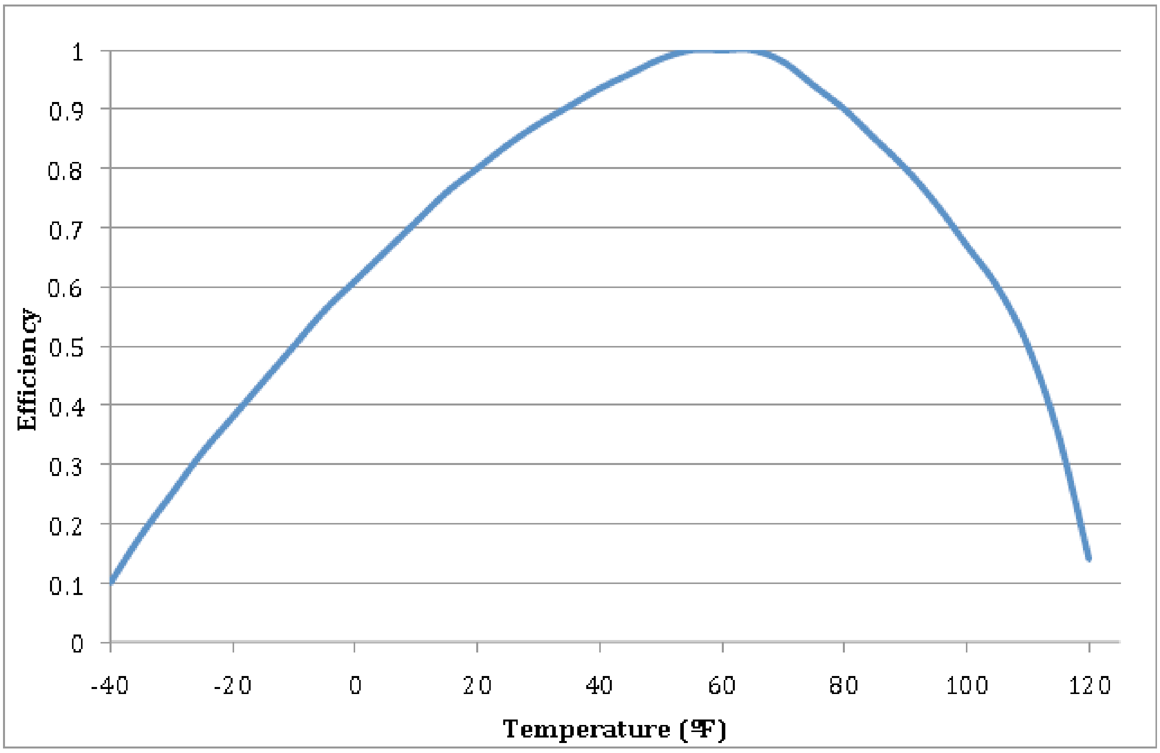


Figure 22: Effect of Temperature on Labor Efficiency (Ibbs and Vaughan, 2012)

- Learning Effect

Repetition promotes familiarity. Therefore, repeated actions require less effort and can be completed in less time as the number of these repetitions increase. This learning effect results in an improvement in labor productivity as controlled by the equation: $Y = AX^b$

Where:

Y = labor hours per unit

X = Cumulative number of units

A = Labor hours to produce first unit (constant)

b = Slope of the line on log-log plot = $\log r / \log 2$.

r = the constant ration, known as the learning curve ratio**.** Figure 23 depict the learning effect on productivity.

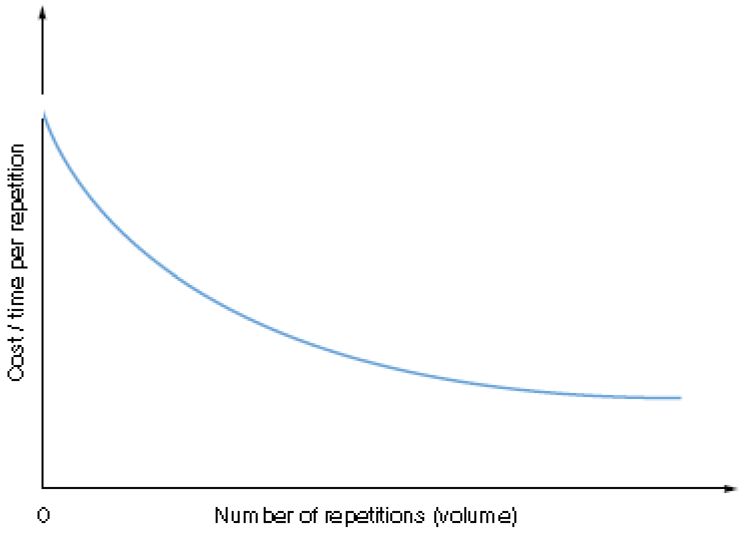


Figure 23: The Learning Curve

2. Do all parameters have real world counterparts?

   All parameters and values used in model building, both causal loop diagram and stock and flow diagram, are consistent with the knowledge of the construction industry and have counterparts in the real world as discussed in the previous question.

3.9.5 Extreme Condition Test

"Models should be robust in extreme conditions. Robustness under extreme conditions means the model should behave in a realistic fashion no matter how extreme the inputs imposed on it may be" Sterman (2000).

In this test, extreme values were given to selected model parameters, and then the simulation generated behavior was compared to the behavior of the real system. The most important variables on the results were evaluated at their extreme values during sensitivity analysis.

As an example of extreme conditions, the model was run by putting the available laborers on 50 hours/week along the entire simulation. The model behavior compared to the real system is shown in Figure 10.

As shown in Figures 24-25, putting the available labor on overtime, which means increasing the number of working hours per week, for successive weeks will cause fatigue to the workers, resulting in productivity loss. As a result, the amount of units accomplished per week is decreased, as a result the man-hours needed to finish the work and the time needed to deliver the project is increases. Extended overtime increases the fatigue effect on productivity; the figure demonstrates the growing gap and detriment.

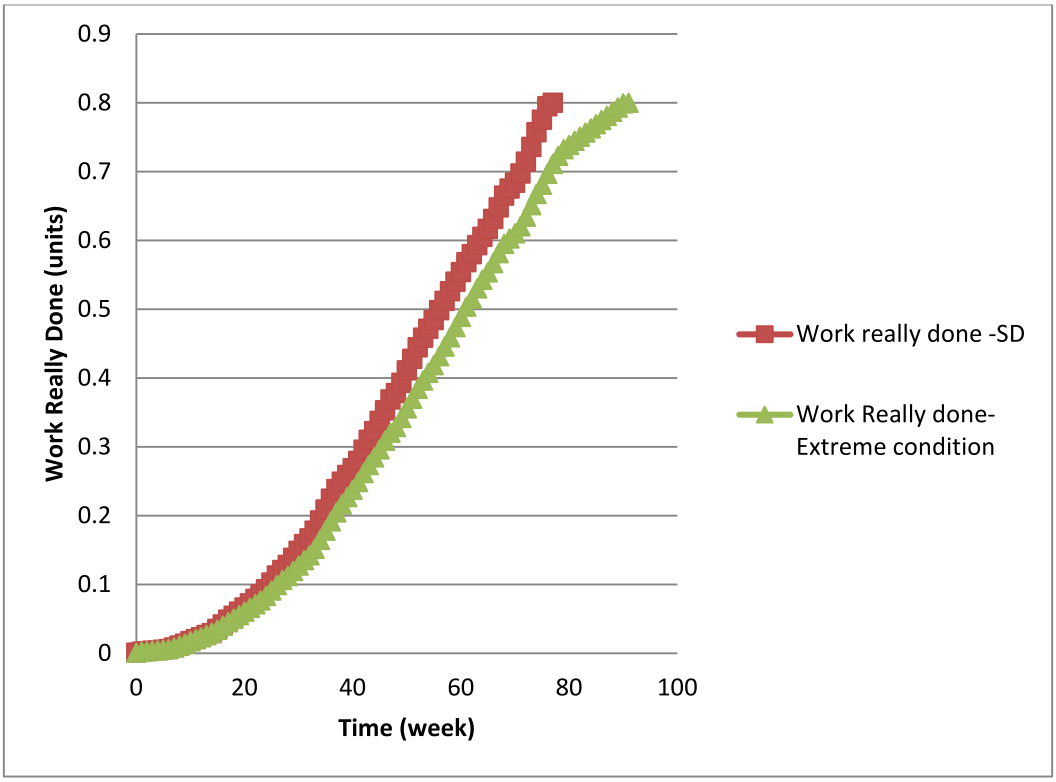


Figure 24: Time vs. Work Really Done -Extreme Conditions

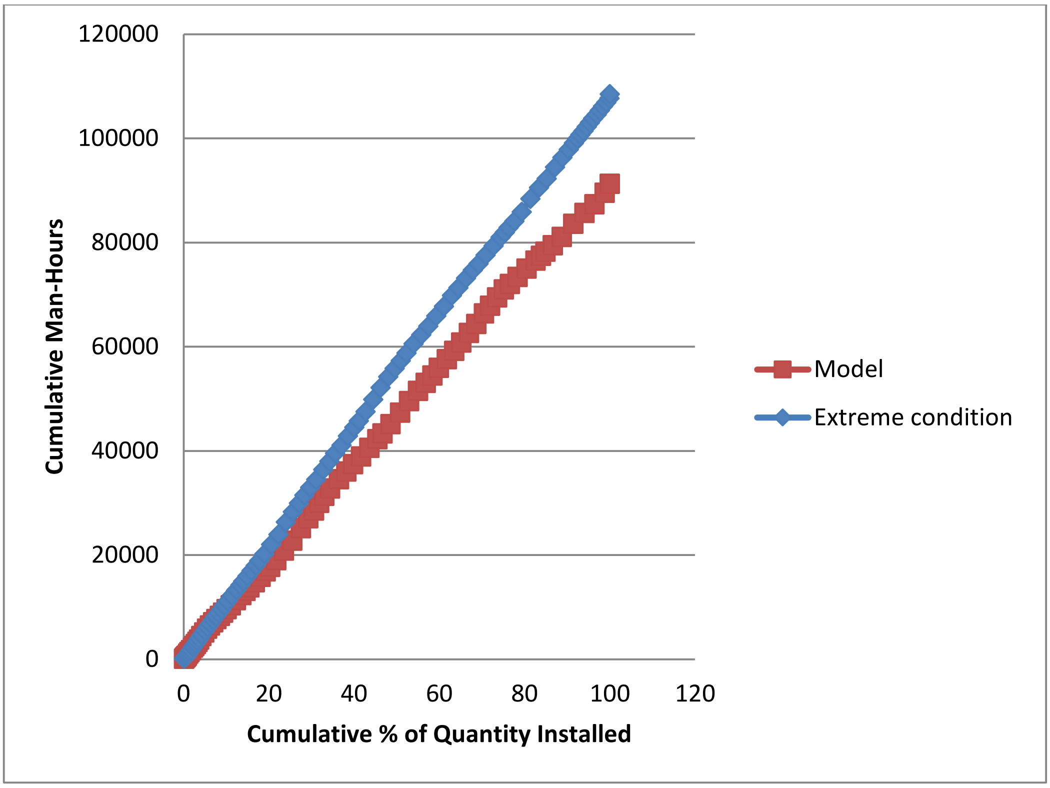


Figure 25: Model Behavior under Extreme Condition Test

3.10 Model Validation

Model behavior validation, and system dynamics model validation in particular, is possibly the most important part of simulation validation in general. Barlas defines model validation as, “establishing confidence in the usefulness of a model with respect to its purposes” (1994). The process by which this is accomplished includes the stages of model conceptualization all the way past the implementation of policy recommendations. System dynamics models have certain characteristics that make standard statistical tests inappropriate. Different tests were suggested to quantitatively evaluate system dynamics behavior, and such tests focused on major time patterns rather than individual data points (Barlas, 1989).

3.10.1 Reference Mode (behavior reproduction)

Here we evaluate the historical fit. As indicated in Figure 26, the results of the simulation, including all the effects, relatively accurately reproduce the project data regarding the work really done. Where this variable is endogenously generated in the model and sufficiently serves the purpose of our investigation (because its value affected by the value of labor productivity), weekly man-hours are used as well as the decision made by the project contractor regarding number of laborers used. The proposed system dynamics model was simulated using exogenous scope change values; these values were added into the “Work To Do” stock. The model considered the new work scope endogenously and addressed the effect on labor productivity and, therefore, on the needed work hours to complete the project.

To compute the correspondence between model output and project actual data, the R-square as well as the adjusted R-square were calculated as follows:

R-Square = ((COVAR (Data 1, Data 2))/ (STDEV (Data 1) *(STDEV (Data 2))))

$$R_{Adj}^2 = 1 - \left[\frac{(1 - R^2)(n - 1)}{n - k - 1}\right]$$

Where;

N is the number of points in data sample.

K is the number of variables in the model.

We observed R-squared equal to 94.63% and adjusted R-squared equal to 94.33%, allowing the conclusion that the reference mode provided by the proposed SD model is valid; the same pattern of behavior is shown with the actual cumulative man-hours.

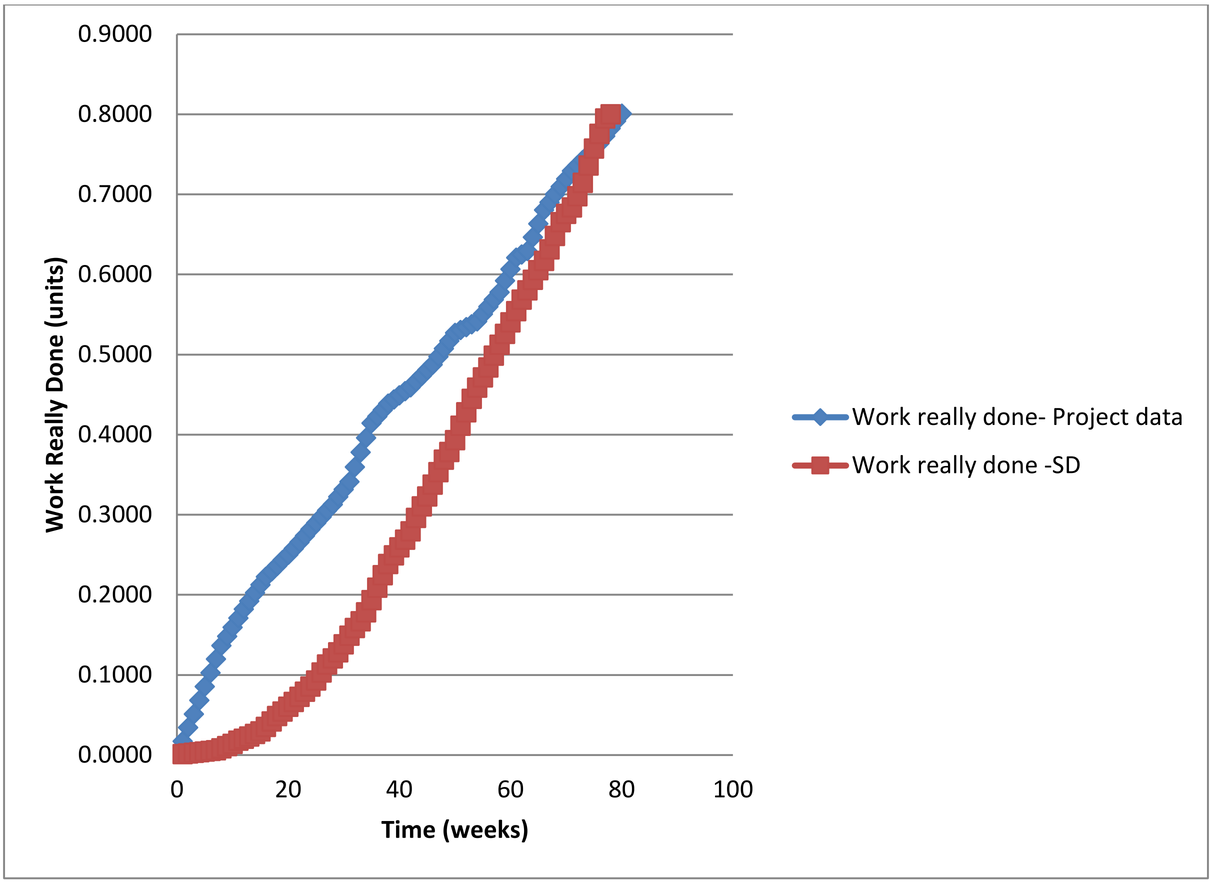


Figure 26: Validation Result – Including All Effects

The model was run again but this time without including the effect of the learning curve; the results are shown in Figure 27. R-squared is equal to 95.34% and adjusted R-squared equal to 95.15%. It must be noted here that both runs are compared to the actual project output. The higher R-squared and adjusted R-squared values implies that the model assumes that the laborers follow a certain learning curve as they become more experienced with the project but in reality they did not acquire the experience in the same rate that the model assumed.

