Fall 1-18-2021

Using System Dynamics to Study the Effect of Change Orders on Labor Productivity

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USING SYSTEM DYNAMICS TO STUDY THE EFFECT OF CHANGE ORDERS ON LABOR PRODUCTIVITY

A thesis Submitted to the

School of Sciences and Engineering

Construction Engineering Department

In partial fulfillment of the requirements for the degree of

Master of Science in Construction Engineering

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January 2020

Acknowledgment

I would like first to thank God for enlightening my path, giving me strength and ability to pursue my studies and finish this research.

I would like to express my sincere appreciation to my advisors Dr. Ossama Hosny, Dr. Ahmed Waly, and Dr. Ibrahim Abotaleb for guiding me throughout my research and giving me support and advice. Their valuable knowledge, motivation and mentorship have inspired and helped me through my research.

Sincere gratitude goes to my mother, Anhar Aly, for her profound support, love, prayers, and passionate encouragement, not only in this research, but in my whole life. Special thanks to my father, Adel Gharib, for being a role model for us and always supporting. Special thanks to my sibling, Eng. Nermeen Gharib for her continuous support and help.

Finally, I would like to thank my friends and colleagues who gave me support and advice whenever needed.

Abstract

Change orders in construction projects lead to numerous negative impacts, including loss of labor productivity, delays, and cost overruns. Owners and contractors are usually in disagreement when it comes to allocating the extent of responsibilities with respect to the resulting overruns. Each party tries to hold the other party fully responsible for such overruns through a series of claims and disputes. Several delay analysis techniques have been developed to aid in settling such disputes, however they do not fully grasp the rippled impacts of change orders and do not assist parties in reaching consensus when it comes to finding the isolated rippled impacts of each change order.

This research aims to develop a framework that supports delay analysis based on dynamic modeling with a focus on the impacts of change orders. System dynamics is utilized as the base modeling methodology due to its capability of capturing rippled impacts and complex interrelations. A novel calibration methodology is also developed to enable using this framework in any construction project. After development and verification, the framework was tested on a sample construction project that faced delays due to change orders. The developed model was able to quantitatively link the productivity losses and delays to each change order, which helped in clearly allocating the responsible parties for the delays. In addition, several what-if-scenarios were conducted to enhance the understanding of how such impacts could have been avoided. This research is envisaged to support owners and contractors in quickly reaching consensus regarding the impacts of change orders; thus, minimizing the corresponding disputes and fostering a healthier contracting environment.

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CHAPTER 1

INTRODUCTION

CHAPTER 1: INTRODUCTION

1.1 Overview

Construction projects comprise several interrelated systems; such as structural, mechanical, electrical, and others. Manipulating one system can result in unexpected change for the rest (Taylor and Ford 2008). Such changes can have adverse effects on productivity, and thus on the overall project schedule and budget. Changes can take place in the specifications, plans, design, equipment, materials, used technology, temporary facilities, time of performance, personnel, construction method, and external conditions (US Government 1984). Change orders have always been an immanent part of the construction industry. It is difficult to come across a construction project that has been executed free of change, which is usually the case since there are more than one party involved in the project's execution (Alaryan and Elbeltagi 2014). The contractual clauses concerning change orders give the Employer the opportunity to freely initiate change orders within the scope of work without altering original contract (Enshassi et al. 2010). As stated by Sterman (1992), in construction projects, change is the expected rather than the anomaly. The resulting changes do not only interfere directly with the workflow, but also have indirect rippled impacts, such as loss of labor productivity and interruptions in workflows, which will result in completing the tasks in larger durations and additional costs. Eventually, these changes lead to disputes between contractors and owners on quantifying the real impacts and allocating the accountable party for the impacts of each change.

Change orders are common in most projects due to the distinguished nature of each project and the limited time and money given for planning. Change can be defined as the event that causes any variation in the project’s original scope of work, design, materials, execution time, or cost of work (Taylor et al., 2012). Change orders arise from different causes. It was found that changing the scope of work by the owner was on the top of the causes, in addition to design errors, and owner’s financial deficiency (Ismail et al., 2012). These change orders have mostly negative impacts on projects.

According to Keane et al. (2010), change orders impacts can be divided into five main categories: (1) time, (2) quality, (3) cost, (4) administrative related impact, and (5) other impacts.

In this research, the focus is geared more towards the impacts of change orders on labor productivity, which in turn impacts time and cost.

1.2 Quantifying the Impacts of Change Orders

The current methodologies for quantifying the impacts of change orders can be categorized into (1) statistical methods, and (2) delay analysis (Serag, 2006). Statistical methods are based on data from several previous projects; where correlations are derived between the change orders in these projects and the corresponding actual impacts that took place. These methods are suitable for predicting the impacts of change orders in future projects, and for providing general statistical information that helps gain insights on how change orders generally impact projects. However, these methods cannot be used for project-specific insights; meaning that when change order takes place in an ongoing project, theses statistical methods cannot be used due to their generalized nature. In this case, delay analysis is used, where certain heuristics are utilized to determine the impacts of concurrent delays that take place due change orders or any delay-causing event in the project. The following sub-sections provide a brief description of the popular statistical methods and the common delay analysis methods used in the industry.

1.2.1 Statistical Methods for Quantifying the Impacts of Change Order

Leonard (1988) carried out one of the earliest research efforts to quantify the effect of the change on labor productivity. Graphical representations helped Leonard represent the correlation between the project's change orders and the accompanying productivity losses. He found that the main reasons behind changes are low labor self-esteem, absence of engineering support, increased work performance, and out of sequence work, which resulted in productivity losses. Hanna (2004) developed a linear regression model to quantify the impact of change orders on labor productivity for small projects at the University of Winsconsin-Madison. Hanna et al. (1999a & b) formulated two statistical models for construction electrical and mechanical projects to estimate labor productivity losses due to change orders. Hanna (2001) cooperated and succeeded in building two models: (a) a logistic regression model that can calculate the probability that projects will be affected by the change order, and (2) a linear regression model that forecasts the lost productivity in a given project due to change orders. In addition, in 2017, Hanna and Iskandar conducted a study using a larger sample of 68 projects focusing mainly on developing a well-analyzed statistical model that predicts lost productivity hours accurately.

Zink (1986) lead a research using the measured mile approach. According to Zink (1986), measured mile approach is identified as the optimum method for calculating lost productivity. His results compare similar activities in both affected and non-affected areas by a change to quantify what leads to inefficient productivity from the change. This technique is favorable since it only accounts for the claimed impact, which tends to avoid questions about the bid estimates' validity. Nevertheless, this approach becomes less ideal in unstable projects since isolating a non-affected period can be difficult.

1.2.2 Delay Analysis

Delay Analysis is a retrospective analysis that is used to quantify the delays that occurred in a construction project and find the responsible party for each of these delays (SCL, 2017). Reports indicate that the majority of construction projects get delayed (OGC 2003). According to Ndekugri et al. (2008), construction project delays frequently happen as a result of several interacted events, in which part of them is the contractors' risk, while others are the owners. These delays are occurrence of any event that will withhold the contractor from achieving the scheduled progress of the project. There are several delay analysis techniques, according to (SCL, 2017.; AACE, 2011; Reams, 1990; and Leary and Bramble, 1988) these techniques are: (1) As-Planned versus As-Built; (2) Impacted As-Planned;(3) Collapsed As-Built (4). Window Analysis; ;(5) Time Impact Analysis. and Details of these methods are described in Chapter 2.

It is challenging to identify the delays caused by a change order. Delay analysis techniques generally target the delays as whole, and not considering the isolated impacts of each delaying event (Al-Kofahi, 2016). There is a gap in the literature when it comes to having the ability to quantify the rippled indirect impacts of change orders and isolate the impacts of each change order. In addition, all these delay analysis methods are based on the critical path method (CPM); which only considers the project activities without considering other parameters such as the productivity of the workforce, the errors in execution, and others.

Due to the limitations of the current statistical and delay analysis methods in quantifying and isolating the rippled impacts of change orders, this research intends to utilize a relatively newer modeling technique, which is system dynamics (SD), as discussed in the following sub-section.

1.3 System Dynamics:

According to (Schwaninger, 2016), system dynamics – often referred to as Systemics – describes a range of wide interconnected different systems leading to a certain result rather than a single system approach. This introduces the wide interest in complex dynamic systems which resemble the reality much better and from this approach, the following definition was introduced by Schwaninger (2016) "System dynamics (SD) is a discipline and a methodology for the modeling, simulation and control of complex, dynamic systems".

The concept of system dynamics was introduced by Professor Jay W. Forrester in 1950s in MIT and has been studied by his students ever then. The MIT definition was about defining the issues or factors as meshes of closed feedback loops connected with lines as flows or relations (Schwaninger, 2016). These relations are in a continuous time domain and are subjected to different delays. The system dynamics may represent the strongest tool in defining the systemic thinking where it illustrates the true dynamic relations between the factors of the systems as much as possible which gives better solution to the proposed problems.

Another definition for the system dynamics was proposed by (Duggan, 2016) which is quoted from the general definition of the model is as following "an external and explicit representation of part of reality as seen by the people who wish to use that model to understand, to change, to manage and to control that part of reality". The numerical system represents part of the reality than needs to be analyzed and managed. This representation includes external and internal relations and precise description. The stocks defining the relations need to be found then the flows and feedbacks are interpreted for the relevant solution for the proposed problem. Stock and Flows can be explained as follows for example, in a factory a stock would be the number of employees working there while the flows are usually inflows, which is the hiring rates and outflows, which is the quitting or layoff rates This simulation approach follows the integration mathematical method where the stocks accumulate their inflows for reaching a solution. The system dynamic systems are finally presented by a series of equations which can be solved using certain simulation tools such as R framework, Anylogic, Vensim, Matlab, and others.

According to Abotaleb (2018), system dynamics building blocks are based on four different types of variables; (1) the level variable which is referred to as (stock), that stock describes the condition of the system; (2) the rate variable which represents the dynamic change in a given period and is mostly connected to the stock and represents the inflow and outflow as shown in

Figure 1; (3) auxiliary variable which is driven from others at a given time and is basically a numerous variable;(4) data variable which is the exogenous elements in which its value change over time but yet independent of anything that might occur to any other variable and aside from the four variables there is a constant which does not change but sometimes if it will be changed it has to be before the simulation run.

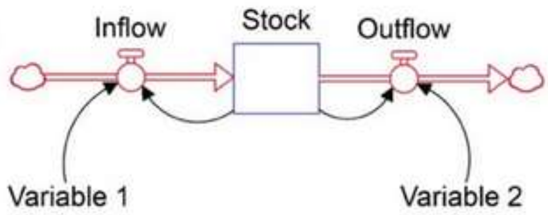

Figure 1 The basic building blocks of system dynamics modeling

Due to its ability to grasp complex relationships, system dynamics has been used in the construction field in applications such as analyzing the dynamic impacts of out-of-sequence work (Abotaleb and El-adaway 2018); assessing impacts of design errors (Han et al. 2011); modeling construction accidents (Maryani et al. 2015); performing construction risk analysis (Afshar et al. 2008; Maiti et al. 2017, and Kheyroddin, 2020); modeling construction workers' safety (Han et al. 2014; Fang et al. 2015; Guo et al. 2018); managing construction waste on-site (Hao et al. 2008), and several other applications as discussed in Chapter 2. However, system dynamics has not been used yet to evaluate the impacts of change orders on construction projects, which is the focus of this research.

1.4 Knowledge Gap

In construction projects, several current delays analysis techniques are available, yet they only consider the activity level and do not grasp the rippled impacts of change orders on other aspects beyond activities. Moreover, there is no consensus on how to isolate the impacts of each individual change order to quantify its weight with respect to the aggregated overall change orders, which cases disagreements among project parties leading to disputes. This research attempts to tackle the abovementioned gap.

1.5 Research Goal

The goal of this research is to develop a new method, utilizing system dynamics, for analyzing delays that arise from change orders. This method, which is in the form of an advanced system dynamics model, enables the simulation and quantification of the rippled impacts of change orders in a retrospective manner. The research objectives to achieve the goal are:

1. Develop a system dynamics model that captures the relationships between productivity, earned value, actual progress, labor hours, and change orders.
2. Formulate a calibration methodology to enable using this model in any construction project.
3. Validate the analytical capabilities of the developed model through testing in a case study.

This model is proposed to be used as a support, rather than a replacement, to traditional CPM-based delay analysis techniques. This model will help project stakeholders have better insights on the impacts of change orders and reach consensus faster regarding that matter, which in turn will reduce disputes and foster a healthier contracting environment.