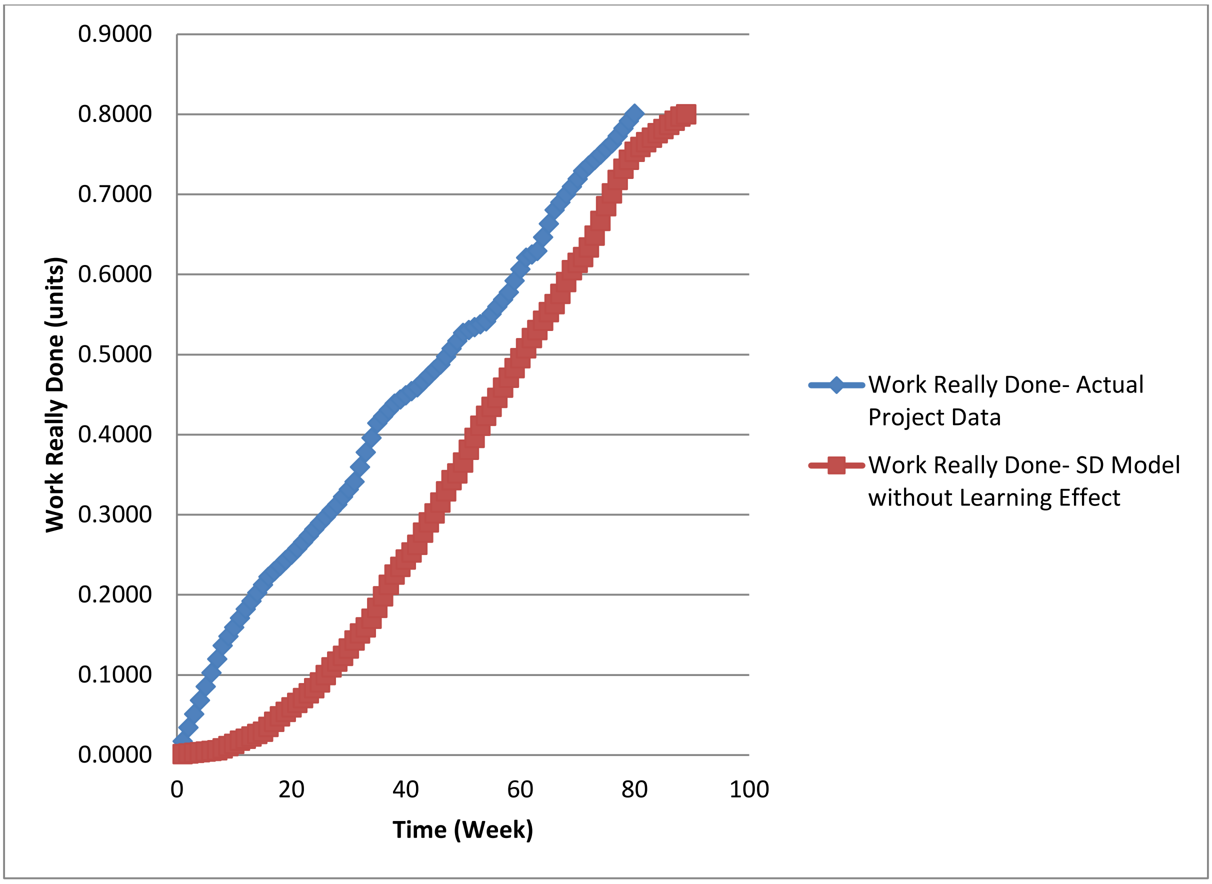


Figure 27: Validation Results – Without Learning Effect

3.10.2 Statistical Behavioral Validation

In this section, Genism model behavior will be assessed using statistical model validation, which implies how successful the model will be when applied to new data. Different statistical validation techniques have been designed with the most appropriate one being a comparison of the values predicted from the Vensim model and an independent validated statistical model (Fahmy, 2015).

A statistical model will build for the actual work done along the project period. Since the available data is limited and it is impossible to collect new data as tabulated in Table 4, the original data will be split into two parts. The first part will be used to build the statistical model and estimate its parameters (highlighted in pink), and the second part will be used to assess the fitted model's predictive ability and to run the model (highlighted in green)

(Mendenhall and Sincich,2007), tabulate the estimated values, and compare them to their counter parts from the Vensim model.

Table 4: Data for Work Really Done From Project Documents

Time	Cumulative Completion
1	0.0171
2	0.0342
3	0.0513
4	0.0684
5	0.0855
6	0.1026
7	0.1197
8	0.1368
9	0.1482
10	0.1595
11	0.1709
12	0.1822
13	0.1923
14	0.2024
15	0.2125
16	0.2226
17	0.2295
18	0.2363
19	0.2432
20	0.2500
21	0.2579
22	0.2658
23	0.2737
24	0.2816
25	0.2895
26	0.2973
27	0.3051
28	0.3129
29	0.3223
30	0.3317
31	0.3411
32	0.3595
33	0.3778
34	0.3962
35	0.4145
36	0.4226
37	0.4307
38	0.4388

Time	Cumulative Completion
39	0.4439
40	0.4490
41	0.4541
42	0.4592
43	0.4663
44	0.4734
45	0.4805
46	0.4876
47	0.4975
48	0.5073
49	0.5172
50	0.5270
51	0.5306
52	0.5342
53	0.5378
54	0.5414
55	0.5505
56	0.5596
57	0.5687
58	0.5778
59	0.5922
60	0.6066
61	0.6210
62	0.6251
63	0.6292
64	0.6463
65	0.6634
66	0.6805
67	0.6902
68	0.6999
69	0.7096
70	0.7193
71	0.7290
72	0.7359
73	0.7428
74	0.7497
75	0.7566
76	0.7635
77	0.7729
78	0.7822
79	0.7916
80	0.8009

Using statistical analysis, a regression equation for cumulative man-hours is developed as follows:

y = Work Really Done, x = week count

$y = 0.02036 + 0.01367 x - 0.000115 x^2 + 0.000001 x^3$

S = 0.0118483   R-Sq = 99.8%   R-Sq. (adj) = 99.7%

The coefficient of determination r² has a value of 99.8% implying that the model equation relating work really done to week can explain 99.8% of the variation present in the data values of work really done.

The plotted cumulative man-hours graph along with its residuals plots are shown in Figures 28 and 29, respectively.

Figure 28: Work Really Done Statistical Model Curve

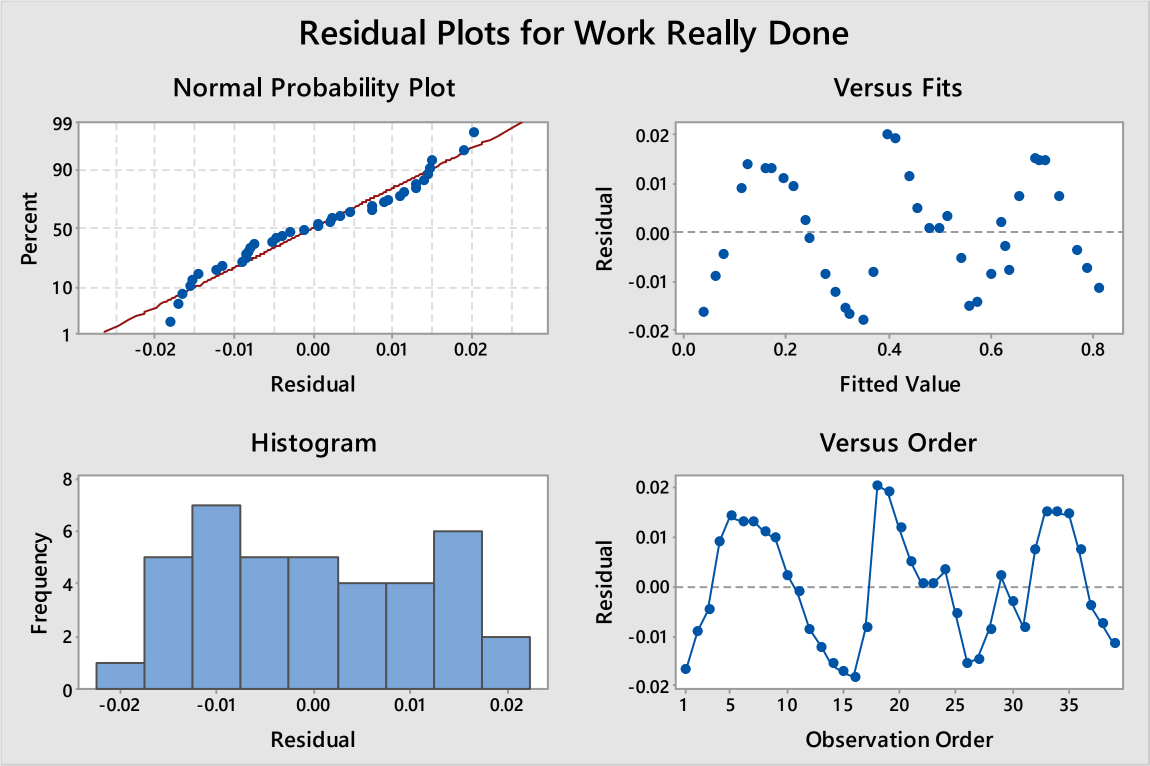


Figure 29: Residual Plots for Work Really Done Statistical Model

We used the second part of the split data to validate the model as presented in Table 5.

Table 5: Validation Data Set for Work Really Done Statistical Model

a	b	c	d	e
Time	**Actual cumulative man-hours**	**Estimated cumulative man-hours**	**% Error = (b-c)/c**	**ABS % Error**
2	0.0342	0.047248	-0.2762	0.276159837
5	0.0855	0.08596	-0.0054	0.005351326
6	0.1026	0.098456	0.04209	0.042089868
9	0.1482	0.134804	0.099	0.099002997
10	0.1595	0.14656	0.08829	0.088291485
13	0.1923	0.180832	0.06342	0.063417979
15	0.2125	0.20291	0.04726	0.047262333
17	0.2295	0.224428	0.02238	0.022376887
20	0.2500	0.25576	-0.0225	0.022521114
21	0.2579	0.265976	-0.0304	0.030363642
23	0.2737	0.286102	-0.0433	0.043348177

a	**b**	**c**	**d**	**e**
Time	**Actual cumulative man-hours**	**Estimated cumulative man-hours**	**% Error = (b-c)/c**	**ABS % Error**
25	0.2895	0.30586	-0.0535	0.053488524
28	0.3129	0.334912	-0.0657	0.065724728
29	0.3223	0.344464	-0.0643	0.064343444
31	0.3411	0.363406	-0.0614	0.061380384
33	0.3778	0.382172	-0.0114	0.011439875
34	0.3962	0.391504	0.01187	0.011867056
36	0.4226	0.410096	0.03049	0.030490422
38	0.4388	0.428632	0.02372	0.023721981
39	0.4439	0.437894	0.01372	0.013715648
41	0.4541	0.456436	-0.0051	0.005117914
43	0.4663	0.475042	-0.0184	0.018402583
44	0.4734	0.484384	-0.0227	0.022676224
46	0.4876	0.503176	-0.031	0.030955371
48	0.5073	0.522152	-0.0284	0.028443825
50	0.5270	0.54136	-0.0265	0.026525787
51	0.5306	0.551066	-0.0371	0.037138927
53	0.5378	0.570712	-0.0577	0.057668316
55	0.5505	0.59071	-0.0681	0.068070627
57	0.5687	0.611108	-0.0694	0.069395262
58	0.5778	0.621472	-0.0703	0.070271871
60	0.6066	0.64256	-0.056	0.055963645
64	0.6463	0.686344	-0.0583	0.058343921
66	0.6805	0.709136	-0.0404	0.040381535
67	0.6902	0.720778	-0.0424	0.042423603
71	0.7290	0.769126	-0.0522	0.052170906
72	0.7359	0.781688	-0.0586	0.0585758
74	0.7497	0.807424	-0.0715	0.071491558
75	0.7566	0.82061	-0.078	0.078002949
79	0.7916	0.875614	-0.096	0.096005774
	Average % Error			0.051609603

As shown in Figure 30, the statistical model predicted data closely resembling the system dynamic model data and thus we can state that our model has been statistically validated.

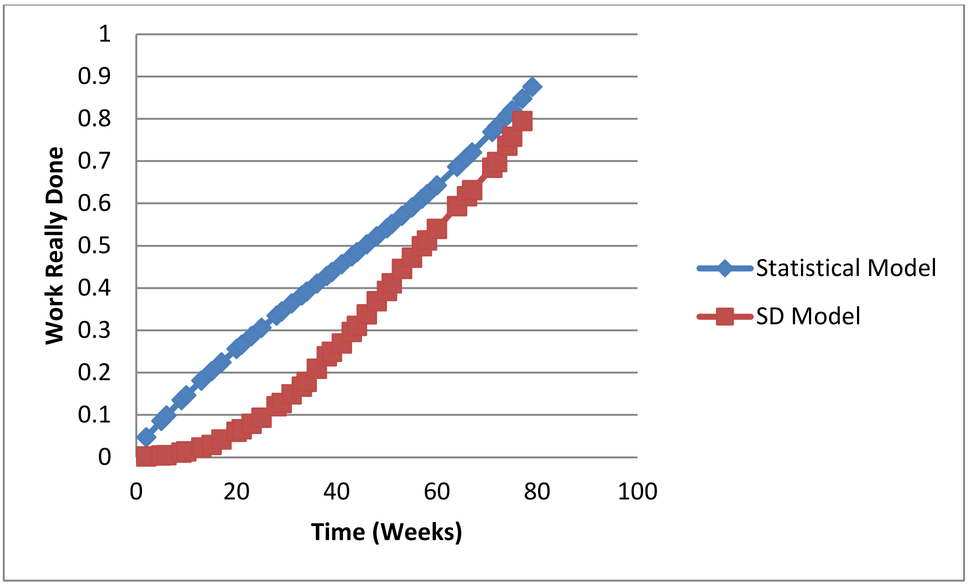


Figure 30: Work Really Done Results of System Dynamics Model Vs. Statistical Model

3.10.3 Sensitivity Analysis

It is valuable to understand the range of behavior of a system dynamics model, given the wide range of extremes in the input. “Performing sensitivity analysis helps the model understand how the model performs under all possible reasonable scenarios” (Warhoe 2014). Sensitivity analysis helps the modeler to make the model more robust through making any corrections recognized from the sensitivity analysis which points out possible weaknesses.

Determining numerical sensitivity can be evaluated by varying any constant that directly impacts productivity. The Vensim software, used to create the system dynamic model in this study, uses the Monte Carlo simulation in the performance of sensitivity analysis to assess the sensitivity of the simulated results, based on evaluating one or a few external constants from their lowest to highest thresholds. For this research, sensitivity analysis is performed to evaluate the impact of overtime, overmanning, temperature, and learning on the behavior of the model when their effects are simulated from their highest to their lowest reasonable thresholds using Monte Carlo multivariate simulation.

For each run of the sensitivity analysis, the model is simulated with all the constant are set to their baseline condition values, then the impact of the factor under consideration is analyzed using the random uniform distribution of the values from their high to low threshold. The number of iterations used in each sensitivity simulation was set to 200, which is the system default in the Vensim system dynamics software, and the resulting graph is called, Sensitivity Graph Percentiles.

Run #1 of the sensitivity analysis analyzed the effect of learning using the random uniform distribution for learning rate from 0.8 (Schwartzkopf, 1995) to 1, where value of 1 assuming no learning. Figures 31 and 32 illustrate the confidence boundaries or ranges for all potential output values of the variables, productivity and work really done, respectively.

The results of the sensitivity analysis show that, the outer bounds of uncertainty (100 %) show a 10% increase in the man-hours required to accomplished one unit, productivity, as the worst case which indicated no learning is acquired by the labors while doing the work which results in finishing only 92% of the work scope at the end of the simulation time for the baseline conditions. And an improvement in the labor productivity by 25% as the best case; resulting in earlier delivery of the project when compared to the baseline condition.