1.6 Thesis Organization

This thesis consists of five chapters (Figure 2) as follows:

Chapter 1- Introduction: This Chapter includes research background information, knowledge gap, and research goal.

Chapter 2 - Literature Review: This chapter is divided into three main areas of study that are a great support to the research, which are:

- Investigating change order and the methods of quantifying it and its impact on labor productivity.
- Explaining what system dynamics is and its uses in the construction research.
- Investigating delay analysis techniques
- Discussing system dynamics and its use in construction project management

Chapter 3 - Research methodology and model development: this chapter explains the model adopted to cover the knowledge gap, reach the research goal and how this model was formulated and verified.

Chapter 4 - Model Validation and application: This chapter represents the application of an actual case study, results, findings, and validation.

Chapter 5 - Conclusion and recommendations: This chapter includes an overview of the research, and a summary of its findings and its gives recommendations for the future research.

Chapter 1 Introduction

- Quantifying the Impacts of Change Orders
- System Dynamics
- Knowledge Gap
- Research Goals

Chapter 2 Literature Review

- Change Orders
- Types of Change Orders
- Methods of quantifying the impact of change orders
- Research utilizing statistical methods for studying the impacts of change orders on labor productivity
- Delay Analysis Techniques
- System dynamics in construction project management
- Summary

Chapter 3 Reseach Methodology and Model Development

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- Calibration Stages
- verification Tests

Chapter 4 Model Validation

- Case study
- What is scenarios

Chapter 5 Conclusion, Limitations and Futur Recommendations

- Conclusion

Figure 2 Thesis Organization

CHAPTER 2

LITERATURE REVIEW

CHAPTER 2: LITERATURE REVIEW

2.1 Overview

This chapter studies the relevant previous research in change orders, system dynamics, and the connection between the two of them. Finally, the literature gap is highlighted.

2.2 Change Orders

A change order is defined as "a written authorization provided to a contractor approving a change from the original plans, specifications, or other contract documents, as well as a change in the cost. With the proper signatures, a change order is considered a legal document." (Means Illustrated Construction Dictionary, 2010). Changes can either be avoidable or impossible to avoid. The avoidable changes are, for example, that one material is replaced by another material for quality purposes. The unavoidable changes are the unforeseeable change, for example, the rework due to the application of new regulations in the construction area. The management section in the construction division of a company should agree on any unavoidable changes, quickly saving time and energy to put their efforts into resolving the problems related to the avoidable changes (Hester et al., 1991).

The Change Orders clause is included in most construction contracts, giving the owner the right to formally request the contractor to carry out any variations in exchange for a reasonable extension of time and associated costs. The additional time and cost resulting from change orders or related directly to changes are mostly compensated for but with some debate. The indirect damages caused by change orders are difficult to assess, along with the linked loss in labor productivity for an entire project, which causes the rise of disputes and disagreements between owners and contractors. In previous research, several causes of change orders were identified as follows: the lack of supervision, out of sequence work, disconnected work, depletion of the learning curve, mobilization and demobilization, processing change orders time, rework, schedule acceleration, clean-up, and processing time for a request for information (Hanna, 2001)

According to a study conducted by Hanna and Iskandar (2017), they found out that change orders occur due to various reasons and they conducted a survey on the causes of change orders in construction projects (Figure 3). Change orders due to additional scope are 39%, changes due to design change represent 26%, changes due to design error represent 18%, and changes due to value engineering represent 2% but rarely happens.

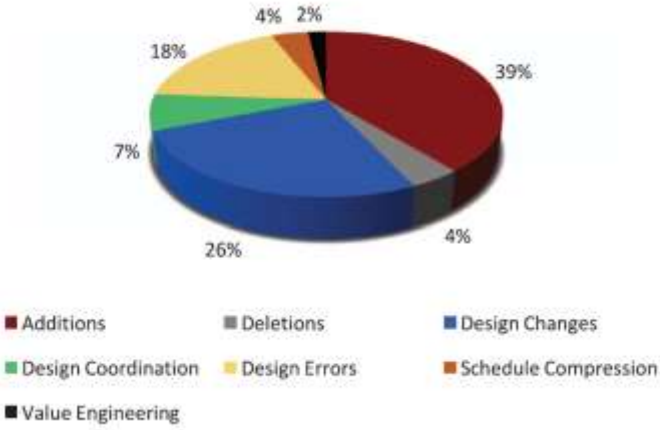

Figure 3 Reasons for change orders (Hanna and Iskandar, 2017)

Change orders have a major impact on construction projects and cause delays. In 2005, the Malaysian government projects were nearly 17% delayed by more than three months or the projects were left due to change orders (Sambasivan and Soon, 2007). Srdić & Šelih (2015) found that change orders and additional request issued by owner are 45.1%. While Hanna et al. (2002) calculated the probability of a project to be impacted by a change order is 54.8%.

2.3 Types of Change Orders

According to Cox (1997), Change orders are categorized into 3 main types:

(1) Formal change order: an official change order written by the owner or one of the owners' representatives in the presence of the site engineer. This change order is to change the contract terms, specifications, and plans. It can be described as a directive change order made by the owner to conduct changes in the main scope of work.

(2) Constructive change order: an extra contract work done according to the owners' representatives' instructions or problems caused by the owner. This is caused by incorrect specification or hidden uncertainties, resulting in additional work. Furthermore, changes are not necessary to be major but can be minor changes that are not expected to change the project's original time or cost. For example, that type of change is when the architect or the construction manager asks the contractor to perform work that was not specified in the original contract.

Nonetheless, the contractor must act rapidly and submit a claim to receive compensations for these kinds of minor changes (Sweet, 1994)

(3) Cardinal change order occurs because of the extensive amount of work required outside the main contract scope of work. This type of change is far away from the original scope of work. Despite the contract's change clause, cardinal changes are considered a violation of the contract made by the owner, which gives the contractor the right to either continue working on the project or quitting. If the contractor decides to carry on working on the project, the contractor should be compensated according to the actual cost of work. Factors of a cardinal change include a drastic adjustment in the cost of work, the quantity of work, or the work's character/nature.

2.4 Methods of Quantifying the Impact of Change Orders

Change orders usually impact other areas that are not directly affected by them (Hanna and Iskandar, 2017). Cumulative impacts of change orders are defined as follows "the costs associated with impact on distance work, and are not readily foreseeable or, if foreseeable, are not ready computable as direct impact costs. The source of such costs is the sheer number and scope of the changes to the contract. The result is an unanticipated loss of efficiency and productivity which usually extends the contractor's stay on the job" (Hanna, 2004)

There are two techniques for quantifying the impact of change orders: the micro approach and the retroactive approach (Iskandar, 2016). First: The micro approach is a proactive technique that allows each event to be evaluated separately. Second: the retroactive approach includes several techniques that evaluate the cumulative impact after the occurrence of the changes. The following methods include both proactive and retroactive techniques (Iskandar, 2016):

Total Cost Technique: This technique is the least favorite, but some courts still accept it. This technique depends on subtracting the estimated cost of the project from the actual cost acquired in which the resulting difference is directly assigned to the owners' responsibilities; that makes this technique very skeptical and should be the last resolution technique to be used. One of the greatest disadvantages of this technique is that it does not emphasize the inefficiencies of the contractor. This technique is mainly used in one of the following four conditions: (1) actual damages and nature of loss that cannot be identified with reasonable precision; (2) the project estimated cost was realistic; 3) the contractor was not accountable for the added costs (4) and the contractor's actual costs were reasonable; (Schwartzkopf 1992).

Modified Total Cost Calculations: The rationale behind this method is that the equation of the total cost method is adjusted so that owners are no longer responsible for contractors' performance inefficiencies and errors in bid estimates. The use of this method is strengthened when the cost attributable to the contractor's inefficiencies is accurately proven (Schwartzkopf 1992).

Measured Mile Calculations: This technique is the most favorable for calculating the productivity losses; it's called the "Gold Standard." In this technique, similar activities are compared on impacted and unimpacted sections of time project to determine the losses in productivity arising from the impact. This technique is considered to be the most favorite because it only considers the claimed impact, a method that avoids uncertainty regarding the legitimacy of cost estimations. A disadvantage of this technique is that in highly distressed projects, it is hard to separate unimpacted from impacted periods. It is correspondingly difficult to find two different periods where similar activities were being executed (Ibbs et al., 2007)).

Industry Publications: The industry publications are frequently used to verify the productivity loss associated with change orders. Courts and dispute resolution boards sometimes accept many reliable industry publications established by familiar researchers and experts.

Experts and Consultants: The experts and consultants' technique is regularly used to validate productivity losses in construction projects. In such a case, the opinion of experts is not satisfactory, and supportive documents, including the analysis of actual situations and project cost data, are required to demonstrate the actually incurred losses in productivity (Schwartzkopf 1992).

Serag (2006), categorized methods of quantifying the impacts of change orders can be as follows (1) statistical methods, and (2) delay analysis, as mentioned in Chapter 1. Here, we describe the significant research efforts conducted using these methods.

2.5 Research Utilizing Statistical Methods for Studying the Impacts of Change Orders on Labor Productivity

Several research efforts have been made to study the impacts of change order on productivity. For example, Cheng et al. (2015) used evolutionary fuzzy support vector machine inference model (EFSIM) to predict the lost productivity caused by changer orders. The model consisted of 8 steps: (1) Training data; (2) Fuzzification; (3) Support vector machine (SVM) training model; (4) Defuzzification; (5) Fast messy genetic algorithm (fmGA) parameter search; (6) Fitness evaluation; (7) Termination criteria; and (8) Optimal prediction model. The model succeeded in showing great ability to be used as a tool of predicting change-order- related lost productivity.

Hanna et al. (1999) conducted a study based on data from 43 projects to develop a linear regression model that predicts the impacts of change orders on labor productivity. The model was based on two parts; (1) hypothesis testing that deals with impacted/not impacted labor productivity by the change orders and compared with the predicted data from percentage of change orders; labor productivity, change in time and project size; and (2) regression analysis that was developed to conduct a model that is able to clarify the impact of different independent variable on labor productivity losses. The statistical analysis was able to show the significant difference between the projects that has change orders and the projects that did not have any. It also showed that the labor productivity losses were higher in the projects impacted with change orders.

Moselhi et al. (2005) developed a neural network model to quantify the impacts of change orders on labor productivity, the model was developed on three stages: (1) Identifying change orders factors that affect labor productivity; (2) modeling the timing impact; and (3) developing a neural network model. In this study a prototype software system and a neural network model were developed to estimate the labor productivity losses percentage due to change orders, in which it compared four other models to the neural network model developed and the results of the analyses indicated that neural network model in comparison to other models was more accurate in estimating the impacts of change orders on productivity.

Al-Kofahi et al. (2020) used system dynamics approach to quantify the impacts of change orders on labor productivity in highway projects. A system dynamic model was formulated on several stages that include;(1) identifying the scope and boundaries of work; (2) creating a causal loop diagram; (3) formulating the system dynamic model. The model was able to provide a causal reasoning to why change orders cause loss in productivity and accordingly increase in working hours and in project duration.

2.6 Delay Analysis Techniques:

The analysis of schedule delays is a conventional problem in nearly all projects. Evaluating schedule delays and allocating them to the resbonsible parties and activities is a tough problem in project management. For example, owner-contractor relations, the schedule delays denote a critical issue, frequently escalating into claims and deflation the profitable outcome of the whole project, linking extensive negotiations and juridical cases, tracing to accountabilities and financial compensations (Guida & Sacco, 2019)

There are several delay analysis techniques used, each one of them is specified for certain use and has its methodology of work and its limitations, following here is the most used delay analysis techniques:

As-Planned versus As-Built

This methodology is technically simple to use if the as built schedule was available in which it compares the activities of the baseline schedule with the as built schedule for detailed assessment of the occurred delays. The most important advantages of this methodology are that: it is simple, easy to use or understand, and not expensive (Lovejoy, 2004). Its main limitations are failure to identify criticality or concurrency of delays and the lack of ability to deal with difficult delay scenarios (SCL 2017; Stumpf 2000; Zack 2001).

Impacted As Planned

This methodology implements the delays that occurred as activated on the as-planned schedule to represent the effect of these delays on the project completion date. The total project delay due to each delaying event is calculated as the difference between the scheduled date of completion before and after adding the delay (SCL 2017; Trauner 1990; Pickavance 2005). Although this methodology is easy and quick to be prepared, it has some weaknesses; it assumes a perfect baseline schedule that did not consider any changes on it and fails to consider any changes in the critical path (SCL 2017; Stumpf 2000; Zack 2001; Wickwire and Groff 2004).

Collapsed As-Built

This methodology is easy to be prepared if there is a reliable as-built schedule in which it already includes all the delays and then remove these delays from the schedule that accordingly creates a "collapsed" as-built schedule, in order to show the progress of the project if those delays were not there. The strengths of this method include producing results of high accuracy (SCL 2017; Lovejoy 2004). While its limitations include the analyst has to identify the as built-critical path and has to make adjustments and insert logical ties as delays are removed (SCL 2017; Zack 2001).

Window Analysis

This methodology is deployed by dividing the total project duration from the as-built schedule into time windows. These time windows are regularly based on project milestones, or major changes in critical path, and if a major delay occurred. These elements determine the required duration for each window and the number of windows and with increasing the number of elements the number of windows increase and their duration decreases which give more accurate results in the analysis (SCL 2017; Finke 1999; Hegazy and Zhang 2005). At the beginning of this technique the first window schedule is updated using the as-built schedule data inclusive any delays happened in that period of that specific window, while keeping the remaining schedule beyond the window as-planned with no change. The results are taken from the difference between the project completion date of the schedule resulting from this and that prior to the review process gives the amount of project delay as a result of the delays within the first window.

Time Impact Analysis

This methodology is a based on the modification of the window analysis technique, which was discussed in the above subsection, with limitation to that in this technique the main focus is on a specific delay not a window of time (SCL 2017; Alkass et al. 1996). The approach assesses the impacts of delays in a chronological order. It begins with incorporating the first delay event is added to the baseline schedule at the time before that delay should begin, this is applied individually on each delay. The project delay is calculated afterwards through getting the difference between the project final date after adding each delay event and the final date before adding any of these delay events. This approach has significant value making it undoubtedly the most reliable technique (SCL 2017). However, this technique consumes time and costs much to operate, particularly in situations where large numbers of delaying events are involved.

According to Nagata et. Al. (2018), Delay Analysis is processed through using the Critical Path Method (CPM) to help analyzing the impacts of delays and other impacts on the schedule of the project. In Table 1, Abotaleb (2018), demonstrated the applicability of system dynamics in construction projects as related to the critical path method and exposed the weakness of the critical path method in comparison to the system dynamics. Despite the several advantages of CPM here are some limitations and shortcomings that can be compensated with system dynamics as will be discussed in the following sub-section.

Table 1 Comparing between critical path method and system dynamics (Abotaleb, 2018)

Perspective	Critical Path Method	System Dynamics
Behavior	Linear	Linear and non-linear
Data type	Quantitative	Quantitative and Qualitative
Capturing managerial corrective actions	Low	Very high
Realistic for project acceleration	Low	Very high
Level of Detail and Focus	Activity	Holistic and feedbacks
Risks and uncertainty management	High	Very high
Evaluating impacts of uncertainty	High	Very high
Evaluating decision level	High	Very high
Estimating accurate project cost, duration and resources	High	Very high
Work schedule	High	Very high
Project control and monitoring	Yes	Yes
Showing interrelationships	Yes	Yes
Accounting for feedback effects	Yes (Low)	Very High
Work specification	Yes	No
Handling multi interdependent components	No	Yes
Productivity impact consideration	No	Yes
Handling multiple feedback processes	No	Yes
Handling non-linear relationships	No	Yes
Computational capability for predictions	No	Yes

2.7 System Dynamics in Construction Project Management:

According to a review study conducted by (*XU & ZOU., 2020*) on the number of researches done using system dynamics in construction project management, Figure 4 was proposed.

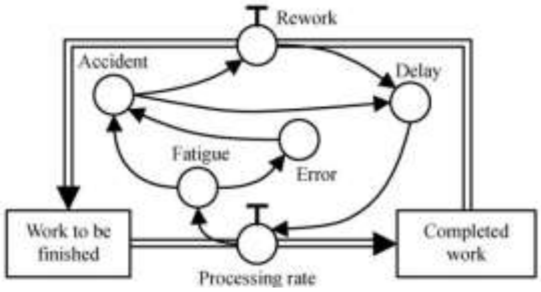

Figure 4 Sample stock-flow diagram (Xu & Zou, 2020)

Figure 5 shows the increasing trend in the interest in the System dynamics in the field of construction project management from 1994 to 2018. (Ahmad et al., 2016) introduced a general guide for the use of system dynamics modeling process in the construction project management which can be distributed into the following stages: determine the system boundaries according to the problem classification and forming the casual loop diagrams (CLD) from a qualitative point of view. The CLD can represent a positive and a negative correlation between the connected variables or factors. For example, if the increase of activity A leads to the increase of activity B and the decrease of activity A leads to the decrease of activity B, then they have a positive correlation and the Arrow from A to B will have a positive sign. Otherwise, they will have a negative correlation. When the CLD forms closed loops with the same arrow's direction, the next stage can be introduced consists of feedback loops which are divided also into positive and negative loops. The CLD is suitable for a qualitative analysis but should be converted to a stock-flow diagram for a quantitative analysis including (stock, flow, auxiliary, and connector). An example of the stock-flow diagram is shown in Figure 5

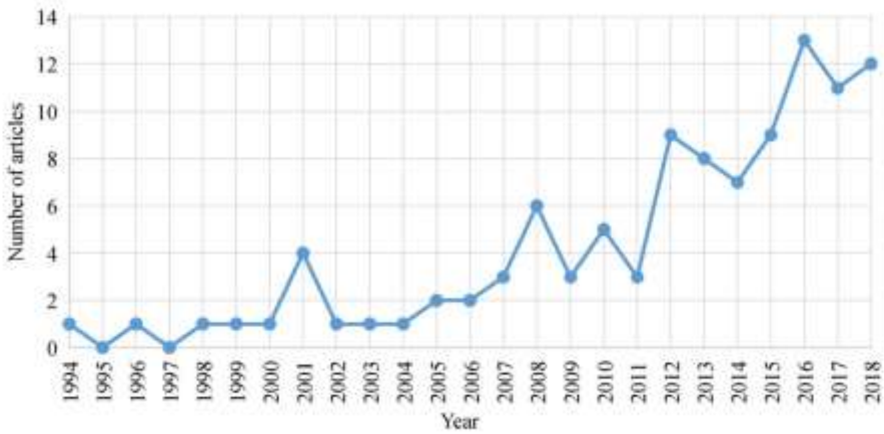

Figure 5 Number of SD-based Construction Management Publications from 1994 to 2018 (XU & ZOU,2020)

In this example, the decrease rate is "processing rate" and the increase rate is the completed work. Therefore, the "process rate" will directly impact the construction progress which is like the Rework variable. "Work to be finished", "processing rate", "completed work", and "rework" form a feedback loop where auxiliary variables act as connectors for accurate calculations such as "fatigue", "delay", and "error". They can be considered as the impact factors of "processing rate" and "rework".

According to another study conducted by (Rodrigues et al., 1995), there is a strong relation between the traditional methods of project management and system dynamics models as their general objectives are mostly the same and each of them individually can be incomplete but they can be integrated with each other; the traditional models have shown deficiencies in coping with the complexity of the strategic issues that appeared in the mega construction projects (Cooper, 1993) but the system dynamics approaches have shown promising results as a tool for supporting the traditional strategic management to reach a sufficient solutions for the possible problems. Also, the system dynamics enhance the capabilities of projects simulation on a much bigger scale.

Another implementation appeared in a research conducted by (Han S. et al, 2013) on forming a system dynamics model for assessing the dynamics of design errors in construction projects and systematically assess their negative impacts. The study was done on a university building project and the results indicated that the developed model could provide better assessment of the negative impact of design errors, which is often underestimated. Based on this, it is concluded that the developed model can assist project managers in better understanding the nature dynamics of design errors and help them recover delayed schedule, particularly for scheduling fast-track projects.

Maryani A. et al (2015) conducted a research using system dynamics approaches in modeling construction accidents. The relations between the causes, accidents and its influence on the supply chain are studied in this research. The system dynamics simulation models are used because of their probabilistic characteristic of variables that best describe the realistic nature of the construction accidents and their different influences. The developed model was able to provide an Occupational Safety and Health (OSH) cost component that needs to be considered and analyzed for better control of the events of the accident as well as providing improvements in the supply chain of contractors and subcontractors.

According to (Liu M et at., 2019), the uses of system dynamics in construction management projects might include but not restricted to the following internal and external complexities: sustainability, planning and control, performance and effectiveness, strategic management, risk analysis and management, site and resource management, knowledge management, and organization and stakeholder management. This increasing use is due to the better simulation and presentation of the complex problems involved and sufficient solving for such problems.

A different study has been conducted for the analysis of risks using system dynamics by (Nasirzadeh et al, 2008) on a bridge construction project. The proposed model was able to consider and quantify different dynamic risks throughout the life cycle of the project and accounted for different feedback loops affecting the overall risk impacts. The different risks were quantified in terms of time, cost, and quality using the object-oriented simulation method. It was concluded that the system dynamics risk analysis approach provided a powerful tool for quantification of the full impact of various risks on the project's performance prior to their occurrence in a virtual reality environment. The results can be reused for similar projects.

A thorough study for the advantage of using system dynamics analysis for cost reduction and schedule optimization was conducted by Jing W. et al., (2019) on the concept of successive legislation periods in Iraq; the data of the previous eleven years were collected for the analysis and the developed model achieved a progressive reduction of 10.9% in project cost and 135.37% improvement in project schedule.

System dynamics has also been used in several other application, some of these applications are as follows.

Abotaleb and El-adaway (2018), used system dyanmics for analyzing the dynamics of Out-Of-Sequence (OOS), the model helped in better understanding the dynamics of OOS work and their relationships with different project feedback system and created a more accurate tool to estimate the indirect and direct impacts of OOS work.

Han et al. (2013), developed a system dynamic model to capture the dynamics of design errors and systematically assess their negative impacts. They concluded that the developed model can assist project managers in better understanding the dynamics of design errors and recovering delayed schedule, mainly under schedule pressure.

Maryani et al. (2015) used system dynamics approach to simulate and analyze the occupational accidents in construction projects and was able to define these accidents and their cost and generated an Occupational Safety Health (OSH) cost factor that need to be controlled in addition to enhancements in the supply chain of subcontractor and supervisors to boost the quality of workers.

Afshar et al. (2008) developed a new risk analysis approach using system dynamics in which the main impacts can be quantified and analyzed. The new approach was able to quantify the different risks on construction projects from time, cost and quality before they occur by creating a learning laboratory in a virtual environment.

2.8 Summary

This chapter presented a review of literature in the fields of change orders and their types, impacts of these change orders and different methods for their quantification, different delay analysis techniques and the relevant work employing system dynamics modeling in construction project management. Previous research studied the impacts of change orders on labor productivity in linear methodologies and calculated the total effect of change orders on construction projects from the total project delay and cost but not the individual impact of each change order on labor productivity.

Delay analysis techniques only consider the activity level and do not grasp the rippled impacts of change orders on other aspects beyond activities. There is no consensus on how to isolate the impacts of each individual change order to quantify its weight with respect to the aggregated overall change orders, which causes disagreements among project parties leading to disputes. Finally, although system dynamics has been proven to be a helpful tool in analyzing several aspects in construction projects, it has not beet yet utilized in analyzing change orders.

CHAPTER 3

RESEARCH METHODOLOGY AND MODEL DEVELOPMENT

CHAPTER 3: RESEARCH METHODOLOGY AND MODEL DEVELOPMENT

3.1 Overview

The research methodology is divided into several stages, all these stages of work.

The stages of work are: (1) determining the exogenous and endogenous elements that affect the labor productivity, (2) forming the dynamic hypothesis, which is based on the endogenous elements, (3) developing a system dynamic model by integrating mathematical equations to the dynamic hypothesis, (4) a multi-stage calibration to assure the work of the model on real projects, (5) performing verification tests, (6) applying the model on an actual case study to imitate the projects' planned and actual circumstances and (7) conducting what-if scenarios to validate the models' capabilities that could help project participants in assessing different project situations in analyzing the dynamics of change orders and its effect on labor productivity. Figure 6 presents a summary of the research methodology. The following sections explain the methodology steps in detail.