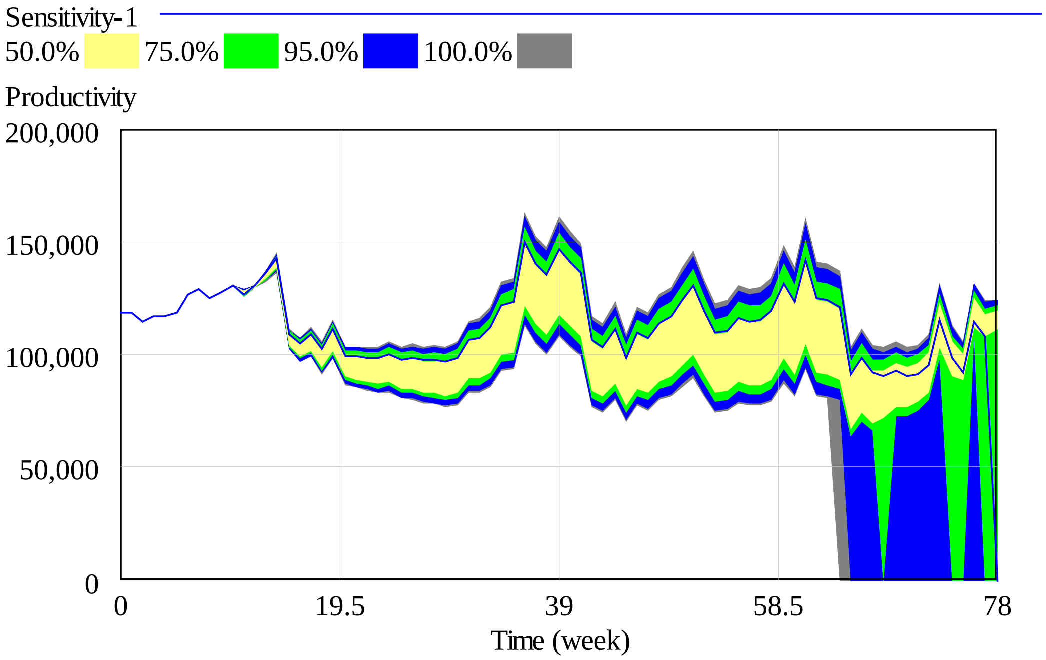


Figure 31: Sensitivity Analysis- Run #1, Productivity

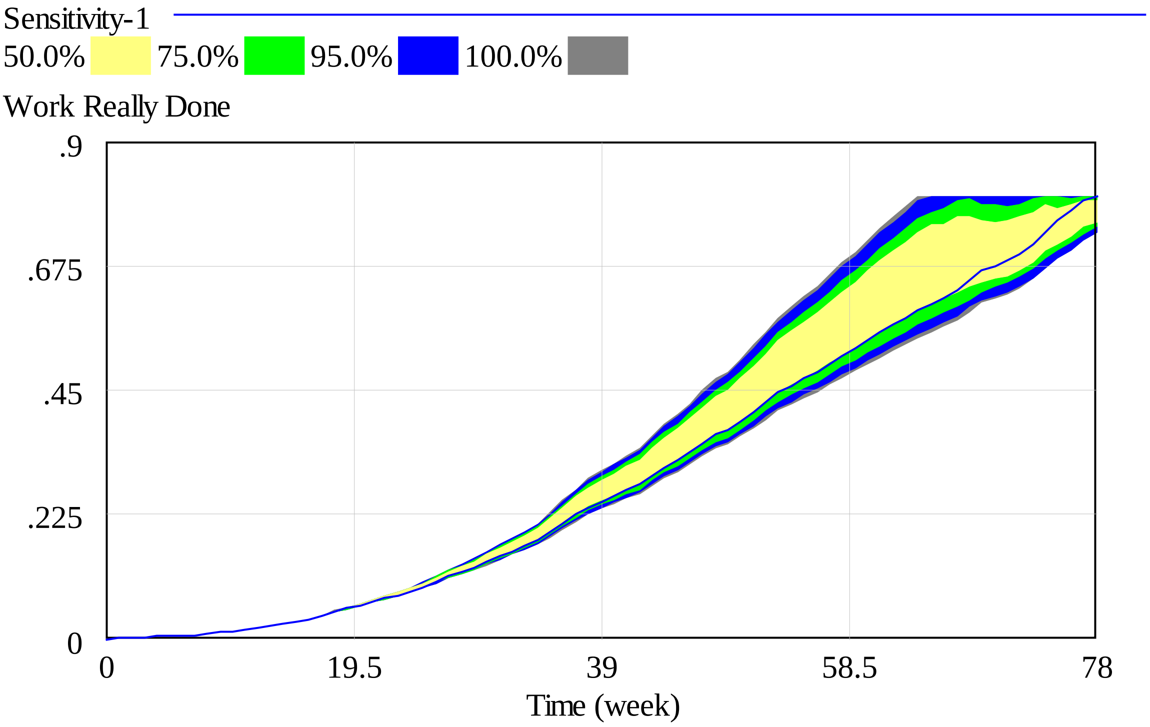


Figure 32: Sensitivity Analysis- Run #1, Work Really Done

Run #2 of the sensitivity analysis analyzed the effect of percent crowding using the random uniform distribution from 0% to 40%. Figures 33 and 34 illustrate the confidence boundaries or ranges for all potential output values of the variables, productivity and work really done, respectively.

The results of the sensitivity analysis show that, with 50% confidence, in the worst case, the man-hours required to accomplished one unit, Productivity, is increased by 27%. Compared to the baseline conditions it can be seen that the occurrence of crowding is limited and this is expected in roadway projects.

For work really done; the outer bounds of uncertainty (95%) show that the project can be delivered two weeks earlier compared to baseline condition as the best case, compared to finish only 84% of the work scope at the end of the simulation as the worst case.

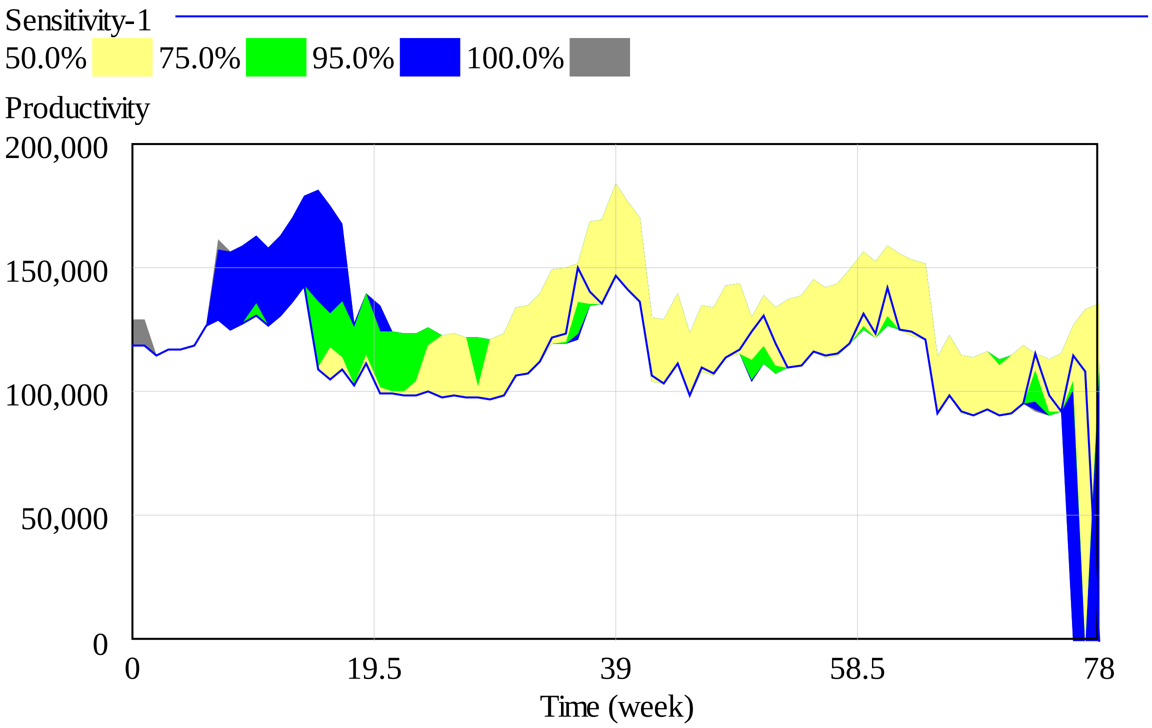


Figure 33: Sensitivity Analysis- Run #2, Productivity

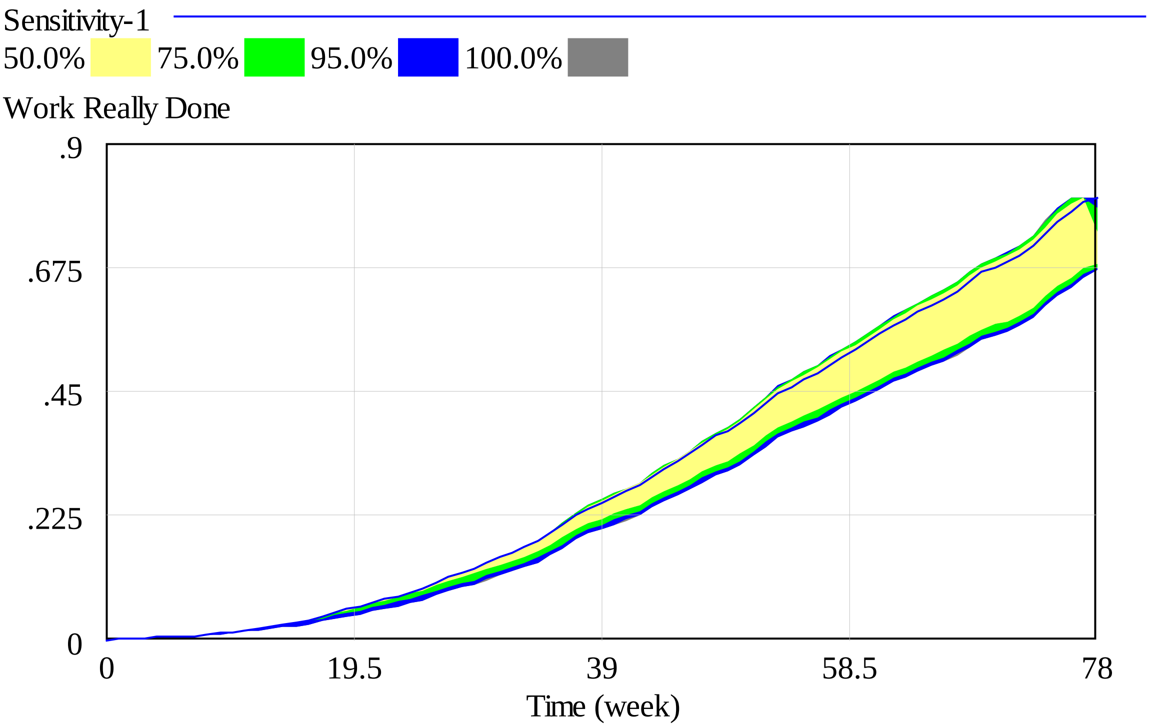


Figure 34: Sensitivity Analysis- Run #2, Work Really Done

Run #3 of the sensitivity analysis analyzed the effect of maximum working hours per week, workweek, using the random uniform distribution from 40hrs/week to 50hrs/week, Figures 35 and 36 illustrate the confidence boundaries or ranges for all potential output values of the variables, productivity and work really done, respectively.

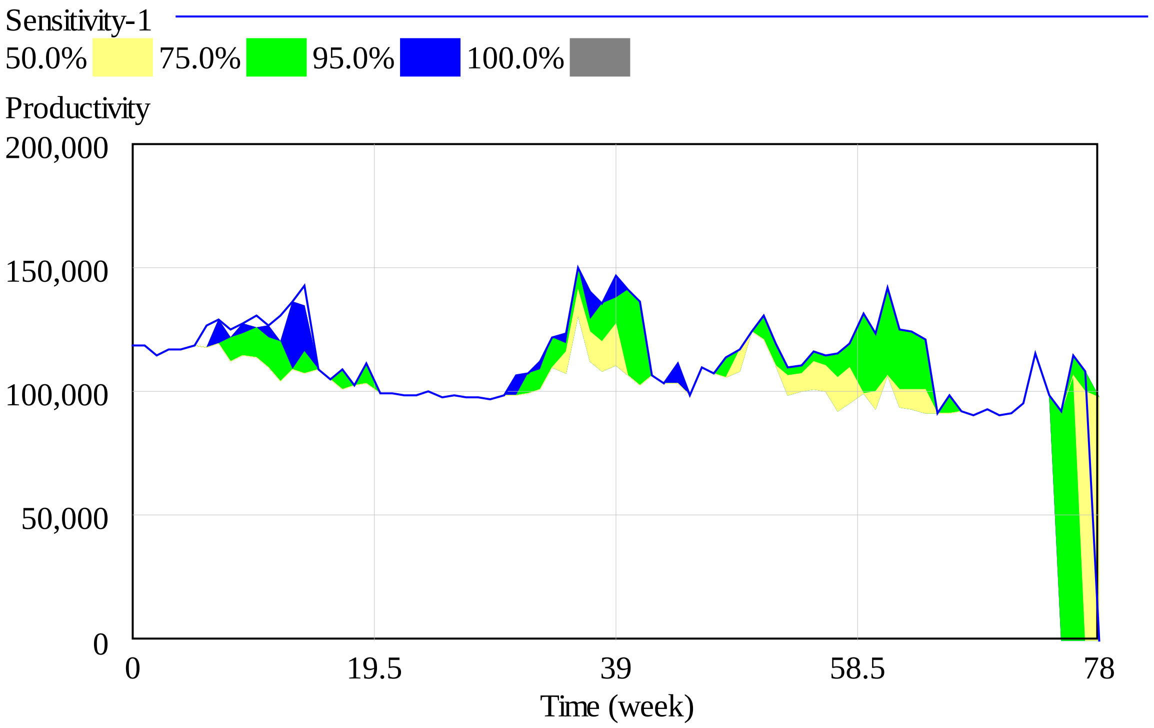


Figure 35: Sensitivity Analysis- Run #3, Productivity

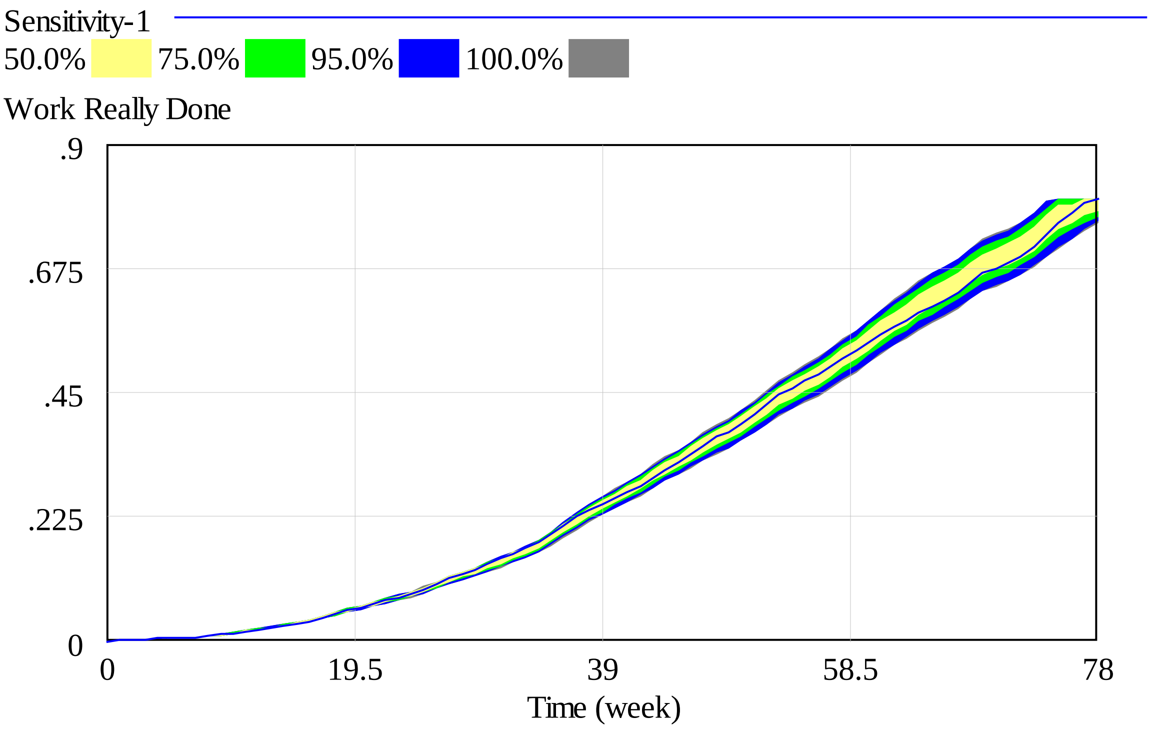


Figure 36: Sensitivity Analysis- Run #3, Work Really Done

Run #4 of the sensitivity analysis analyzed the effect of learning, crowding and overtime. Figures 37 and 38 illustrate the confidence boundaries or ranges for all potential output values of the variables, productivity and work really done, respectively.

The results of the sensitivity analysis show that, the outer bounds of uncertainty (100 %) show a 34% increase in the man-hours required to accomplished one unit, productivity, as the worst case, and an improvement in the labor productivity by 46% as the best case.

For work really done; the outer bounds of uncertainty (100%) show that the project can be delivered 16.5 weeks earlier compared to baseline condition as the best case, compared to finish only 80% of the work scope at the end of the simulation as the worst case.