3.2 Determining the Exogenous and Endogenous Elements Affecting the Labor Productivity

The first step is to determine the exogenous and endogenous elements in order to be able to formulate the dynamic hypothesis. The endogenous elements are the internal elements that get affected by external elements, which are the exogenous elements, and there are some elements that will be excluded from the study to concentrate on the effect of change orders by itself and be able to study the impact of each one individually. Accordingly, the main focus is on change orders and their effect on labor productivity. There are several elements affecting the labor productivity, for instance (1) project management efficiency, (2) adverse weather condition, (3) rework, (4) errors, (5) overtime, (6) change orders, (7) schedule delays, (8) remaining work, (9) schedule pressure (10) crowding, and (11) out of sequence work (Zakeri et al., 1996; Abdul Kadir et al., 2005). For the sake of this research, change orders effect on the project was the only element taken into consideration to study its effect in detail on the labor productivity.

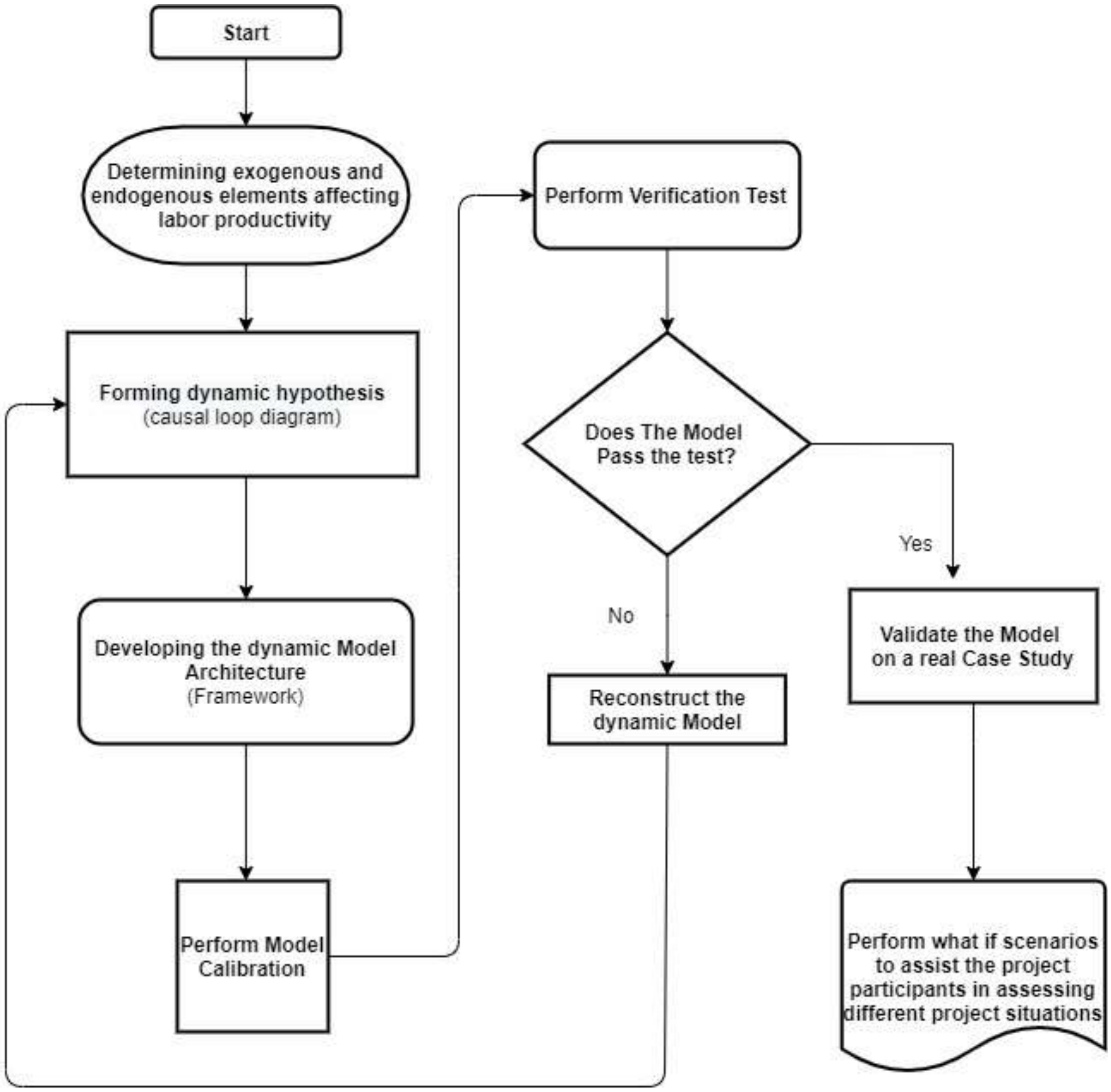

Figure 6 Research Methodology

3.3 Formulating the Dynamic Hypothesis

The second stage is forming the dynamic hypothesis; After determining the elements that will be used in the causal loop, the dynamic hypothesis is formed, which is the causal loop diagram, cause-effect loops that are formed in circular chains rather than linear ones. Based on the cause-and-effect relationships among the different elements, the causal loop is formed to demonstrate the relationships among these different elements as shown in Figure 7, which shows 3 different causal loops which are connected together by arrows with either a negative sign that demonstrates an adverse relationship or a positive sign that demonstrates a directly proportional relationship. Following is the main causal loops and their relationships together.

1. Work to be done →+ Man Hours →+ Work Done →- Work to be done
2. Change Orders → + Work to be done →+ Man Hours → + Work Done → -Work to be done
3. Change Orders →-Labor Productivity →+Work Done →- Work to be done

When a change order is added, the work units needed to finish the project is increased and the number of items that needs to be done. To elaborate more about the above relationships; (1) when the labor man hours increase the work accomplished increases; (2) when change orders are added, the work needed to be done increases, which leads to the increase of manhours too in order to be able to accomplish the extra work; (3) change orders decrease the labor productivity, which directly affects the work done.

The elements shown in Figure7 they are taken into consideration in this research. The model focuses on the relationship between change orders and labor productivity losses. In the following section, the main dynamic model is discussed, which consists of two interconnected modules: (1) the average production and (2) the workflow module.

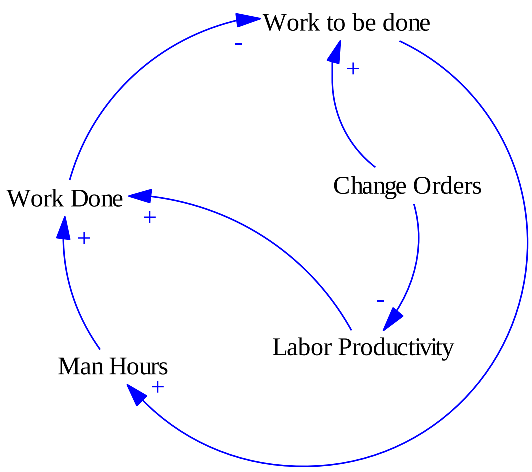

Figure 7 Dynamic Hypothesis "Causal Loop"

3.4 Developing the Dynamic Model Architecture

In this section, the main model will be discussed and elaborated. The model's main concept is based on the proposed model by Li et al. (2014) and Taylor and Ford (2008), with some changes to meet the purpose of this research. This model underwent several stages to be constructed and developed. In these modules, the Construction activities are not represented as tasks but are represented as the flow of work units in which progress (or workflow) is measured by US dollars rather than individual activities. Following are the stages of developing the architecture model, calibrating the work modules, and Verifying it.

3.4.1 The Stage of Developing the Planned Progress Module

In the First Stage, the planned progress workflow module Figure 8 was formed first of two stocks, which are "Work to be done" stock and "Work Done" stock; they are both in an integrated relationship with the flow, which is "productivity." The units of “Work Done” and “Work to be Done” stocks is monetary value (EGP, USD, or any currency used by the project). The units of the “productivity” flow is the total monetary value produced by the total labor resources in each time step, for example USD/week or EGP/week. First, the "Work to be done" was represented in the model as a "Level variable," which is one of the variable types that determine the dynamic behavior of a system. In which there are different types of variables in Vensim "Auxiliary, Constant, data, initial, level, lookup, reality check, string, subscript and time base." The stock "Work to be done" was represented in this model as a level variable with an initial value of "Constant,". This initial value represents the total planned cost of the project (Planned Progress total value), that was presented as "-productivity".

$$Work\ to\ be\ Done_t = Initial\ Value + \int_0^T -Productivity_t \quad \text{......................Equation 1}$$

where t is the time step (each time step is a week in the context of this research but it can be changed to a day in smaller projects). With the increase of productivity, the Work done is increased, and the Work to be done will be decreased. The second main stock in the model here is the "Work Done", which has an initial value of zero, as we started with the project, we had no productivity yet, with the increase of productivity the work done will be increased.

$$Work\ Done_t = \int_0^T Productivity_t \quad \text{..Equation 2}$$

Productivity in this model is represented as the product of the "average production per Man hr" and the "manhours". The units of "average production per Man hr" is the monetary output of each man hour, for example USD per week per man hour.

$Productivity_t = Average\ production\ per\ manhrs_t * manhrs_t$…………….Equation 3

The Average productivity is based on different phases of work which is represented by the average production module and will be further elaborated in an upcoming subsection, while the manhours is conducted from the planned manhours schedule and is represented as a function of time to find the right manhours corresponding each week.

To elaborate more about Figure 8, there is an initial value of total work X EGP that is moving from the work to be done to the work done. The work to be done represents the total amount of planned work schedule, while the work done represents the total work that was done to this point. This work to be done is moving through the productivity, which is a factor of the average production per man hours multiplied by manhours for each unit of time. The work done is based on simulation and calibration of the module with an objective of minimizing the square error between the simulated project planned progress and the actual planned progress that is afterwards was compared to the project planned progress to validate the module work efficiency.

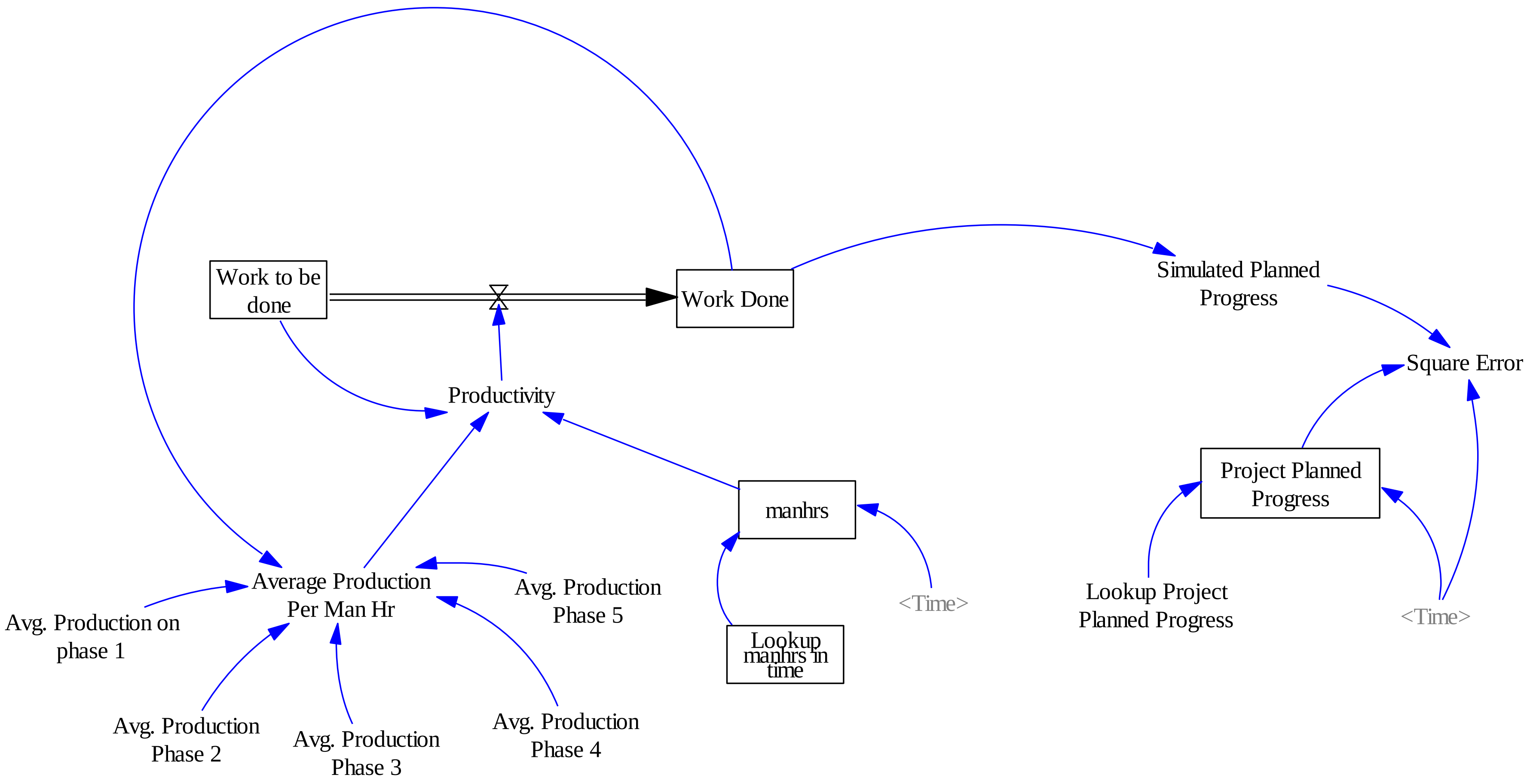

Figure 8 Planned Progress Workflow

3.4.2 The Stage of Developing the Earned Value (EV) Progress Module (Workflow Module)

In this stage the final workflow module, as shown in Figure 9, is developed based on the previous module and its calibration on sample data. The EV module is based on the actual work outputs after any specified time in the project accordingly it represents the actual work progress of the project until that time. In this module the "Work to be done" moves to the "EV ". The "Work to be done" stock moves to the "EV" stock through the productivity flow which yet to be elaborated on in the next subsection. “Work to be done” is set first with an “Initial value” which represents the total EV cost of the project. In this module the productivity is not only a factor of manhours and average production per man hours module but also is affected by the VO variables.