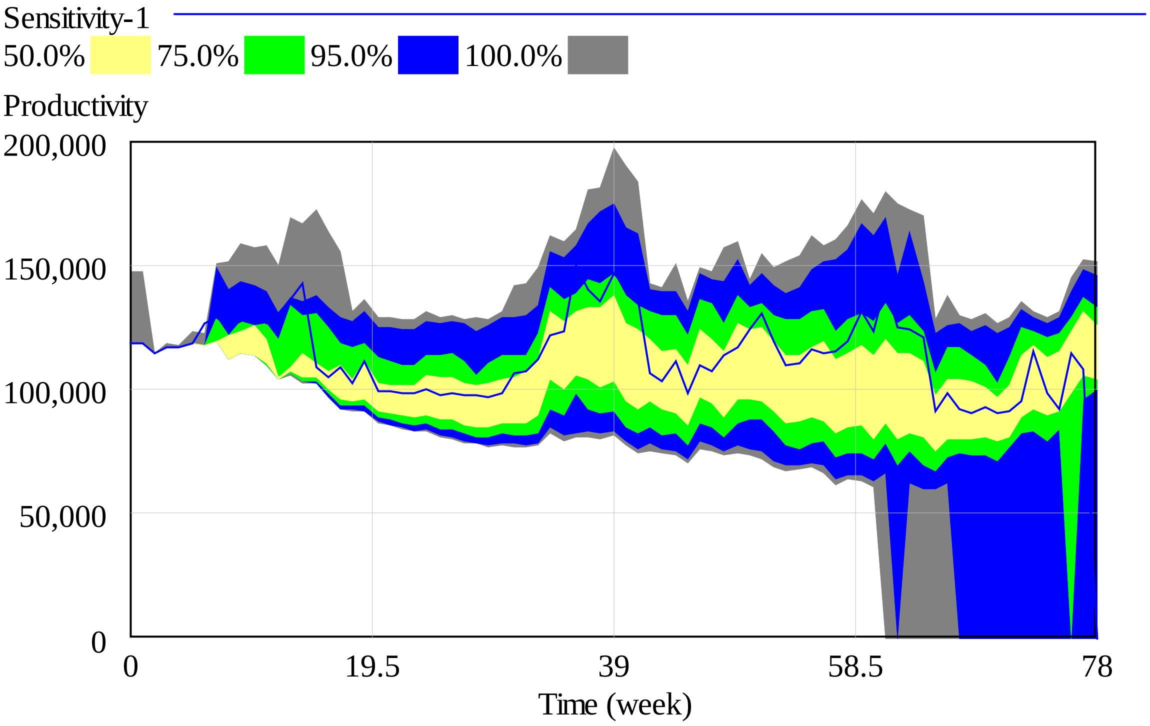


Figure 37: Sensitivity Analysis- Run #4, Productivity

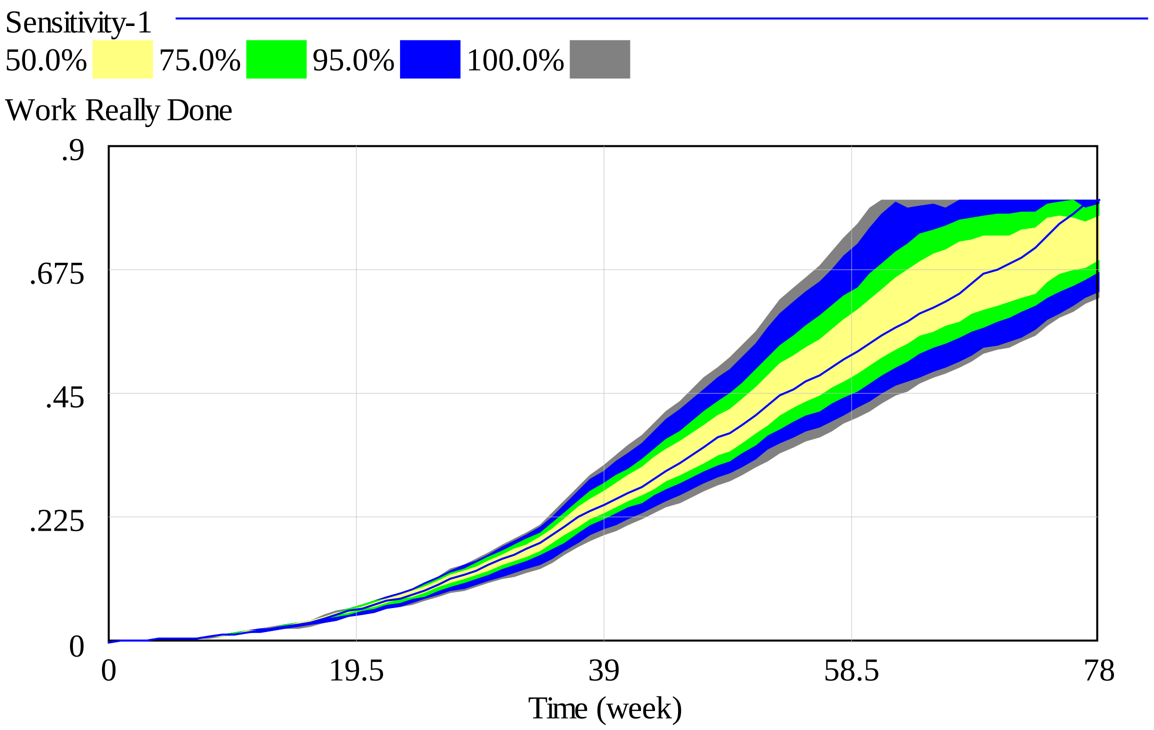


Figure 38: Sensitivity Analysis- Run #4, Work Really Done

Run #5 of the sensitivity analysis analyzed the effect of crowding and overtime. Figures 39 and 40 illustrate the confidence boundaries or ranges for all potential output values of the variables, productivity and work really done, respectively.

The results of the sensitivity analysis show that, the outer bounds of uncertainty (95 %) show a 25% increase in the man-hours required to accomplished one unit, productivity, as the worst case, and an improvement in the labor productivity by 25% as the best case.

For work really done; the outer bounds of uncertainty (100%) show that the project can be delivered 4 weeks earlier compared to baseline condition as the best case, compared to finish only 79% of the work scope at the end of the simulation as the worst case

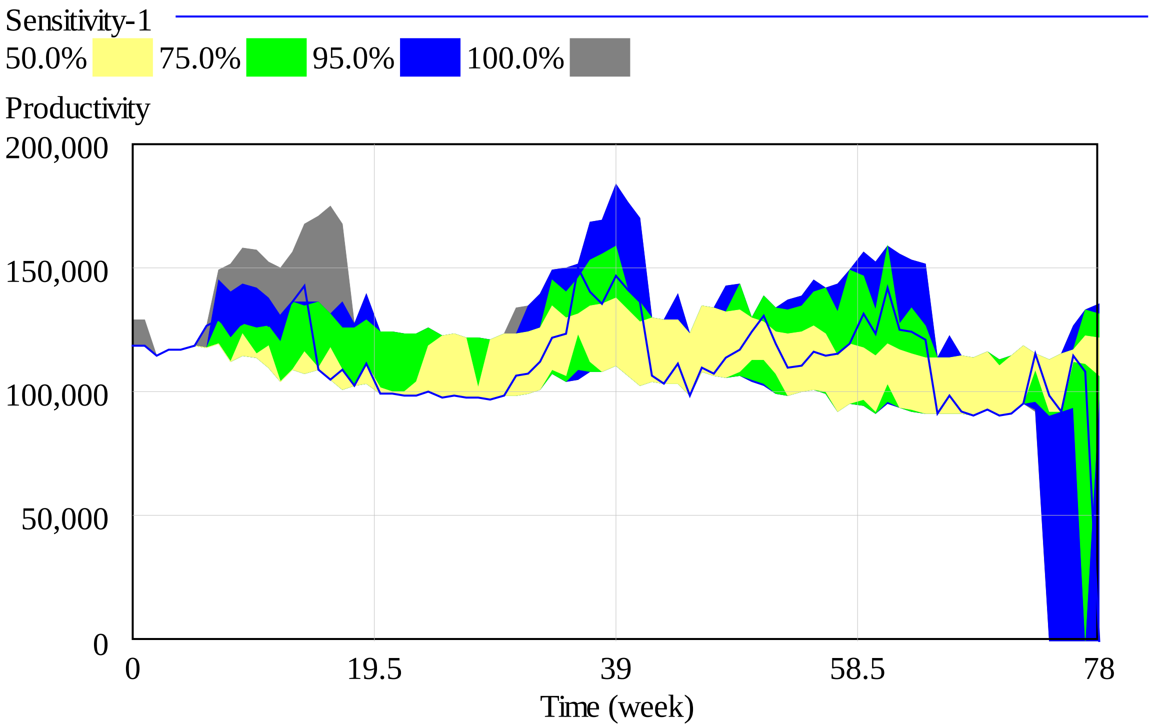


Figure 39: Sensitivity Analysis- Run #5, Productivity

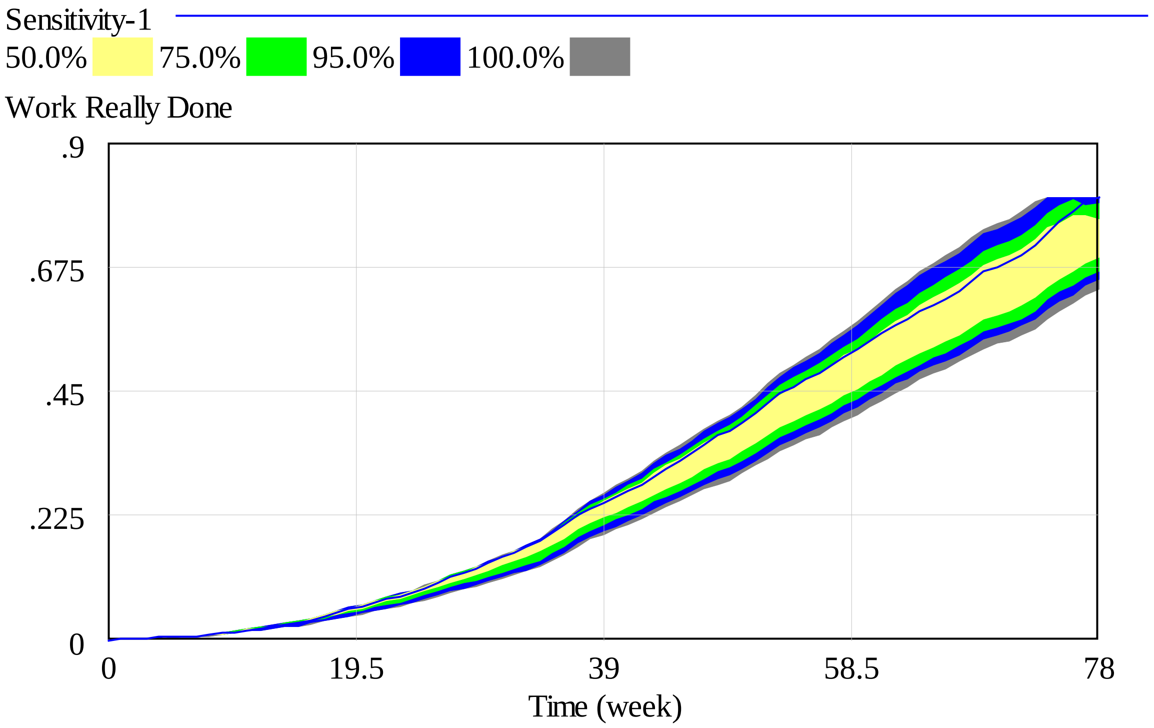


Figure 40: Sensitivity Analysis- Run #5, Work Really Done

Run #6 of the sensitivity analysis analyzed the effect of learning and overtime. Figures 41 and 42 illustrate the confidence boundaries or ranges for all potential output values of the variables, productivity and work really done, respectively.

The results of the sensitivity analysis show that, the outer bounds of uncertainty (100 %) show a 0.3% increase in the man-hours required to accomplished one unit, productivity, as the worst case, and an improvement in the labor productivity by 44.8% as the best case. For work really done; the outer bounds of uncertainty (100%) show that the project can be delivered 15.8 weeks earlier compared to baseline condition as the best case, compared to finish only 86.5% of the work scope at the end of the simulation as the worst case.

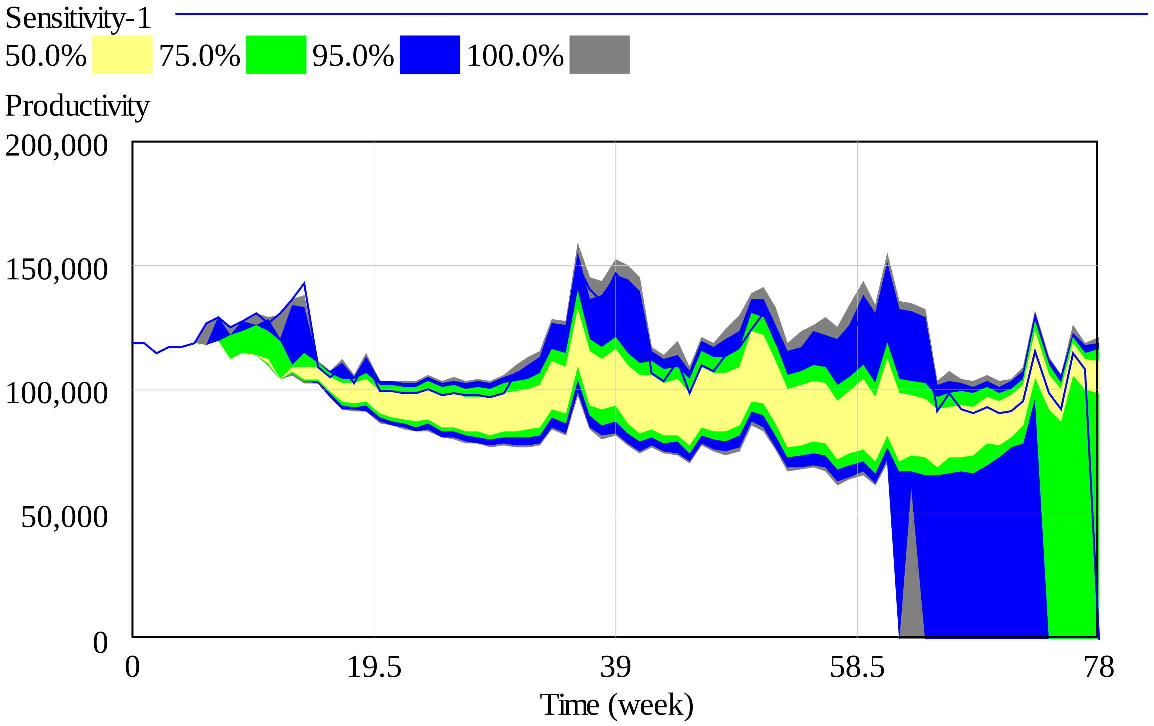


Figure 41: Sensitivity Analysis- Run #6, Productivity

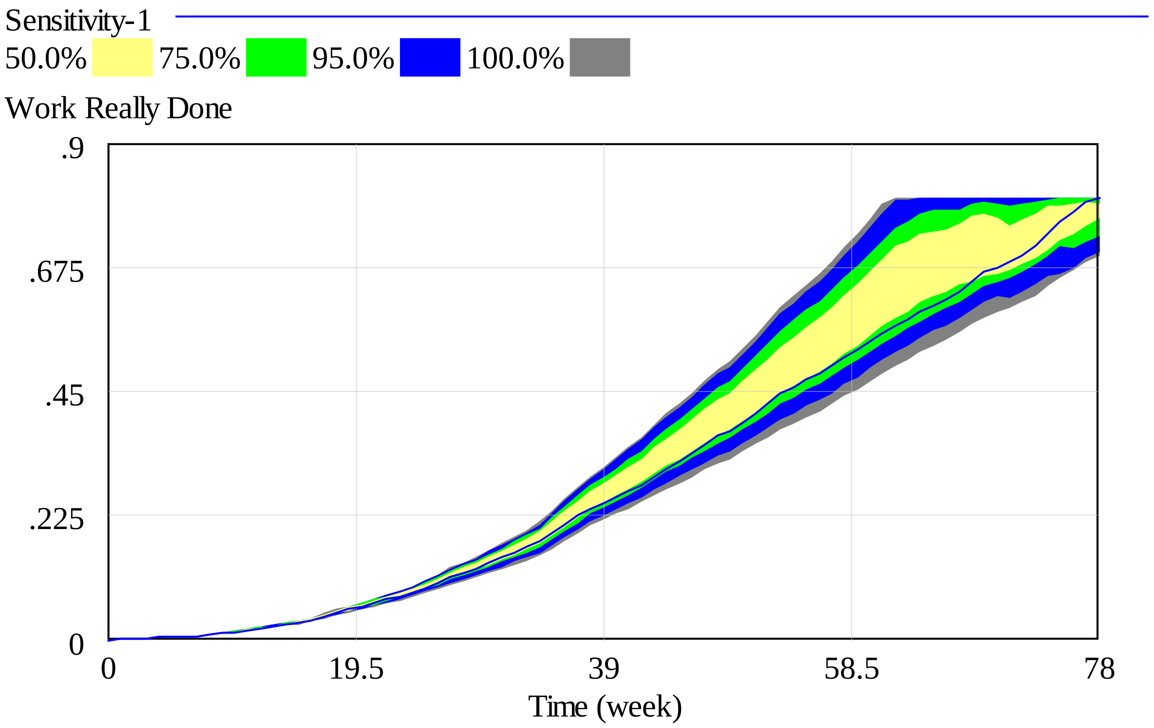


Figure 42: Sensitivity Analysis- Run #6, Work Really Done

Run #7 of the sensitivity analysis analyzed the effect of learning and crowding. Figures 43 and 44 illustrate the confidence boundaries or ranges for all potential output values of the variables, productivity and work really done, respectively.

The results of the sensitivity analysis show that, the outer bounds of uncertainty (100 %) show a 37% increase in the man-hours required to accomplished one unit, productivity, as the worst case, and an improvement in the labor productivity by 40% as the best case.

For work really done; the outer bounds of uncertainty (100%) show that the project can be delivered 14.5 weeks earlier compared to baseline condition as the best case, compared to finish only 76.8% of the work scope at the end of the simulation as the worst case.

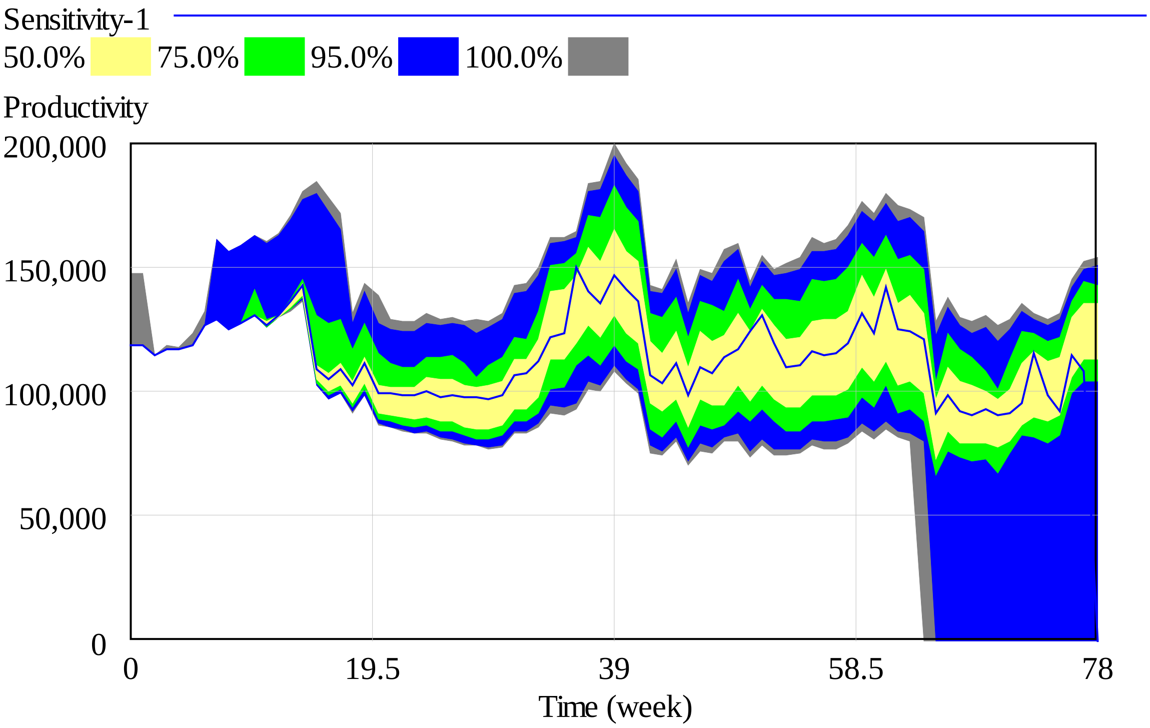


Figure 43: Sensitivity Analysis- Run #7, Productivity

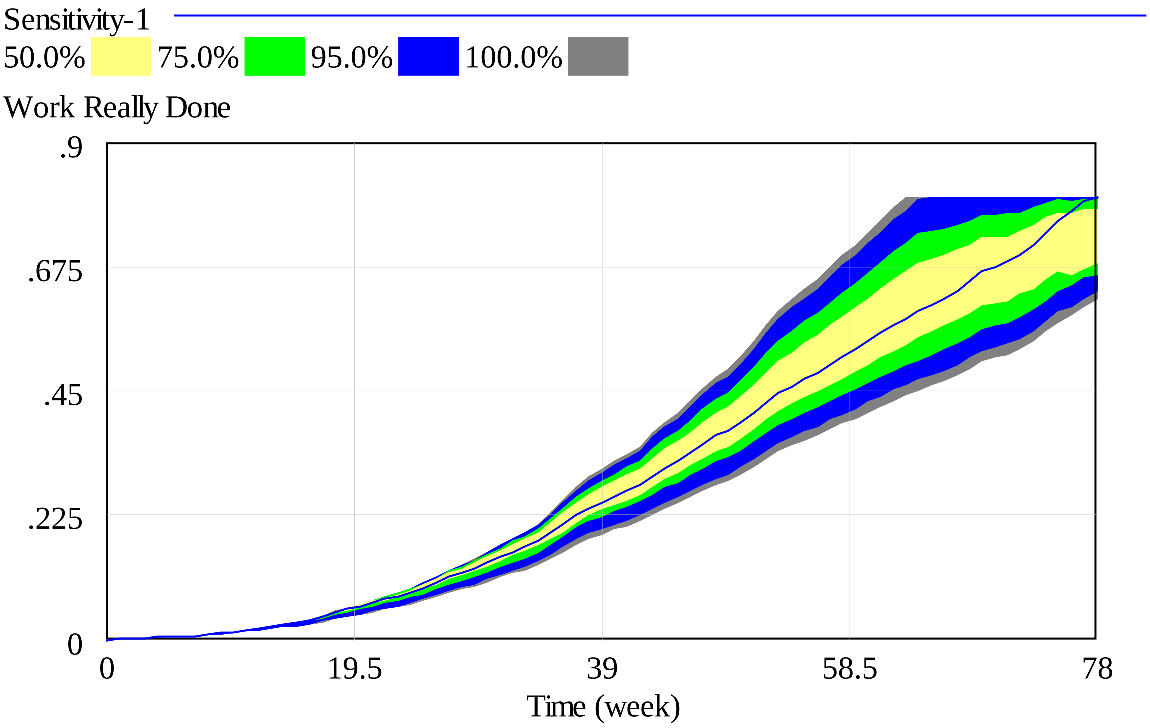


Figure 44: Sensitivity Analysis- Run #7, Work Really Done

Run #8 of the sensitivity analysis analyzed the effect of Temperature using the random uniform distribution from 54F to 91F; these values were chosen based on the maximum and minimum temperatures recorded at the project location. Figures 45 and 46 illustrate the confidence boundaries or ranges for all potential output values of the variables, productivity and work really done, respectively.

The results of the sensitivity analysis show that, the outer bounds of uncertainty (100 %) show a 18% increase in the man-hours required to accomplished one unit, productivity, as the worst case, and an improvement in the labor productivity by 4.5% as the best case.

For work really done; the outer bounds of uncertainty (50%) show that the project can be delivered 3 weeks earlier compared to baseline condition as the best case, compared to finish only 84.4% of the work scope at the end of the simulation as the worst case.

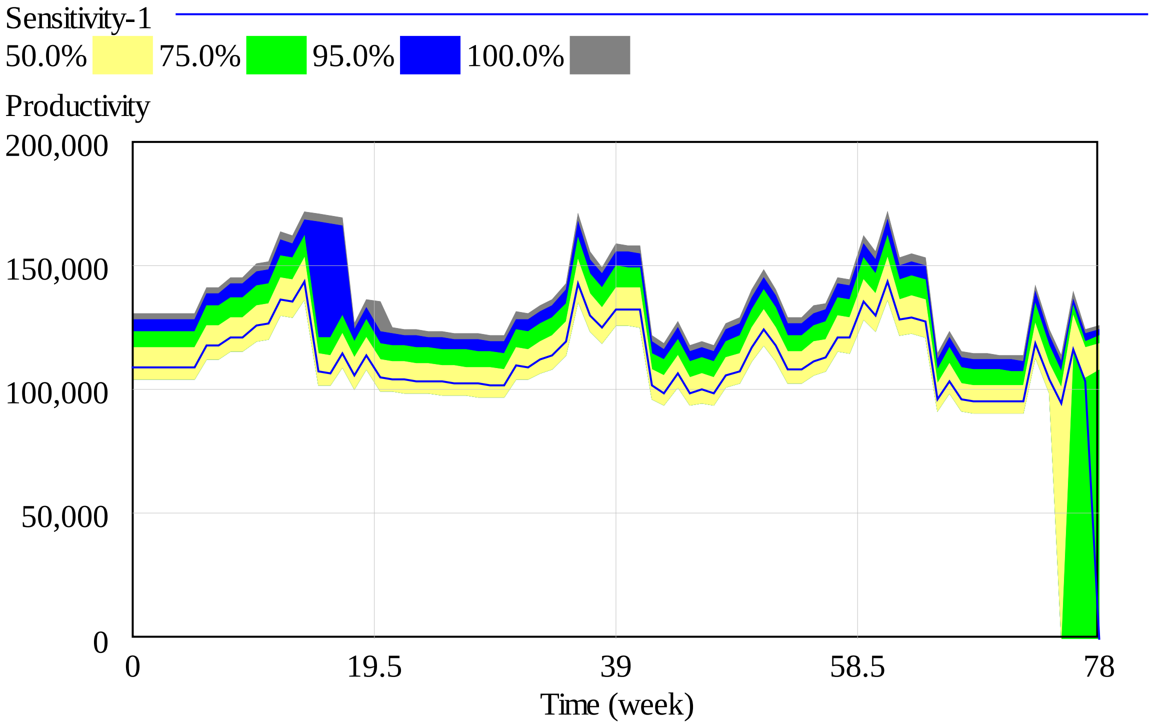


Figure 45: Sensitivity Analysis- Run #8, Productivity

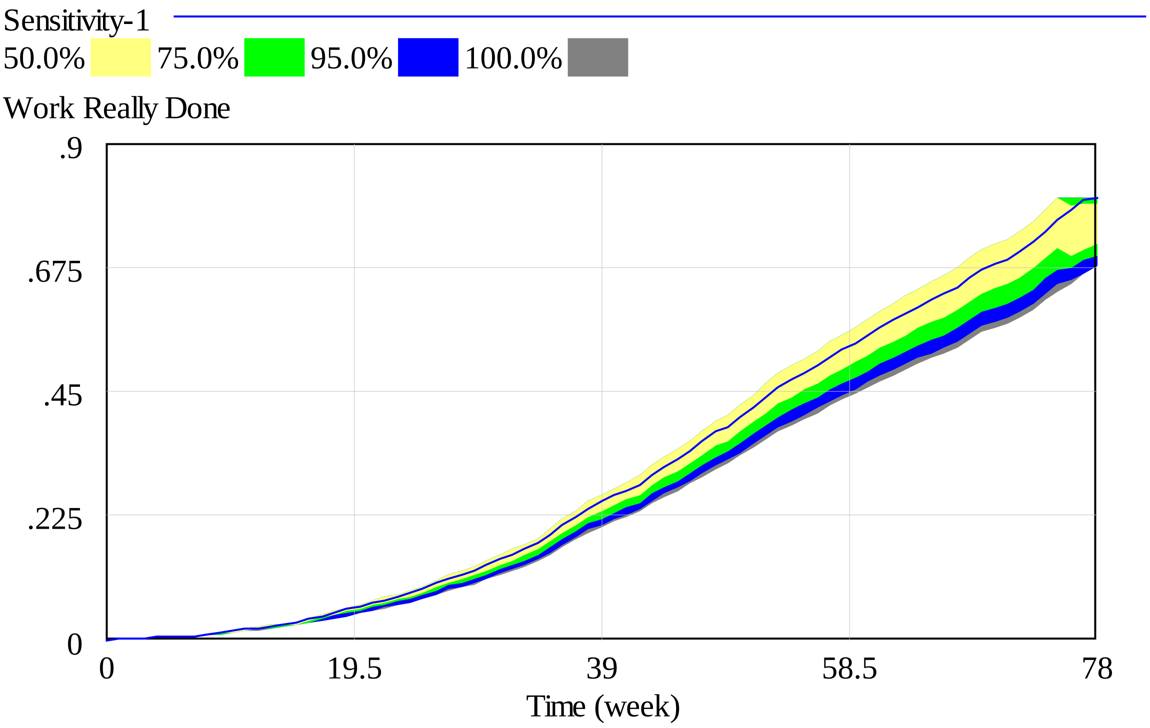


Figure 46: Sensitivity Analysis- Run #8, Work Really Done

Run #9 of the sensitivity analysis analyzed the effect of Temperature, learning, crowding, and overtime. Figures 47 and 48 illustrate the confidence boundaries or ranges for all potential output values of the variables, productivity and work really done, respectively.

The results of the sensitivity analysis show that, the outer bounds of uncertainty (100 %) show a 18% increase in the man-hours required to accomplished one unit, productivity, as the worst case, and an improvement in the labor productivity by 28% as the best case.

For work really done; the outer bounds of uncertainty (100%) show that the project can be delivered 18 weeks earlier compared to baseline condition as the best case, compared to finish only 71% of the work scope at the end of the simulation as the worst case.

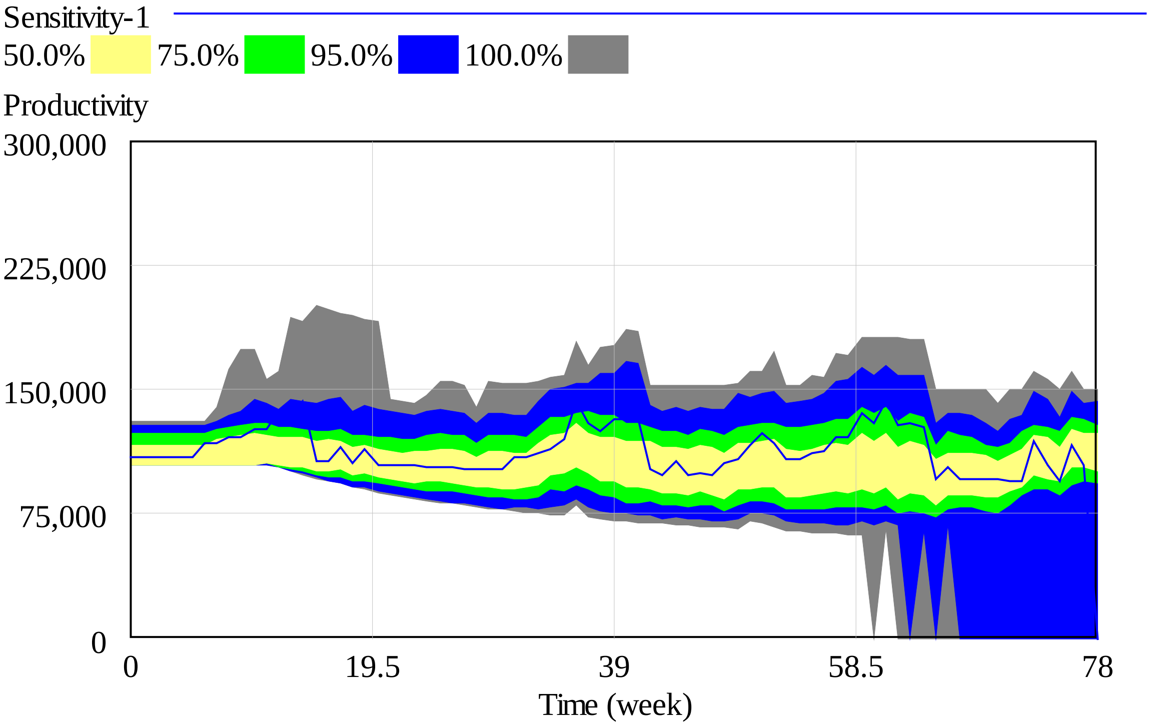


Figure 47: Sensitivity Analysis- Run #9, Productivity

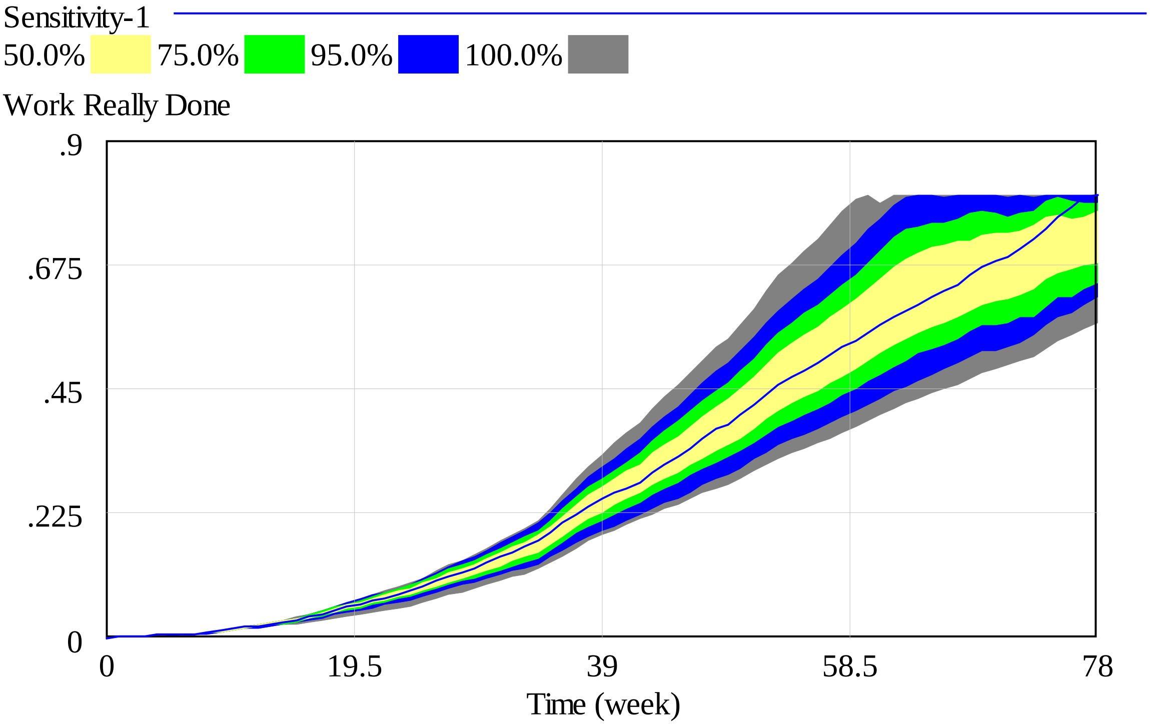


Figure 48: Sensitivity Analysis- Run #9, Work Really Done

Run #10 of the sensitivity analysis analyzed the effect of Temperature, crowding, and overtime. Figures 49 and 50 illustrate the confidence boundaries or ranges for all potential output values of the variables, productivity and work really done, respectively.