$$Work\ to\ be\ Done_t = Initial\ value + \int_0^T -Productivity_t \text{...........................Equation 4}$$

With the increase of productivity, the work to be done will be decreased. The second main stock in the model here is the "Work Done", which has an initial value of zero, as we start with the project, we have no productivity yet, with the increase of productivity the work done will be increased.

$$EV_t = \int_0^T Productivity_t \text{..Equation 5}$$

Productivity in this model is represented as the product of the "average production per Man hr" and the "manhours" and the VOs effect of X number of change orders

$$Productivity_t = (Average\ production\ per\ manhrs_t * manhrs_t) * effect\ of\ VON_t$$

To elaborate more about Figure 9, there is an initial value of total actual work X EGP that is moving from the work to be done to the EV. The work to be done represents the total amount of actual work schedule, while the EV represents the total work that was done to this point. This work to be done is moving through the productivity, which is a factor of the average production per man hours multiplied by manhours for each unit of time taking in consideration the effect of VOs (change orders) added to the project up until this point in time which will be elaborated in an upcoming subsection. The EV is based on simulation and calibration of the module with an objective of minimizing the square error between the simulated EV and the project actual EV that is afterwards was compared to the project simulated EV to validate the module work efficiency.

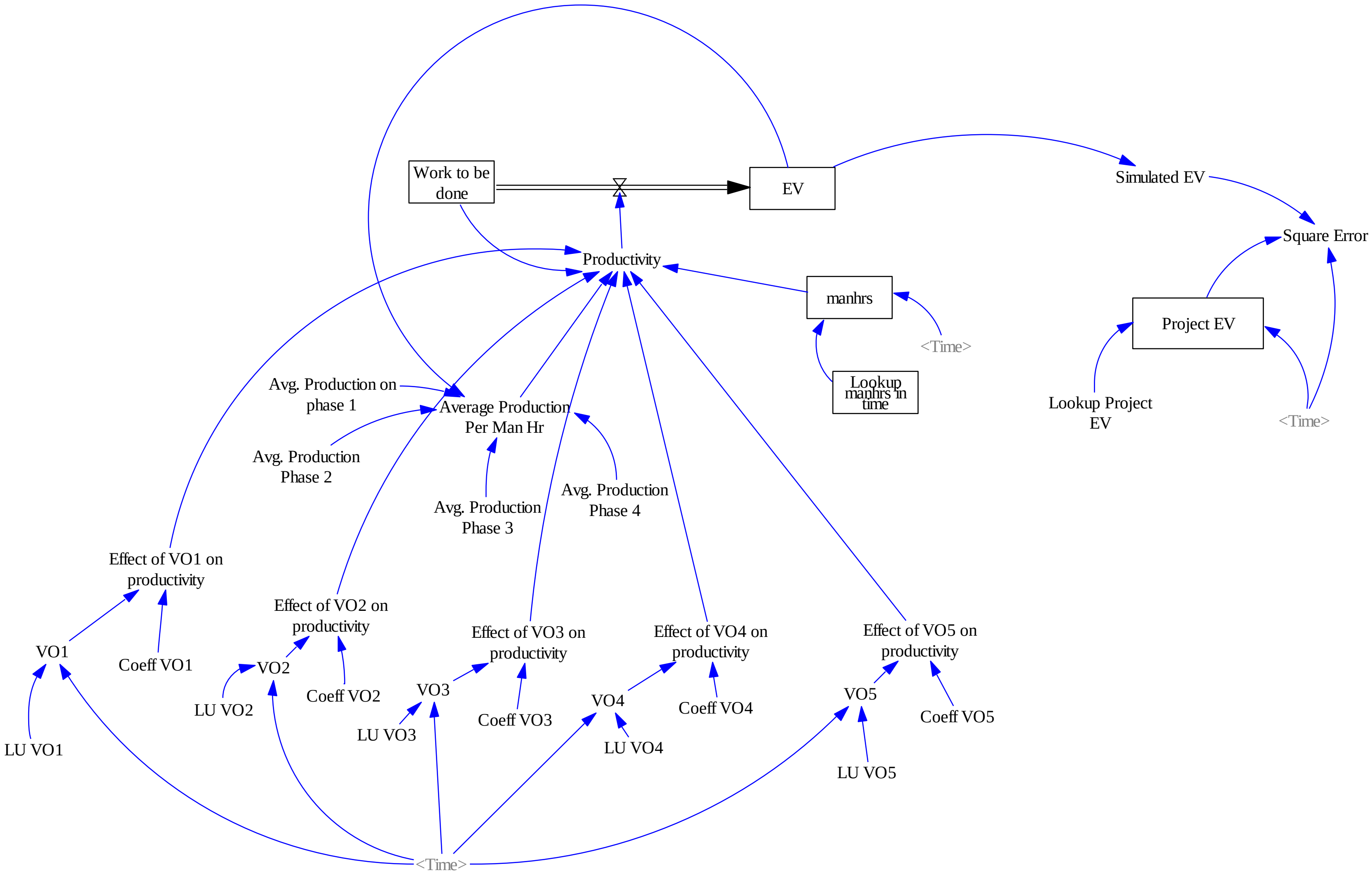

Figure 9 EV Workflow (Model Architecture)

3.4.3 Average Production Module

The average production module is responsible mainly on identifying the average production per man hours for different time segments for a specific number of man hours in which these numbers are represented in a weekly basis.

This module is based on the criteria that a project goes into several stages of work and have produced a different production rate for each of these stages. The start was by estimating that there is only one average production that will serve the production and get the simulated EV curve same as the EV, but after several trials, and for the sake of this research, it was found that the average production has to be divided into 4 different stages, each stage at time (t) is selected and multiplied by the corresponding manhours for each unit of time. Meanwhile, it can be further developed into more phases based on the project needs. The value of each phase is identified using simulation by adding the optimization criteria with an objective function of minimizing the square error between the simulated EV and Actual EV as shown in Figure 10.

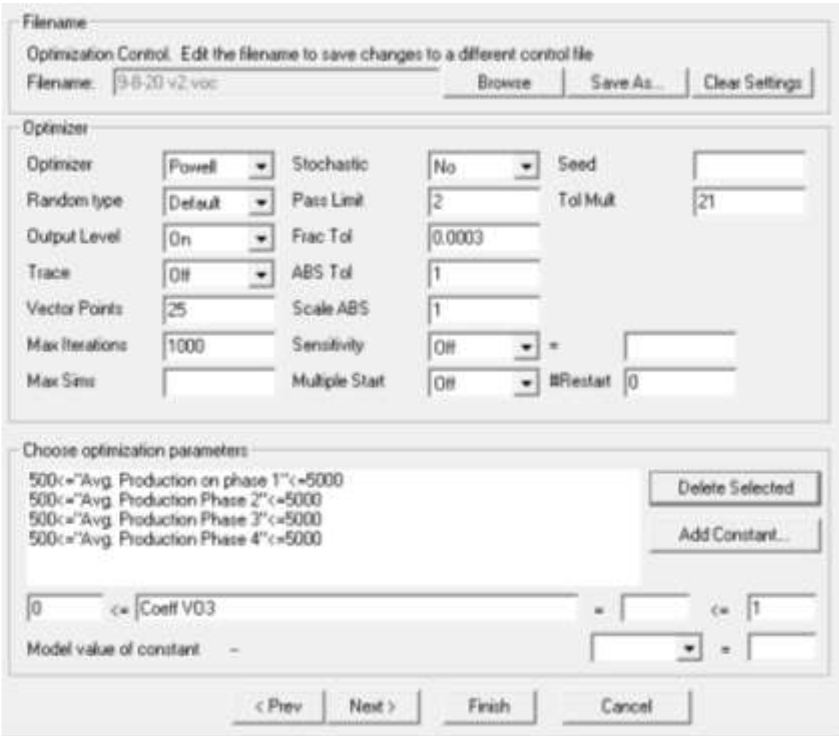

Figure 10 Average Production Per Man hours module

Figure 11 shows the module of the average production per manhours which employs the following equations

$$Productivity_t = Average\ Production\ per\ manhrs\ X\ manhrs$$

$$Average\ Production\ per\ manhrs_t = \begin{cases} Avg.Production\ Phase\ 1, & EV_t \leq EV_{1,2} \\ Avg.Production\ Phase\ 2, & EV_{1,2} < EV_t \leq EV_{2,3} \\ \dots & \\ Avg.Production\ Phase\ N, & EV_{N-1,N} < EV_t \end{cases}$$ ……………………………Equation 6

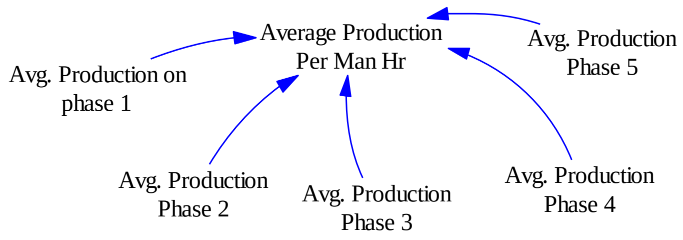

Figure 11 Avg. Production Module Variables

3.4.4 Applying Change Orders

This is the final stage in the model development where the Change Orders are added in the final stage of building the model by adding each change order separately, adding the time that includes the change order as a variable of 1 and the time that the change order does not occur in as zero. When the change orders are added the effect of them is shown on the productivity and the equation of productivity is updated as follows:

$$Productivity_t = average\ production\ per\ manhrs_t * manhrs_t * effect\ of\ VON_t\ on\ productivity$$ ……………………………………………………..Equation 7

In this research we took into consideration five change order, but unlimited number of change orders can be added using the same criteria. In which, the model can find in time (t) the change order that occurred within and take its result from a variable.

(0>effect of VON≤1)

Figure 12 shows the causal diagram forming the change orders module. As the amount of change orders increase, effect on the productivity will be more significant.

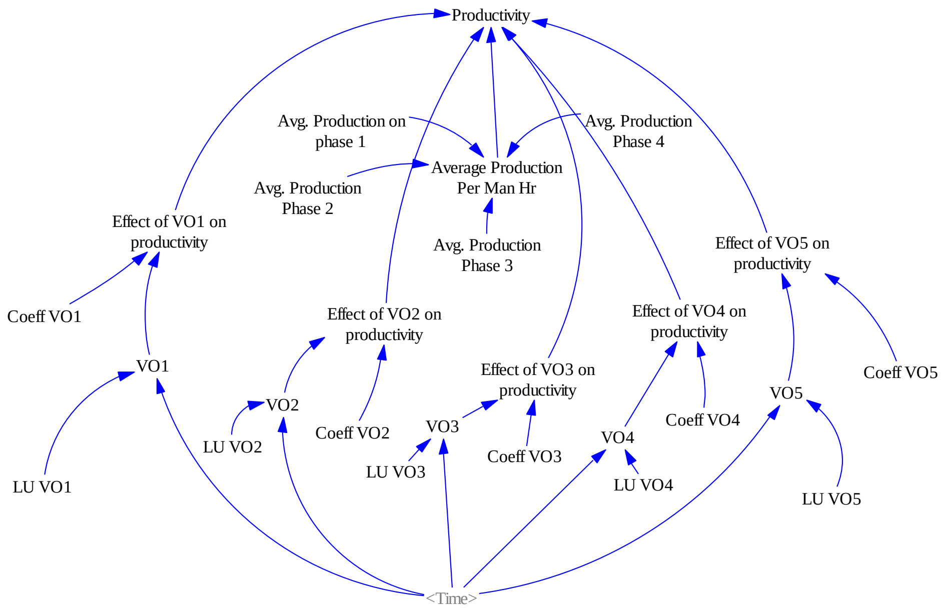

Figure 12 Change Order Module

3.5 Calibration Stages

After developing model architecture and all the interconnected modules, two calibration stages are developed. Calibration is estimating the model elements to match the actual given data to the simulated (Oliva 2003). In this stage the model elements are calibrated to imitate the required output that from the given data. If this model failed to meet the required result, it means that the model is inefficient and not correct and the model architecture must be checked and rebuilt again, which means that the model calibration is the only way to determine whether the model workability.