The results of the sensitivity analysis show that, the outer bounds of uncertainty (100 %) show a 26% increase in the man-hours required to accomplished one unit, productivity, as the worst case, and an improvement in the labor productivity by 23% as the best case.

For work really done; the outer bounds of uncertainty (100%) show that the project can be delivered 8 weeks earlier compared to baseline condition as the best case, compared to finish only 71% of the work scope at the end of the simulation as the worst case.

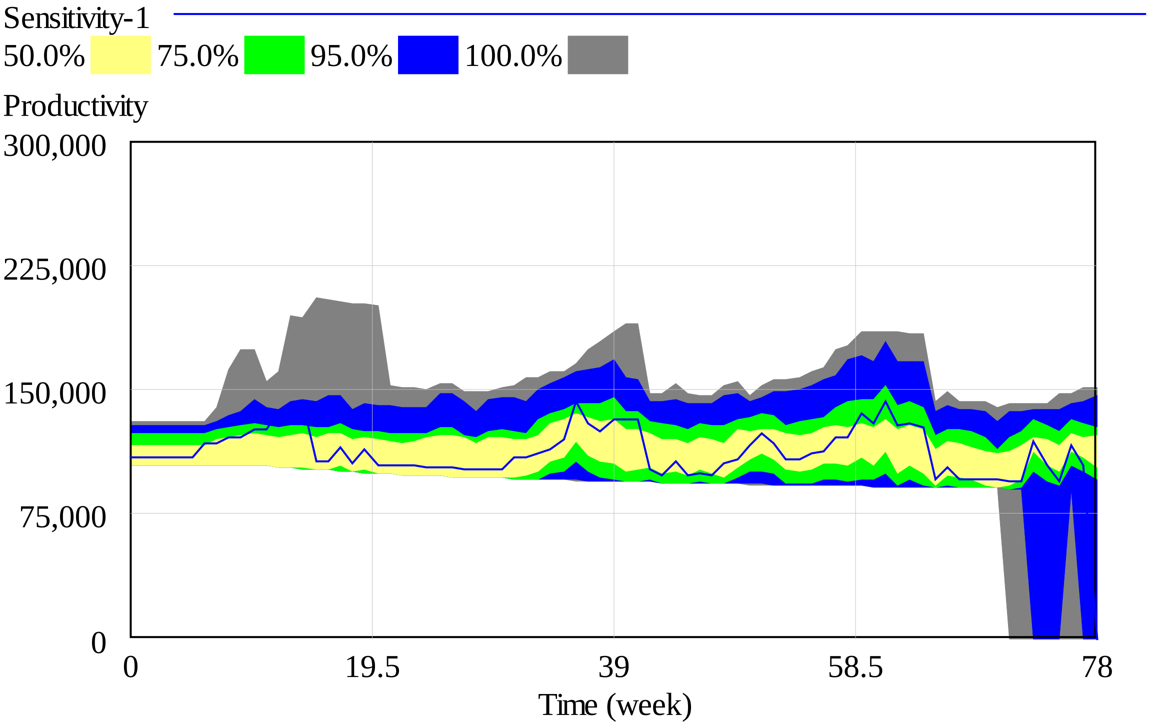


Figure 49: Sensitivity Analysis- Run #10, Productivity

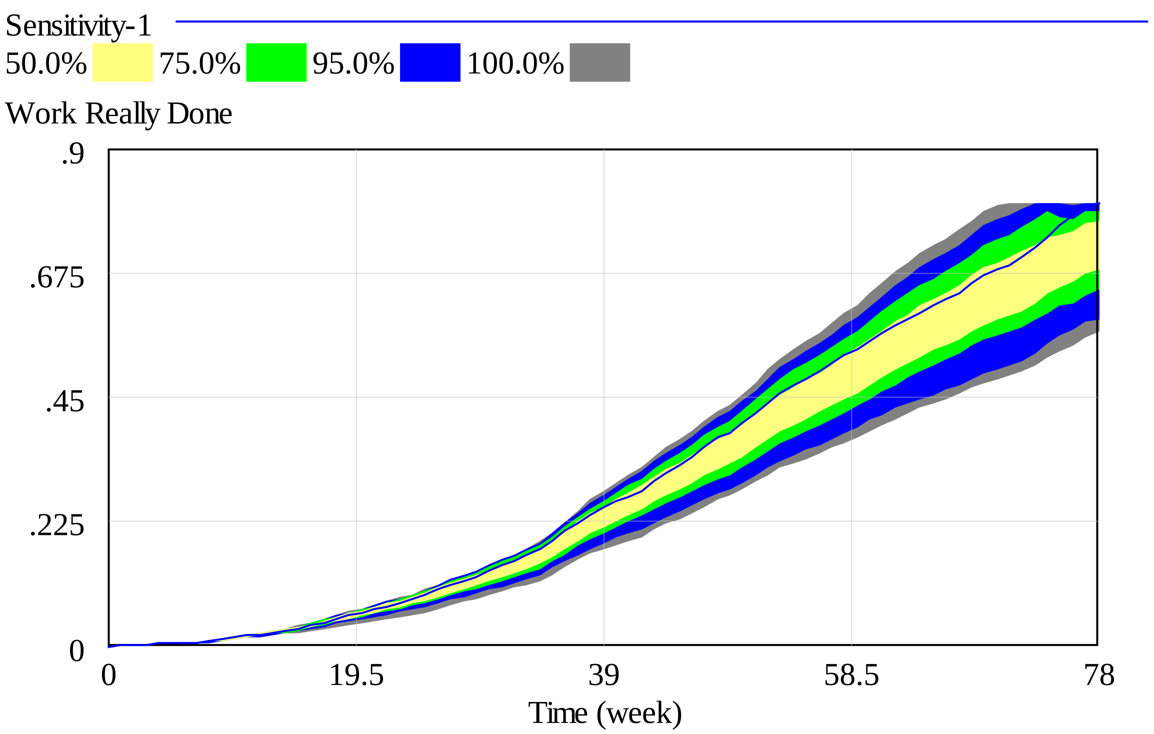


Figure 50: Sensitivity Analysis- Run #10, Work Really Done

Run #11 of the sensitivity analysis analyzed the effect of Temperature, crowding, and learning. Figures 51 and 52 illustrate the confidence boundaries or ranges for all potential output values of the variables, productivity and work really done, respectively.

The results of the sensitivity analysis show that, the outer bounds of uncertainty (100 %) show a 47.6% increase in the man-hours required to accomplished one unit, productivity, as the worst case, and an improvement in the labor productivity by 23% as the best case.

For work really done; the outer bounds of uncertainty (100%) show that the project can be delivered 17 weeks earlier compared to baseline condition as the best case, compared to finish only 66% of the work scope at the end of the simulation as the worst case.

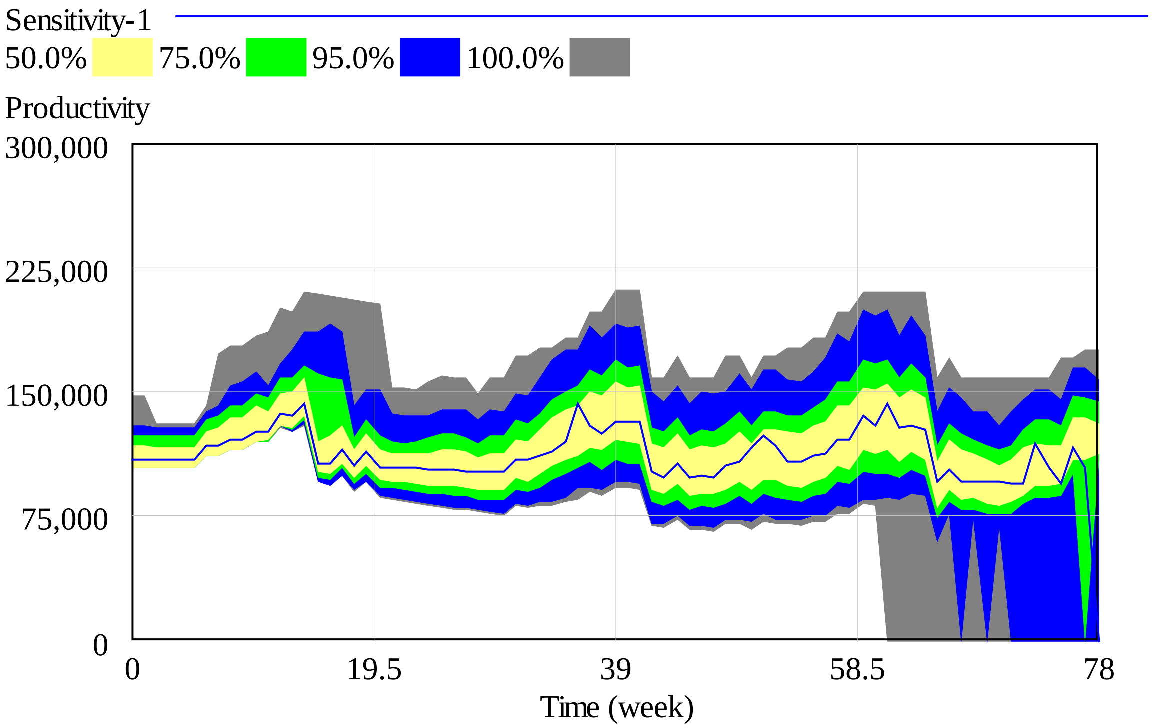


Figure 51: Sensitivity Analysis- Run #11, Productivity

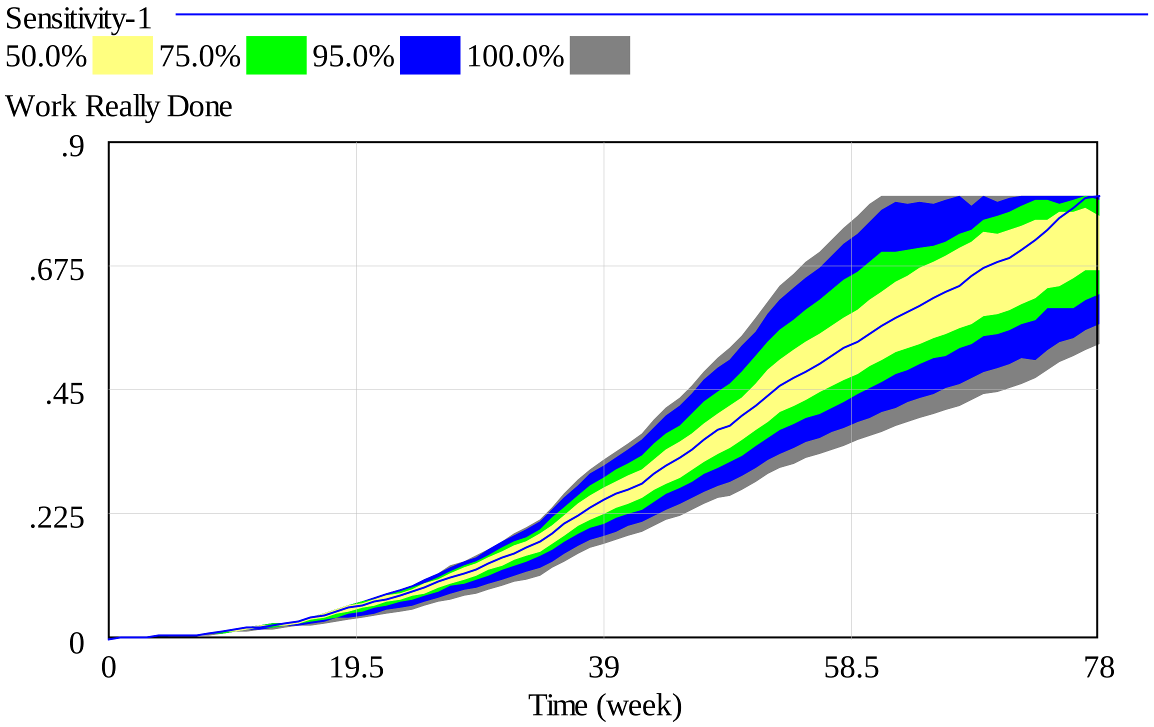


Figure 52: Sensitivity Analysis- Run #11, Work Really Done

Run #12 of the sensitivity analysis analyzed the effect of Temperature, overtime, and learning. Figures 53 and 54 illustrate the confidence boundaries or ranges for all potential output values of the variables, productivity and work really done, respectively.

The results of the sensitivity analysis show that, the outer bounds of uncertainty (100 %) show a 32.4% increase in the man-hours required to accomplished one unit, productivity, as the worst case, and an improvement in the labor productivity by 43.8% as the best case.

For work really done; the outer bounds of uncertainty (100%) show that the project can be delivered 19 weeks earlier compared to baseline condition as the best case, compared to finish only 80% of the work scope at the end of the simulation as the worst case.