The following subsections describe the model variables, and the objective function for each calibration stage that is used in the optimization problem. The used system dynamics software uses Powell hill climbing algorithm for optimization (Ventana Systems Inc. 2017). Every calibration has its own variables and objective function that is only specified for the same type of projects. These variables are then obtained from calibration, not from the actual project data. Each calibration with its variables and objective can be only used for a specific type of project but that does not mean that the same model cannot be used for any other project. The same model can be used to any other project, but the variables and object function must be changed to match the requirement of that specific project and must be calibrated to obtain new values.

3.5.1 Calibration Stage 1

In this stage the target is to calibrate the input data to imitate the planned progress of a project. In which, the VO is not taken into consideration according to the planned schedule where it shows the planned work of a project without any effect of change orders. The calibrated model takes into consideration the different phases of average productivity, which is divided into four different stages and the planned man hours. The main objective function is to minimize the square error, while the variables are “Average production phase N”. The objective function in this stage is to minimize the square error between the project planned progress and the simulated planned progress:

$Minimize\ \sum_{t=0}^{TP_d}(PPP_t - SPP_t)^2$……………………………………………..Equation 8

Where; PPP_t : Project Planned Progress at time t

SPP_t : Simulated Planned Progress at time t

TP_d : The total project duration in weeks that the project is planned to finish

3.5.2 Calibration Stage 2

After the success of calibration stage 1 and the ability of the model to imitate the planned project progress with the simulated planned progress, the objective of stage 2 is to enable the model to imitate the data from the actual work progress (EV) with the simulated actual work progress (Simulated EV) taking into consideration the effect of change orders (VO) on the work performance while taking the actual man hours. The Earned Value represents the actual work percentage. In this stage the optimization variables will be the different phases of “Average productivity N” and the coefficient of VO N”. The main objective function is to minimize the square error, while the variables are “Average production phase N” and “Effect of VON. The objective function is also to minimize the square error between the project EV and the simulated EV is as follows:

$Minimize\ \sum_{t=0}^{TAP_d}(PEV_t - SEV_t)^2$……………………………………….…………Equation 9

Where; PEV_t : Project EV at time t

SEV_t : Simulated EV at time t

TAP_d : The total actual project duration in weeks that the project actually finished

3.6 Model Verification

In system dynamics, a model must be verified before it can be applied in any project. Verification in the context of system dynamics is the process of making sure the output is numerically correct, the behavior resulting from changing the values of the parameters is correct, and the model is structurally sound. Sterman (2000) has developed several tests that are used by system dynamics researchers to verify models. According to Sterman (2000) there are main verification tests have to be applied to the model to check if it will work correctly with the project on hand or not and if the testing failed that means that the causal loop diagram or the stock and flow diagrams are not having the correct relationship. In such case, the model must be restructured again then retested and this can go on until the dynamic model passes these tests. The verification tests according to Sterman (2000) are:

a) **Boundary Adequacy** to answer the question "Are the important concepts for addressing the problem endogenous to the model?". This test is done by direct inspection to the equations in the model and diagrams for exogenous variables to make sure that all the variables are entered correctly with no errors and the change order is correctly added as endogenous variable.

b) **Structure Assessment** to answer the question "Is the model structure consistent with relevant descriptive knowledge of the system?". This test is based on the cause-and-effect relationship between the different variables and by checking whether the model is behaving as it should be when adding a change order in which the number of work units increase as they should or not.

c) **Dimensional Consistency** to answer the question "Is each equation dimensionally consistent without the use of parameters having no real world meaning?" This is done by checking measurement units for all variables and constants and make sure that they're dimensionally consistent.

d) **Parameter Assessment** to answer the question "Are the parameter values consistent with relevant descriptive and numerical knowledge of the system? This test is specified in assuring that the data given to the model is from an actual case study and based on existing project data and knowledge given in previous research.

e) **Extreme Conditions** to answer the question of "Does each equation make sense even when its inputs take on extreme values? This test is based on giving the model extreme values and perform simulation then comparing it to the behavior of the real system in different what-if-scenarios.

In this research, it should be stated that after the model was completely developed, all of the abovementioned verification tests were applied using hypothetical values for inputs and the model successfully passed all of them. With this, the model is verified.

CHAPTER 4

MODEL VALIDATION

CHAPTER4: MODEL VALIDATION

4.1 Overview on Validation

In this chapter after developing the system dynamic model and after passing all the required verification tests, the model is applied on an actual case study to demonstrate its analytic abilities and validate its performance. Validation in system dynamics is a specific and distinguish concept from other approaches; it depends on the modeling purpose and the model's application. Here, the purpose of validation is to ensure that the model can replicate the behavior of a real project in terms of planned progress and actual progress. Once the model is able to take the inputs (weekly man hours, total budgeted work, and change orders) and use these inputs to produce simulated planned and actual curves that are matching the project's planned and actual curves, it is considered validated (Abotaleb and El-Adaway 2018). When such a model is validated, what-if scenarios can be conducted with considerable trust and faith in the resulting output.

In the following sub-sections, we present a case study of a real construction project; where the model was successfully validated, and subsequent what-if scenarios were conducted to find meaningful insights about the ripples and isolated impacts of the change orders in that project.

4.2 Description of the Case Study

The dynamic model is utilized on a project of a whole residential parcel in a gated compound consisting of 71 residential villas. The project was planned to be executed in 119 weeks with a total budget cost of £238,138,410. The project encountered several change orders, which was one of the main factors that resulted in delays and loss in productivity, which was reflected on the actual work progress. When the data for the project was collected, the project was in week 97 with a progress of only 48.15% and according to the estimate made by the planning team and after the update, the project will end at week 187, which is 68 weeks more than the planned duration. The name of the project is not mentioned in this research for confidentiality of the data, while the actual data can be used for the purpose of developing the model and validating it. The following data were gathered from the project (shown in Tables 2,3,4, 5 and 6)

- Planned progress, Actual progress, Manhours Planned and Actual, and Detailed Change Orders All over the project.

Table 2 Actual Project Data (1-5)

	Budget Cost	Cumm Budget Cost	Actual Cost	Cumm Actual Cost	EV	Cumm EV	Budget manhrs	Cumm Budget manhrs	Acual Manhrs	Cumm Actual Manhrs
24-Dec-17			$88,890.61	$88,890.61	$88,890.61	$88,890.61			2	2
31-Dec-17			$327,907.89	$416,798.50	$327,907.89	$416,798.50			125	127
7-Jan-18			$371,513.34	$788,311.83	$371,513.34	$788,311.83			211	338
14-Jan-18	$361,031.48	$361,031.48	$380,950.72	$1,169,262.55	$380,950.72	$1,169,262.55	29	29	183	521
21-Jan-18	$373,978.36	$735,009.84	$464,613.09	$1,633,875.64	$464,613.09	$1,633,875.64	155	184	196	717
28-Jan-18	$379,042.60	$1,114,052.44	$527,887.06	$2,161,762.70	$527,887.06	$2,161,762.70	180	364	274	991
4-Feb-18	$379,042.60	$1,493,095.03	$546,621.09	$2,708,383.79	$546,621.09	$2,708,383.79	606	970	539	1530
11-Feb-18	$488,054.26	$1,981,149.29	$786,782.14	$3,495,165.93	$777,480.50	$3,485,864.30	328	1298	509	2039
18-Feb-18	$600,879.22	$2,582,028.51	$859,489.32	$4,354,655.25	$839,674.68	$4,325,538.98	423	1721	413	2452
25-Feb-18	$701,867.19	$3,283,895.70	$885,545.18	$5,240,200.43	$866,660.87	$5,192,199.85	482	2203	610	3062
4-Mar-18	$923,206.65	$4,207,102.35	$1,048,955.69	$6,289,156.12	$1,031,908.11	$6,224,107.95	647	2850	436	3498
11-Mar-18	$1,377,277.11	$5,584,379.45	$1,146,689.92	$7,435,846.04	$1,130,131.74	$7,354,239.69	622	3472	703	4201
18-Mar-18	$1,533,685.78	$7,118,065.24	$1,182,255.99	$8,618,102.03	$1,167,226.13	$8,521,465.82	732	4204	498	4699
25-Mar-18	$1,758,823.28	$8,876,888.52	$1,196,762.00	$9,814,864.03	$1,182,623.71	$9,704,089.52	1018	5222	674	5373
1-Apr-18	$1,764,849.49	$10,641,738.01	$1,239,717.06	$11,054,581.09	$1,226,509.05	$10,930,598.57	970	6192	1088	6461
8-Apr-18	$1,770,581.66	$12,412,319.66	$1,248,357.45	$12,302,938.53	$1,235,742.46	$12,166,341.03	838	7030	478	6939
15-Apr-18	$1,781,114.24	$14,193,433.90	$1,249,677.09	$13,552,615.62	$1,237,466.10	$13,403,807.13	1002	8032	570	7509
22-Apr-18	$1,791,230.64	$15,984,664.54	$1,250,536.79	$14,803,152.41	$1,238,613.42	$14,642,420.55	914	8946	728	8237
29-Apr-18	$1,798,659.00	$17,783,323.54	$1,252,259.76	$16,055,412.17	$1,240,766.99	$15,883,187.54	519	9465	815	9052
6-May-18	$2,061,196.27	$19,844,519.81	$1,254,248.02	$17,309,660.19	$1,242,827.14	$17,126,014.68	786	10251	502	9554
13-May-18	$2,226,808.72	$22,071,328.53	$1,256,071.58	$18,565,731.76	$1,244,480.26	$18,370,494.94	1372	11623	685	10239
20-May-18	$2,250,729.88	$24,322,058.42	$1,265,954.32	$19,831,686.08	$1,252,998.58	$19,623,493.52	1059	12682	762	11001
27-May-18	$2,253,081.72	$26,575,140.14	$1,271,532.29	$21,103,218.37	$1,256,956.84	$20,880,450.37	1250	13932	925	11926
3-Jun-18	$2,188,095.15	$28,763,235.29	$1,303,481.03	$22,406,699.41	$1,282,113.09	$22,162,563.45	989	14921	630	12556
10-Jun-18	$2,165,478.85	$30,928,714.13	$1,311,683.79	$23,718,383.20	$1,288,488.26	$23,451,051.71	769	15690	572	13128
17-Jun-18	$2,185,748.82	$33,114,462.95	$1,311,683.79	$25,030,066.99	$1,288,488.26	$24,739,539.97	219	15909	96	13224
24-Jun-18	$2,188,661.43	$35,303,124.39	$1,305,920.14	$26,335,987.13	$1,280,422.29	$26,019,962.25	1404	17313	569	13793
1-Jul-18	$2,200,936.92	$37,504,061.31	$1,341,934.21	$27,677,921.34	$1,316,366.18	$27,336,328.44	1096	18409	592	14385

Table 3 Actual Project Data (2-5)

	Budget Cost	Cumm Budget Cost	Actual Cost	Cumm Actual Cost	EV	Cumm EV	Budget manhrs	Cumm Budget manhrs	Acual Manhrs	Cumm Actual Manhrs
8-Jul-18	$2,159,555.17	$39,663,616.49	$1,358,671.22	$29,036,592.56	$1,330,534.40	$28,666,862.83	1371	19780	1135	15520
15-Jul-18	$2,166,755.63	$41,830,372.12	$1,373,857.78	$30,410,450.34	$1,345,041.09	$30,011,903.92	1579	21359	1192	16712
22-Jul-18	$2,184,546.46	$44,014,918.58	$1,549,001.54	$31,959,451.88	$1,524,476.15	$31,536,380.07	1722	23081	1303	18015
29-Jul-18	$2,617,012.40	$46,631,930.98	$1,567,956.03	$33,527,407.92	$1,544,674.14	$33,081,054.21	1524	24605	1178	19193
5-Aug-18	$2,699,068.26	$49,330,999.23	$1,547,848.17	$35,075,256.09	$1,522,822.06	$34,603,876.27	1996	26601	1241	20434
12-Aug-18	$2,700,965.91	$52,031,965.14	$1,499,495.48	$36,574,751.57	$1,471,696.00	$36,075,572.27	2060	28661	1245	21679
19-Aug-18	$2,700,965.91	$54,732,931.05	$1,472,867.41	$38,047,618.98	$1,445,130.52	$37,520,702.79	1582	30243	662	22341
26-Aug-18	$2,700,965.91	$57,433,896.96	$1,440,056.96	$39,487,675.94	$1,412,696.45	$38,933,399.24	353	30596	220	22561
2-Sep-18	$2,710,733.28	$60,144,630.23	$1,501,327.51	$40,989,003.45	$1,461,661.94	$40,395,061.19	1823	32419	1147	23708
9-Sep-18	$2,710,147.58	$62,854,777.82	$1,457,344.33	$42,446,347.77	$1,413,720.21	$41,808,781.39	1476	33895	1172	24880
16-Sep-18	$2,485,270.25	$65,340,048.07	$1,527,525.01	$43,973,872.78	$1,492,039.99	$43,300,821.38	1157	35052	1209	26089
23-Sep-18	$2,552,158.97	$67,892,207.04	$1,665,441.81	$45,639,314.59	$1,630,429.51	$44,931,250.89	1868	36920	1757	27846
30-Sep-18	$2,483,660.20	$70,375,867.23	$1,683,553.90	$47,322,868.49	$1,645,108.66	$46,576,359.55	1935	38855	1997	29843
7-Oct-18	$2,975,997.07	$73,351,864.30	$1,701,591.64	$49,024,460.13	$1,634,794.32	$48,211,153.87	1166	40021	1414	31257
14-Oct-18	$2,975,997.07	$76,327,861.37	$1,658,408.03	$50,682,868.16	$1,575,909.41	$49,787,063.28	1533	41554	2114	33371
21-Oct-18	$2,975,997.07	$79,303,858.44	$1,708,089.66	$52,390,957.82	$1,610,783.74	$51,397,847.02	1776	43330	2155	35526
28-Oct-18	$2,975,997.07	$82,279,855.51	$1,673,296.65	$54,064,254.47	$1,563,437.79	$52,961,284.82	1823	45153	1923	37449
4-Nov-18	$3,002,679.55	$85,282,535.06	$1,689,406.89	$55,753,661.36	$1,565,469.06	$54,526,753.87	1401	46554	1440	38889
11-Nov-18	$2,771,367.35	$88,053,902.40	$1,658,773.13	$57,412,434.49	$1,528,375.97	$56,055,129.84	1176	47730	1624	40513
18-Nov-18	$2,970,897.24	$91,024,799.64	$1,653,951.00	$59,066,385.48	$1,503,650.19	$57,558,780.04	1697	49427	1620	42133
25-Nov-18	$3,066,469.39	$94,091,269.03	$1,573,887.45	$60,640,272.93	$1,421,515.43	$58,980,295.47	1869	51296	1484	43617
2-Dec-18	$3,187,043.35	$97,278,312.38	$1,548,482.67	$62,188,755.60	$1,382,003.35	$60,362,298.82	2061	53357	1905	45522
9-Dec-18	$3,124,763.61	$100,403,075.99	$1,546,197.79	$63,734,953.39	$1,371,076.35	$61,733,375.17	2128	55485	2021	47543
16-Dec-18	$3,015,663.66	$103,418,739.66	$1,485,099.88	$65,220,053.27	$1,300,674.43	$63,034,049.60	2792	58277	2273	49816
23-Dec-18	$3,075,698.97	$106,494,438.63	$1,457,322.09	$66,677,375.36	$1,242,539.51	$64,276,589.11	2605	60882	2400	52216
30-Dec-18	$3,120,725.45	$109,615,164.07	$1,412,807.23	$68,090,182.60	$1,170,354.14	$65,446,943.25	2928	63810	1748	53964
6-Jan-19	$3,120,725.45	$112,735,889.52	$1,346,864.53	$69,437,047.13	$1,105,859.85	$66,552,803.11	2789	66599	1454	55418
13-Jan-19	$3,132,674.69	$115,868,564.21	$1,331,157.97	$70,768,205.10	$1,083,675.39	$67,636,478.50	2249	68848	1061	56479

Table 4 Actual Project Data (3-5)

	Budget Cost	Cumm Budget Cost	Actual Cost	Cumm Actual Cost	EV	Cumm EV	Budget manhrs	Cumm Budget manhrs	Acual Manhrs	Cumm Actual Manhrs
20-Jan-19	$3,164,701.23	$119,033,265.44	$1,365,747.78	$72,133,952.87	$1,087,755.59	$68,724,234.08	2508	71356	951	57430
27-Jan-19	$3,335,415.99	$122,368,681.43	$1,368,896.63	$73,502,849.51	$1,088,815.24	$69,813,049.33	2471	73827	1082	58512
3-Feb-19	$3,639,940.86	$126,008,622.29	$1,384,770.40	$74,887,619.91	$1,094,247.88	$70,907,297.21	2391	76218	1045	59557
10-Feb-19	$3,647,235.52	$129,655,857.81	$1,430,667.35	$76,318,287.26	$1,100,102.51	$72,007,399.71	2973	79191	1195	60752
17-Feb-19	$3,647,235.52	$133,303,093.33	$1,433,246.86	$77,751,534.12	$1,101,477.51	$73,108,877.22	2724	81915	1228	61980
24-Feb-19	$3,647,235.52	$136,950,328.85	$1,451,038.90	$79,202,573.02	$1,113,638.21	$74,222,515.43	2293	84208	1433	63413
3-Mar-19	$3,647,235.52	$140,597,564.37	$1,451,038.90	$80,653,611.92	$1,113,638.21	$75,336,153.64	2576	86784	1261	64674
10-Mar-19	$3,647,235.52	$144,244,799.89	$1,451,038.90	$82,104,650.82	$1,113,638.21	$76,449,791.86	2641	89425	1125	65799
17-Mar-19	$3,642,127.51	$147,886,927.40	$1,455,229.10	$83,559,879.92	$1,117,828.41	$77,567,620.26	2744	92169	1305	67104
24-Mar-19	$3,611,479.43	$151,498,406.84	$1,484,246.92	$85,044,126.84	$1,144,414.65	$78,712,034.91	2679	94848	1516	68620
31-Mar-19	$3,611,479.43	$155,109,886.27	$1,489,415.77	$86,533,542.61	$1,146,341.38	$79,858,376.29	2385	97233	1437	70057
7-Apr-19	$3,590,961.05	$158,700,847.31	$1,489,415.77	$88,022,958.38	$1,146,341.38	$81,004,717.68	2416	99649	897	70954
14-Apr-19	$3,542,379.92	$162,243,227.24	$1,489,415.77	$89,512,374.15	$1,146,341.38	$82,151,059.06	2371	102020	1158	72112
21-Apr-19	$3,574,264.09	$165,817,491.32	$1,489,415.77	$91,001,789.93	$1,146,341.38	$83,297,400.44	2071	104091	1096	73208
28-Apr-19	$3,474,400.40	$169,291,891.73	$1,489,415.77	$92,491,205.70	$1,146,341.38	$84,443,741.83	1668	105759	1020	74228
5-May-19	$3,327,937.50	$172,619,829.23	$1,489,415.77	$93,980,621.47	$1,146,341.38	$85,590,083.21	1628	107387	919	75147
12-May-19	$3,325,718.95	$175,945,548.17	$1,489,415.77	$95,470,037.24	$1,146,341.38	$86,736,424.59	1162	108549	675	75822
19-May-19	$3,197,209.56	$179,142,757.73	$1,489,415.77	$96,959,453.01	$1,146,341.38	$87,882,765.98	1318	109867	645	76467
26-May-19	$2,897,645.90	$182,040,403.63	$1,489,415.77	$98,448,868.78	$1,146,341.38	$89,029,107.36	1356	111223	745	77212
2-Jun-19	$2,885,566.04	$184,925,969.67	$1,489,415.77	$99,938,284.55	$1,146,341.38	$90,175,448.74	1075	112298	507	77719
9-Jun-19	$2,837,149.09	$187,763,118.76	$1,489,415.77	$101,427,700.33	$1,146,341.38	$91,321,790.13	306	112604	84	77803
16-Jun-19	$2,819,514.57	$190,582,633.32	$1,529,678.73	$102,957,379.06	$1,149,794.26	$92,471,584.39	1739	114343	515	78318
23-Jun-19	$2,743,231.94	$193,325,865.26	$1,547,060.72	$104,504,439.78	$1,154,485.64	$93,626,070.03	1745	116088	667	78985
30-Jun-19	$2,709,305.35	$196,035,170.61	$1,590,078.95	$106,094,518.73	$1,160,108.64	$94,786,178.67	1696	117784	920	79905
7-Jul-19	$2,629,766.67	$198,664,937.28	$1,590,078.95	$107,684,597.68	$1,160,108.64	$95,946,287.31	1470	119254	701	80606
14-Jul-19	$2,488,918.52	$201,153,855.80	$1,590,078.95	$109,274,676.63	$1,160,108.64	$97,106,395.94	1984	121238	865	81471
21-Jul-19	$2,217,756.38	$203,371,612.18	$1,599,464.70	$110,874,141.33	$1,160,773.41	$98,267,169.35	1746	122984	992	82463
28-Jul-19	$2,108,370.64	$205,479,982.82	$1,616,412.34	$112,490,553.67	$1,164,432.41	$99,431,601.76	1999	124983	1077	83540

Table 5 Actual Project Data (4-5)

	Budget Cost	Cumm Budget Cost	Actual Cost	Cumm Actual Cost	EV	Cumm EV	Budget manhrs	Cumm Budget manhrs	Acual Manhrs	Cumm Actual Manhrs
4-Aug-19	$2,018,217.75	$207,498,200.57	$1,643,012.25	$114,133,565.93	$1,181,068.21	$100,612,669.97	2123	127106	1173	84713
11-Aug-19	$2,015,303.11	$209,513,503.68	$1,643,012.25	$115,776,578.18	$1,181,068.21	$101,793,738.18	1675	128781	705	85418
18-Aug-19	$1,989,606.96	$211,503,110.64	$1,643,449.16	$117,420,027.34	$1,181,068.21	$102,974,806.39	363	129144	160	85578
25-Aug-19	$1,905,648.91	$213,408,759.54	$1,646,070.58	$119,066,097.92	$1,181,068.21	$104,155,874.60	2012	131156	1006	86584
1-Sep-19	$1,759,136.63	$215,167,896.17	$1,646,070.58	$120,712,168.50	$1,181,068.21	$105,336,942.81	1354	132510	773	87357
8-Sep-19	$1,658,221.82	$216,826,117.99	$1,692,320.49	$122,404,489.00	$1,191,011.23	$106,527,954.04	1994	134504	924	88281
15-Sep-19	$1,643,079.20	$218,469,197.20	$1,703,151.75	$124,107,640.75	$1,192,062.54	$107,720,016.58	1180	135684	991	89272
22-Sep-19	$1,459,243.98	$219,928,441.17	$1,717,593.42	$125,825,234.17	$1,193,464.30	$108,913,480.88	957	136641	1135	90407
29-Sep-19	$1,238,917.69	$221,167,358.86	$1,727,421.41	$127,552,655.58	$1,193,464.30	$110,106,945.18	678	137319	1301	91708
6-Oct-19	$1,145,439.65	$222,312,798.51	$1,733,013.41	$129,285,668.99	$1,193,464.30	$111,300,409.48	707	138026	1080	92788
13-Oct-19	$1,002,867.29	$223,315,665.79	$1,733,013.41	$131,018,682.39	$1,193,464.30	$112,493,873.78	631	138657	849	93637
20-Oct-19	$994,906.81	$224,310,572.61	$1,733,013.41	$132,751,695.80	$1,193,464.30	$113,687,338.07	508	139165	1438	95075
27-Oct-19	$959,808.73	$225,270,381.33	$1,658,615.21	$134,410,311.01	$1,112,518.45	$114,799,856.52	281	139446	1241	96316
3-Nov-19	$951,170.89	$226,221,552.22				$114,799,856.52	211	139657		96316
10-Nov-19	$921,992.24	$227,143,544.46					160	139817		
17-Nov-19	$900,108.25	$228,043,652.72					158	139975		
24-Nov-19	$900,108.25	$228,943,760.97					125	140100		
1-Dec-19	$900,108.25	$229,843,869.22					185	140285		
8-Dec-19	$900,108.25	$230,743,977.48					167	140452		
15-Dec-19	$900,108.25	$231,644,085.73					151	140603		
22-Dec-19	$900,108.25	$232,544,193.98					160	140763		
29-Dec-19	$900,108.25	$233,444,302.23					141	140904		
5-Jan-20	$900,108.25	$234,344,410.49					115	141019		
12-Jan-20	$421,524.27	$234,765,934.76					132	141151		
19-Jan-20	$341,760.27	$235,107,695.03					104	141255		
26-Jan-20	$341,760.27	$235,449,455.31					55	141310		
2-Feb-20	$341,760.27	$235,791,215.58					59	141369		
9-Feb-20	$341,760.27	$236,132,975.85					68	141437		