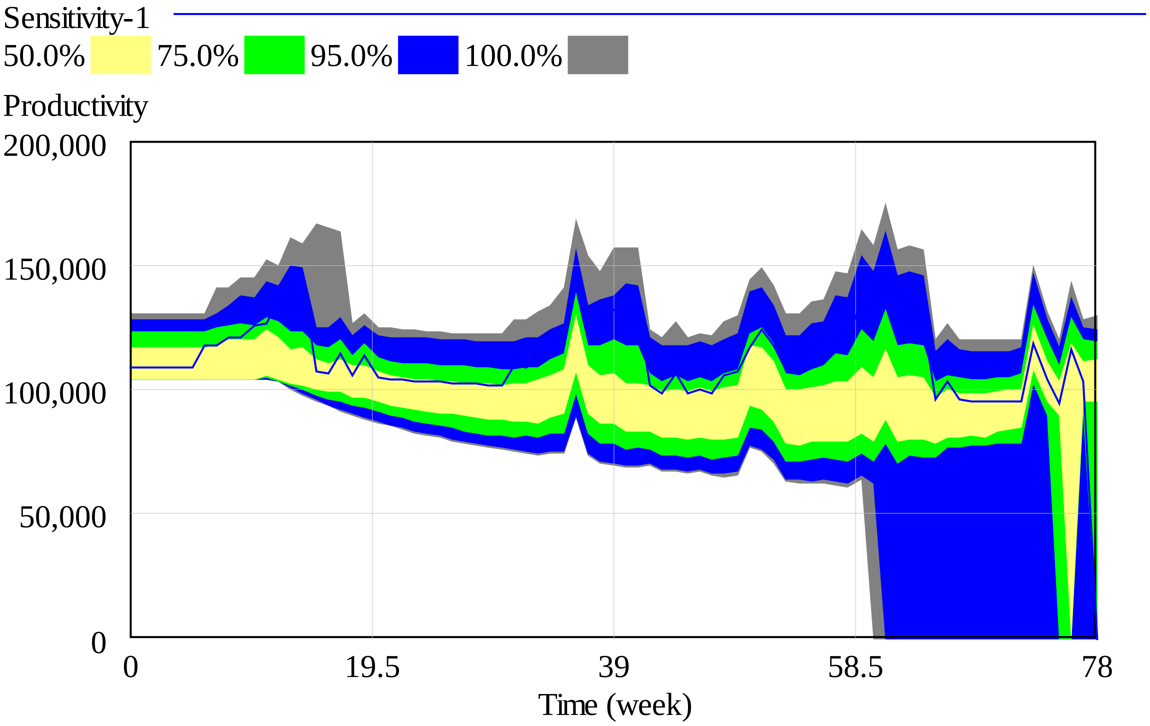


Figure 53: Sensitivity Analysis- Run #12, Productivity

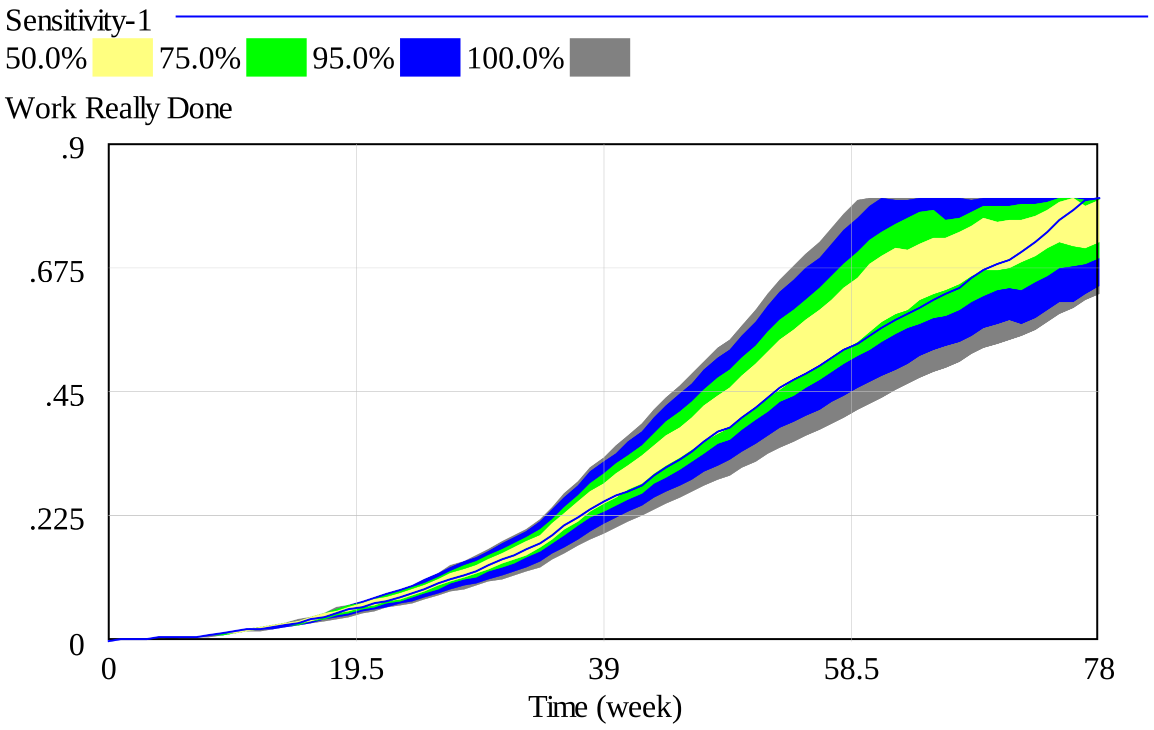


Figure 54: Sensitivity Analysis- Run #12, Work Really Done

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Background

After data collection and preparation, a system dynamics model was developed to quantify the effect of owner's change orders on man-hours needed to complete the project, as a result of productivity change. In addition to change order impact, the proposed model defines and quantifies the impacts of other contributing factors to the loss in labor productivity, namely, overtime and fatigue, temperature, labor crowding, and learning curve effect. Moreover, we performed verification and validation of the model.

4.2 Projects Analysis

Different road construction projects were analyzed using the proposed model to quantitatively measure the impact of the change in the project on labor productivity. Additionally, we assessed the consequences of this change on man-hours spent to accomplish the work during the period of project impacted by the issuance of the change order. The projects were analyzed using both system dynamics model and "Measured Mile" approach, which is considered the most acceptable and popular approach in litigation compared to all available productivity loss quantification methods. The results obtained from those two approaches were compared and conclusions were extracted.

4.2.1 Case Study #1:

FDOT has engaged a primary contractor to widen and add lanes for a road in the state project "XXXXXXX". This primary contractor hired a sub-contractor to build the cement concrete pavement of this road. The scope of work of this sub-contract included placing 74781SY plain cement concrete pavement (12 1/2"). The cost of the work was agreed in

$5,608,575.00. After 12 weeks of work, a change order (Supplemental Agreement) was issued by the owner to increase the scope of work by 11%, due to the plan's modification.

The model was employed to analyze the impact of change order on labor productivity based on the FDOT daily work reports, contract documents, change orders, and inspection reports. The results of the model were then compared with the actual data, and the results obtained from the measured mile approach.

Referring to Figure 55, the distance between the red lines presents the period in which the contractor work is impacted by the change order. Based on the unimpacted period it can be verified that the contractor best performance on site during the unimpacted period is almost 0.3381 man-hours per unit. This value is the measured mile value, as well as the baseline value used to start the model simulation.

Figure 56 demonstrates the change in laborers' productivity along the project period for the actual data, measured mile approach, and system dynamic modeling simulation. It can be clearly seen that the contractor's laborers were working inefficiently even prior to the issuance of the change order when comparing the actual productivity values to the measured mile productivity values. Using system dynamics simulation, the reasons behind these inefficiency values can be explained by calculating the expected labor productivity on site after introducing the factors that might affect their productivity. Namely, these include fatigue due to change order, overcrowding, temperature, and learning curve effects.

The analysis shows an average loss of 11% along the project length, due to placing the available personnel on extended overtime. The loss in this case can be attributed to the fatigue effect, whereas 3% average loss in productivity occurred due to overmanning. This loss can be explained by the crowding effect on productivity; as the number of laborers increased onsite, so increased site congestion, which negatively affects productivity. Less than 1% of loss in productivity is attributed to temperature effect. The results also show an average increase of 20% to labor productivity due to learning effect; this can be attributed to the experience gained by the labor each time they repeat the same activity.

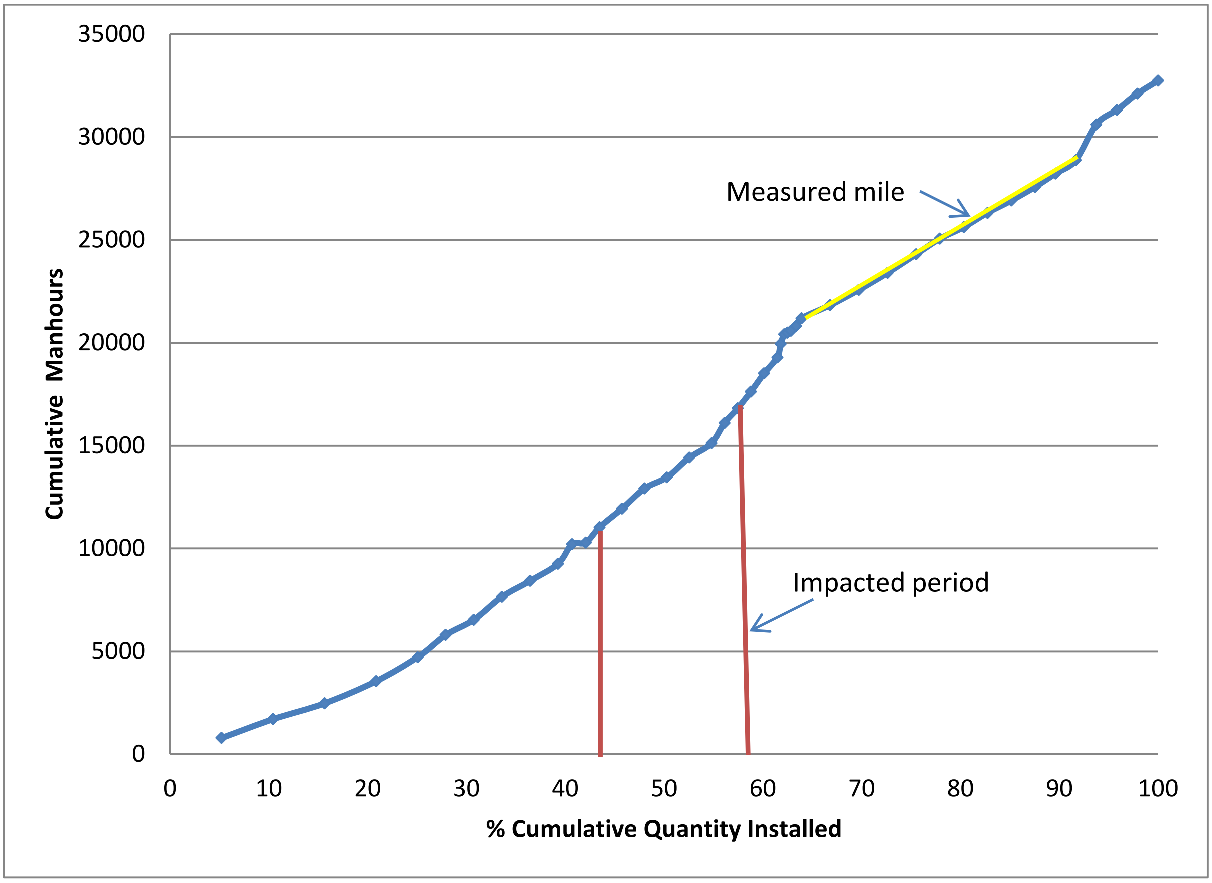


Figure 55: Case #1- Actual % Cum. Quantity Installed Vs. Actual Cum. Man-hours

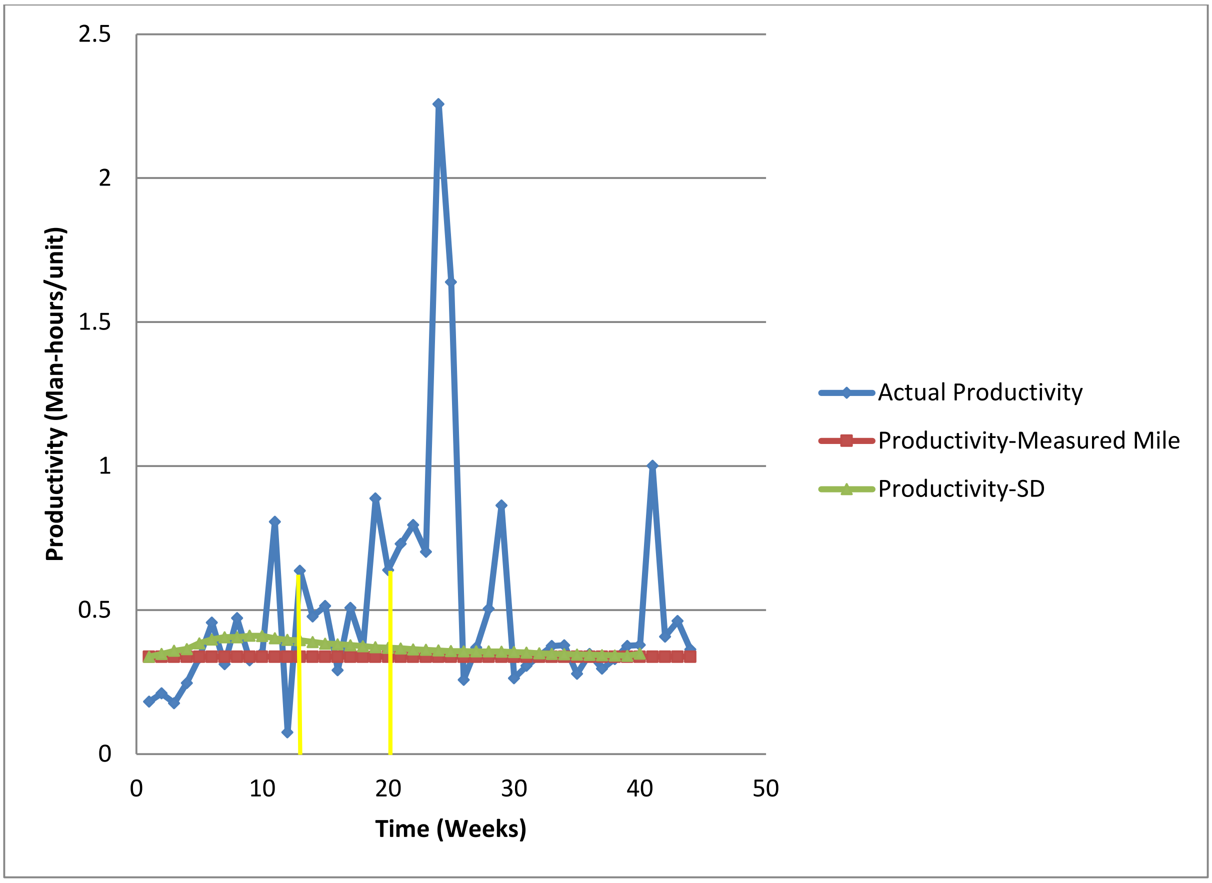


Figure 56: Case #1- Time vs. Productivity

Figure 57 presents the relationship between percent of cumulative amount installed and actual cumulative man-hours spent during installation. According to the Figure, it took fewer actual labors-hours to install the first 15% of the project than the estimated labors-hours from both measured mile and system dynamics models. This can be attributed to the freshness of the labors at the beginning of the project, the first three weeks of the work. Later on - and considering the placement of the available workers on overtime, crowding of labors in some periods of the project - the number of labor-hours needed to install a certain amount of units increased. This dynamic is demonstrated by the increase in the slope of the actual data series.

In the system dynamic series, a steeper slope can be seen in the beginning as a consequence of the effect of fatigue and crowding on productivity. However, as the labors repeat the same activity more and more, they gain experience, which makes the tasks easier to perform. As a result, we verify decrease in time and effort needed to perform the task, leading to improvement in labor productivity. It also can be seen, based on the system dynamics model, that the project can be completed with fewer total number of work hours (29054 hrs.) which are delivered earlier (40 weeks) than the actual values of 32747 hrs. and 44 weeks, respectively.

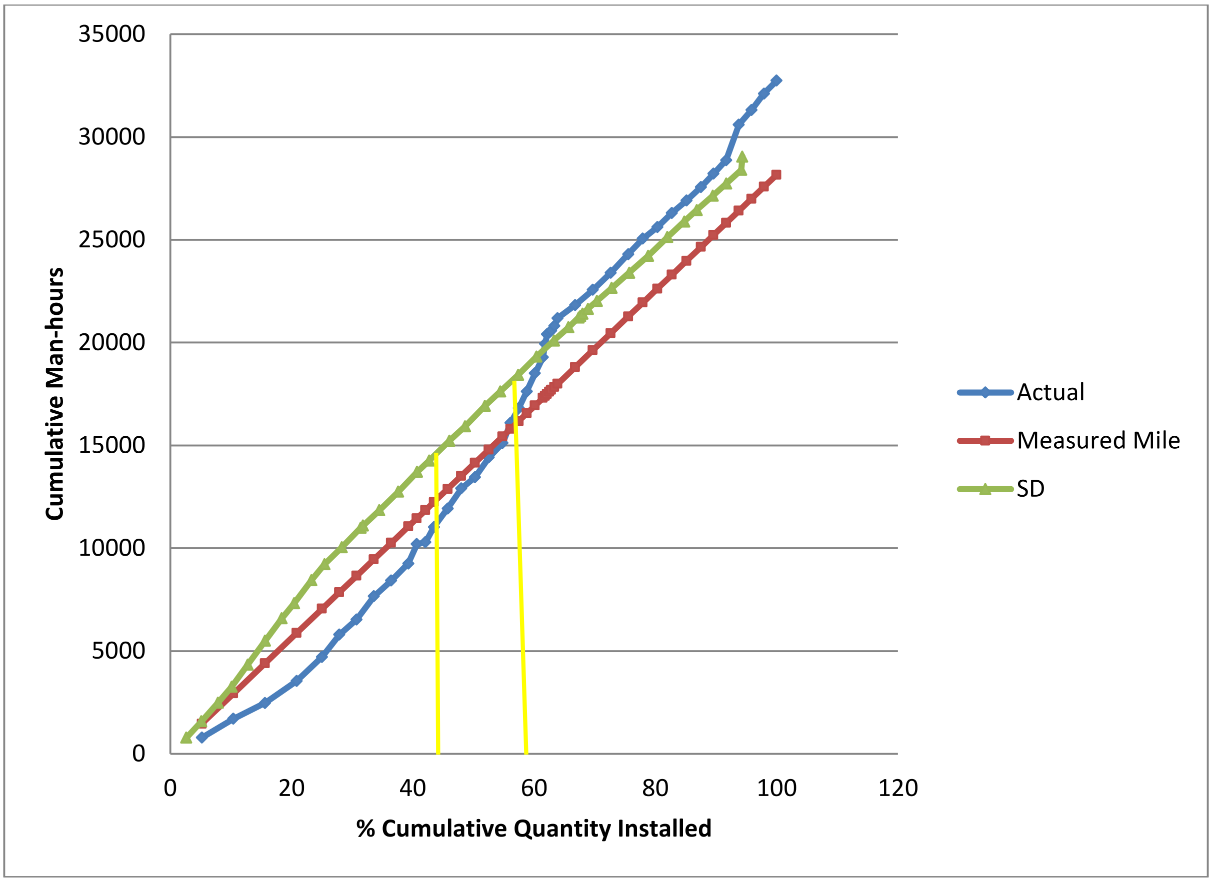


Figure 57: Case #1- % Cumulative Quantity Installed Vs. Cumulative Man-Hours

The calculations for the inefficient work hours during the impacted period of the project are shown in Table 6.

Table 6: Case #1- Calculation on Inefficient Work Hours

week	Work hours	Quantity installed	Should have - Measured Mile	Inefficient Work (Measured Mile)	Work hours-SD
13	745	1170.33	395.69	349.31	111
14	902	1885.92	637.63	264.37	745
15	970	1885.92	637.63	332.37	902
16	550	1885.92	637.63	-87.63	970
17	958	1885.92	637.63	320.37	550
18	704	1885.92	637.63	66.37	958
19	987	1110.80	375.56	611.44	704
20	710	1110.80	375.56	334.44	987
Total	6526		4334.96	2191.04	5927

Therefore, using the measured mile approach, the contractor will request the owner to be compensated for 2191 man-hours due to productivity loss. In contrast, when using the system dynamics modeling approach, it can be seen that the extra man-hours used by the contractor (599 man-hours) are not justified.

4.2.2 Case Study #2:

FDOT has engaged a primary contractor to perform an 8-mile road resurfacing in the state project number “XXXXXXX.” The total bid amount equals to $ 3,396,600.00. After 28 weeks of work, a change order (Supplemental Agreement) was issued by the owner to increase the scope of work by 3% due to plan’s modification.

The model was employed to analyze the impact of the change order on labor productivity, based on the FDOT daily work reports, contract documents, change orders, and inspection reports. The results of the model were then compared with the actual data and with the results obtained from the measured mile approach.

According to Figure 58, the distance between the red lines presents the period in which the contractor work is impacted by the change order, based on the unimpacted period. It can be observed that the contractor's best performance on site during the unimpacted period is almost 8948.4 man-hours/unit. This value is the measured mile value, and the baseline value used to start the model simulation.

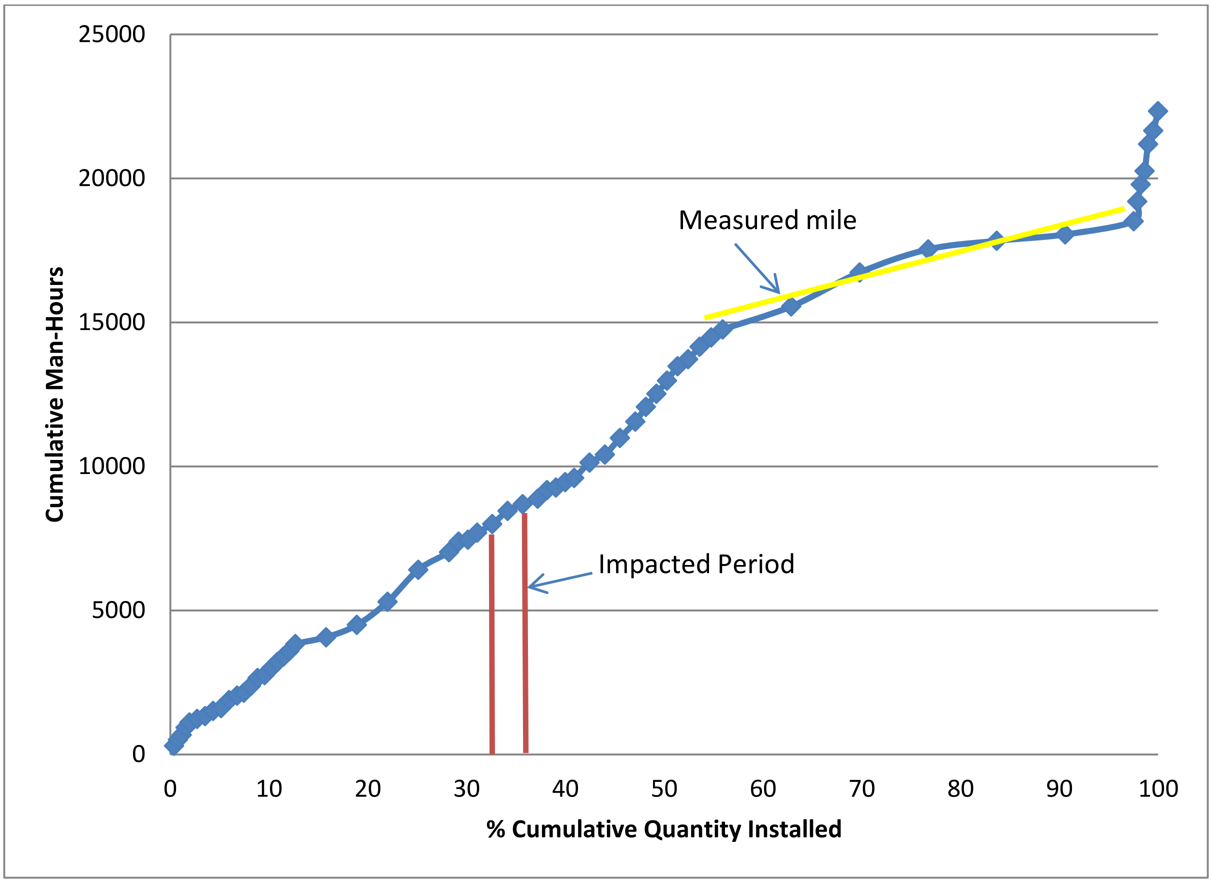


Figure 58: Case #2- Actual % Cum. Quantity Installed vs. Actual Cum. Man-Hours

Figure 59 shows the change in laborers' productivity along the project period for the actual data, measured mile approach, and system dynamic modeling simulation. It can be verified that the contractor’s laborers were working inefficiently, even prior to the change order issuance when comparing the actual productivity values to the measured mile productivity. Using system dynamics simulation, the reasons behind these inefficiency values can be explained through the results of expected labor productivity on site after introducing the factors that might affect their productivity, namely, fatigue due to change order, overcrowding, temperature, and learning curve effects.

The analysis reveals an average loss of 3% along the project length, occurred due to placing the available personnel on overtime. The loss, in this case, can be attributed to the fatigue effect. Also, about 2% of average loss in productivity occurred due to overmanning. This loss can be explained by the crowding effect on productivity since the number of laborers increased onsite, leading to site congestion and negatively affecting productivity. About 7% of loss in productivity is attributed to temperature effect. The results also indicate an average increase of 27% to labor productivity due to learning effect which can be attributed to the experience gained by repeating the same activity.

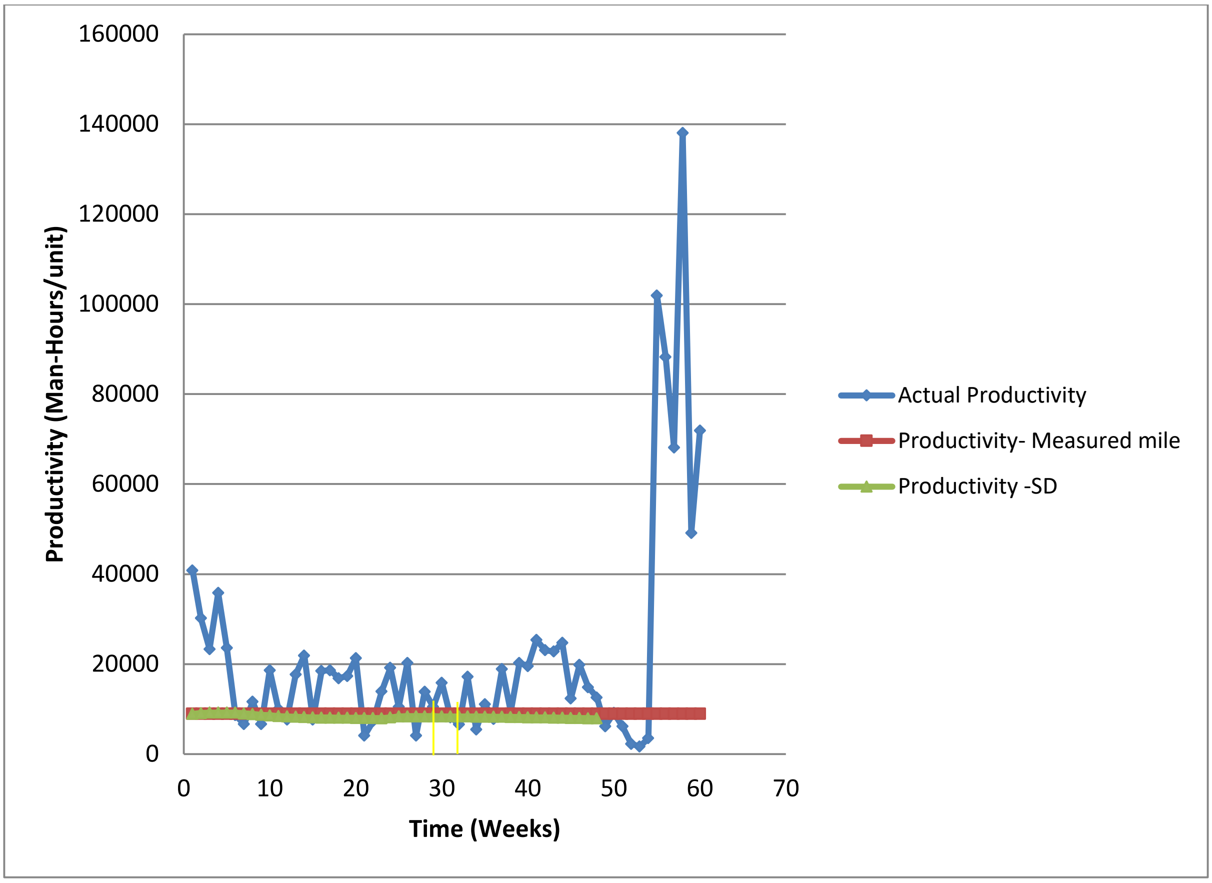


Figure 59: Case #2- Time vs. Productivity

Figure 60 displays the relationship between percent of cumulative amount installed, and actual cumulative man-hours spent during installation. According to the Figure, an expressive number of working hours is not justified when comparing the estimated laborers' hours using system dynamics simulation and that which were actually spent on site.

The system dynamic series starts revealing a reduction in the slope after execution of about 63% of the project work. We can imply that the effect of learning starts to play an important role in improving productivity as it eliminates the negative impact of fatigue, crowding and temperature on labor productivity. Based on the system dynamics model results, the project can feasibly be completed with fewer total number of work hours (15184.3 hrs.) and delivered earlier (48 weeks), compared to the actual values of 22338 hrs. and 60 weeks, respectively.

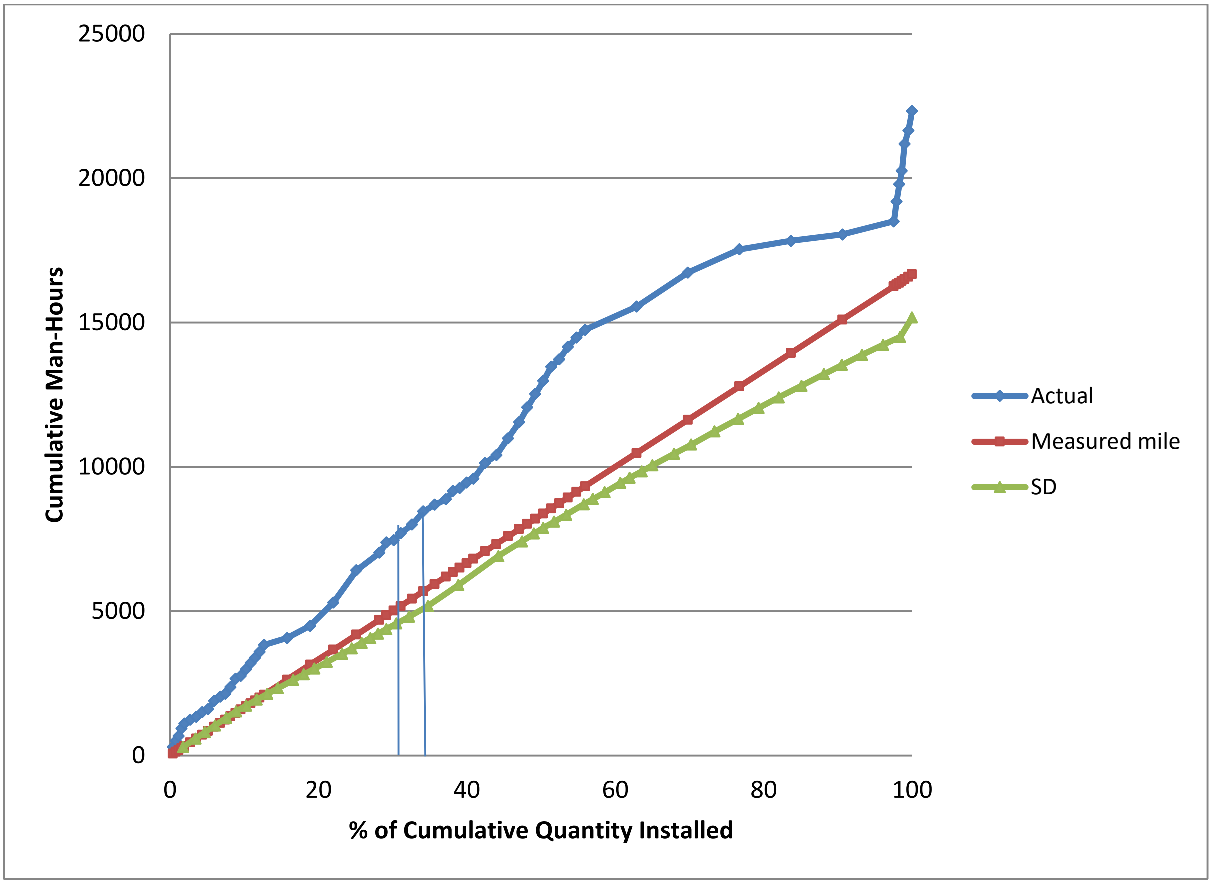


Figure 60: Case #2- % Cumulative Quantity installed vs. Cumulative. Man-Hours

The calculations for the inefficient work hours during the impacted period of the project are shown in Table 7.

Table 7: Case #2- Calculation on Inefficient Work Hours

Week	Work hours	Quantity installed	Should have worked-Measured Mile	Inefficient Work - Measured Mile	Work hours-SD
29	300	0.03	255.03	44.97	240
30	453	0.03	255.03	197.97	365.89
31	234	0.03	255.03	-21.03	184
Total	987		765.09	221.91	789.89

Therefore, using the measured mile approach, the contractor will request the owner to be compensated for 221.91 man-hours due to productivity loss, whereas using the system dynamics modeling approach, it can be seen that the extra man-hours used by the contractor (197 man-hours) are not justified.

CHAPTER 5: CONCLUSIONS

This research highlighted the problem of productivity loss resulting from owner-liable change orders in construction projects. Focus was on disagreements on quantification method of changes and resultant productivity loss costs in road construction projects Therefore, we developed and validated a system dynamics model to analyze the changes in labor productivity due to owner change orders to address the disputes between owner and contractor. Subsequently, we analyzed different road construction projects using two methods: measured mile analysis and system dynamics model. The results were compared and analyzed as follows.

The research strengths are:

- Most productivity loss studies were financed from the contractor part and rely on the contractor's data. In this research, however, the data used derived from the owner part and includes daily work reports of the owner, contract documents, change orders & inspection reports.

− Base line productivity helps prove what portion of the productivity loss can be attributed to the owner changes. This compares the best productivity achieved by the contractor, which is the model's baseline productivity, with actual hours.

− The model takes into account not only the work-hours, but also the amount of items installed. The productivity shows improvement due to learning curve theory, which states that productivity rises with the increase of the quantity installed. Thus, including the quantity installed to the analysis allows for the learning curve to be applied to productivity loss analyses.

- The model accounts for the non-linear behavior that real projects experience.

- The model provides causal logic to explain why the impact of disruptions and delays would lead to productivity loss and result in an increase of working hours needed to complete the project.

The major findings in the research:

-The measured mile approach argues that an unimpacted part of the project is analyzed to determine the actual productivity along the project period. In productivity loss claims, the analysis assumes that the difference between actual outcomes and the measured mile prediction is all claimable, whereas some or all of this difference may be under the contractor' responsibility. Using the system dynamics modeling, the productivity loss is linked to its causes, thus the inefficiencies due to the contractor part are able to be considered during the calculations.

- As the percent of scope change increases, the difference between the measured mile and the system dynamics model predictions become larger.

- The quantity installed has a great impact on the productivity improvement, a phenomenon explained by the learning curve theory.

- The temperature has a great impact on the labor productivity.

Research Contributions:

- Most of the published models that study the problem of loss of productivity suggested linear models (Hanna 1999a, Hanna 1999b, and Serag,2010) while in this research the nonlinear relationships between different factors and productivity are taking into account during the model formulation.
- For the contractor to be entitled to compensation; the productivity claim must prove that the contractor suffered a loss; the owner caused the loss, and the value of the loss. The available methods used to quantify the loss in labor productivity; assumes that all the loss during the impacted period is due to the owner part which is not always true.

Using the system dynamics modeling, the productivity loss is linked to its causes, thus the inefficiencies due to the contractor part are able to be considered during the calculations.

For future researches more variables should be studied to check their impact on the productivity loss.

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