Table 6 Actual Project Data (5-5)

	Budget Cost	Cumm Budget Cost	Actual Cost	Cumm Actual Cost	EV	Cumm EV	Budget manhrs	Cumm Budget manhrs	Acual Manhrs	Cumm Actual Manhrs
16-Feb-20	$341,760.27	$236,474,736.13					67	141504		
23-Feb-20	$341,760.27	$236,816,496.40					51	141555		
1-Mar-20	$341,760.27	$237,158,256.68					30	141585		
8-Mar-20	$324,174.46	$237,482,431.14					32	141617		
15-Mar-20	$218,659.60	$237,701,090.73					39	141656		
22-Mar-20	$218,659.60	$237,919,750.33					27	141683		
29-Mar-20	$218,659.60	$238,138,409.92					10	141693		
5-Apr-20	$218,659.60	$238,357,069.52					10	141703		
12-Apr-20	$62,474.17	$238,419,543.69					18	141721		

4.2.1 Validating Calibration Stage 1

The developed dynamic model was calibrated to the project using calibration stage 1. The model was able to achieve a replication of the planned progress. Figure 13 clearly shows that there is no significant difference between the planned progress and the simulated planned from the calibration.

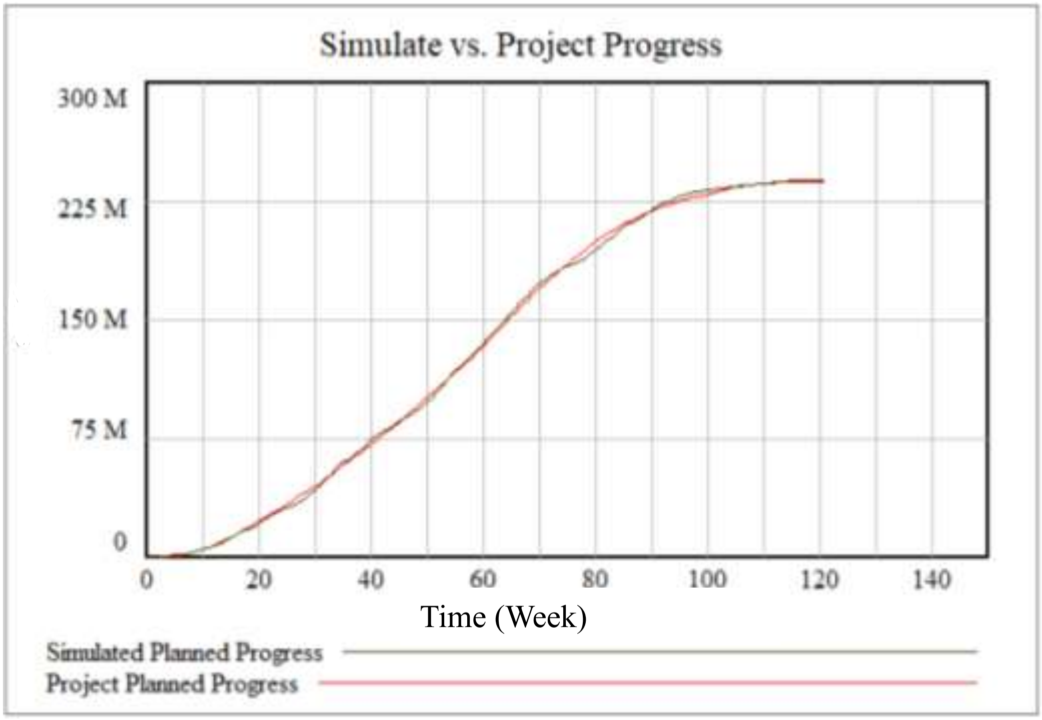

Figure 13 Project Planned Progress after Calibration

4.2.2 Validating Calibration Stage 2

The developed dynamic model was calibrated to the project using calibration stage 2 Figure 14. The model was able to achieve a replication of the EV progress Figure 15. In this figure, it is clearly recognized that there is no significant difference between the EV progress and the simulated EV from the calibration with the Change Order added.

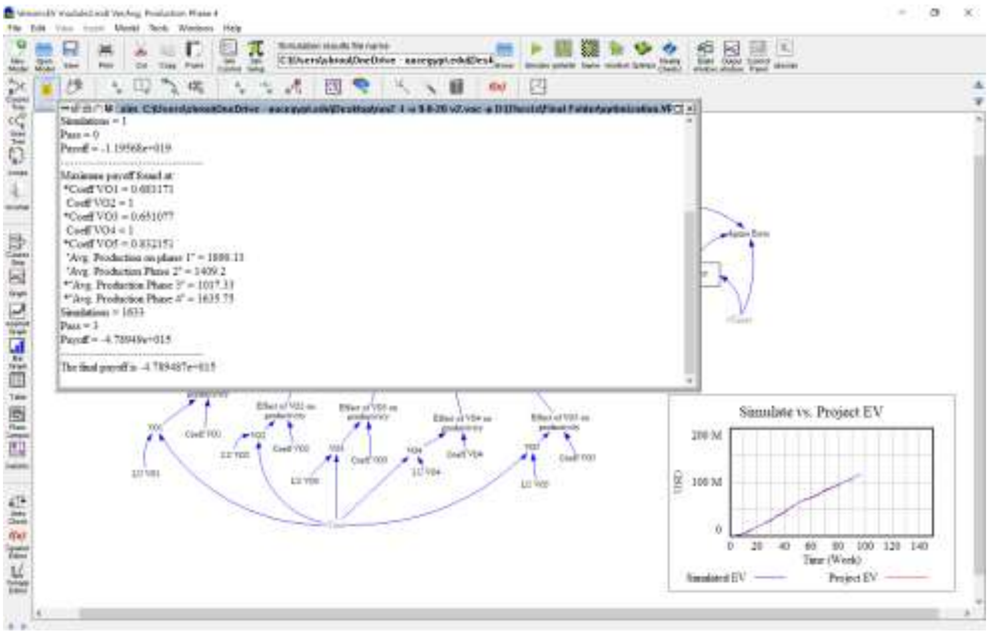

Figure 15 EV Calibration

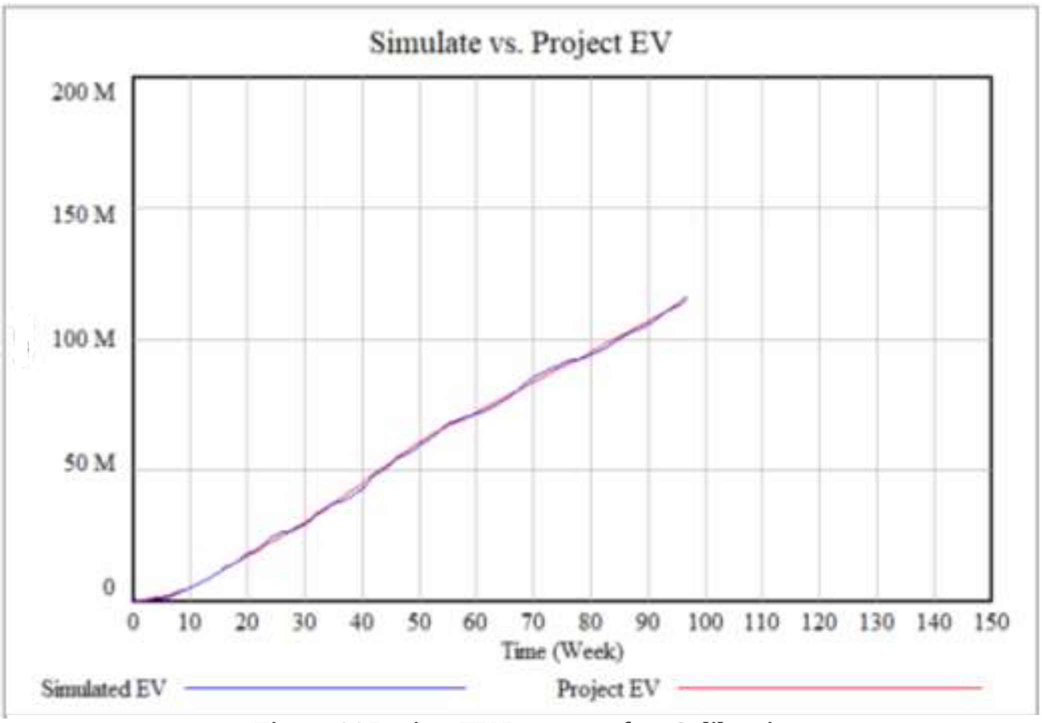

Figure 14 Project EV Progress after Calibration

4.3 The Effect of Change Orders on the Project and What-If Scenarios

In this section a different what-if analysis will be deployed to test the effect of each change order independently through modeling 15 different scenarios as follows.

4.3.1 Effect of removing VO1

The effect of removing the first change order (VO1) on the actual project progress (Project EV) is shown below. When VO1 was removed, the simulated project curve did not imitate the project EV progress curve and it showed that the simulated project progress was faster than the EV progress as shown in figure 16. Afterwards the model was calibrated to generate the effect of removing VO1 "variable" through minimizing the square error to imitate the project EV. Figure 17 shows the independent effect of removing VO1; if VO1 has no effect the result should be 1 but, in this case, the resulted effect 0.9149; accordingly, the direct effect is (1-0.9149) *100= 8.5% on the manhours. Figure 18 demonstrates the productivity graph, with the presence of VO1 is lower than without its presence, and the impacts is highest between weeks 30 and 65 (the highest gap in the overall weekly productivity)

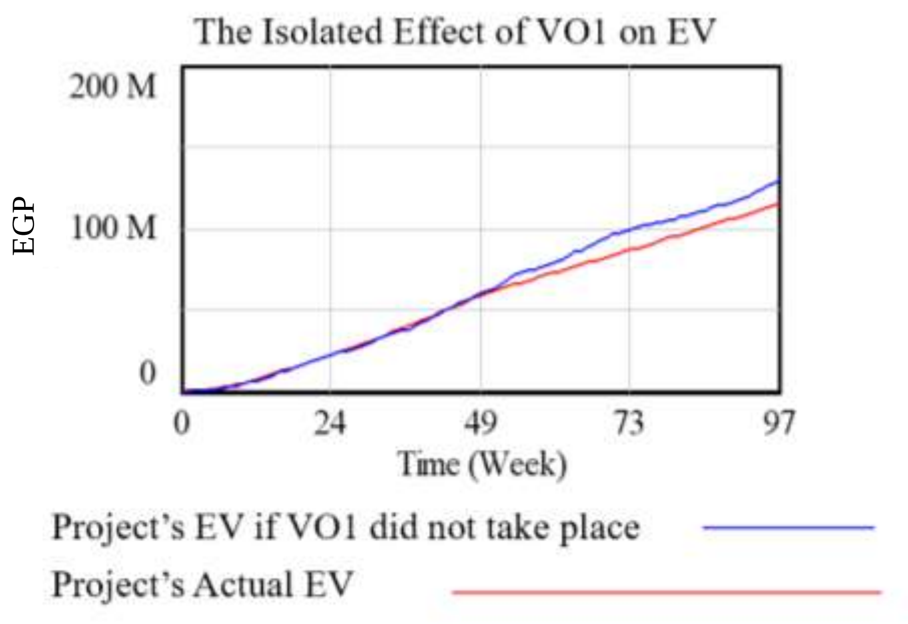

Figure 16 The Isolated Effect of VO1 on EV

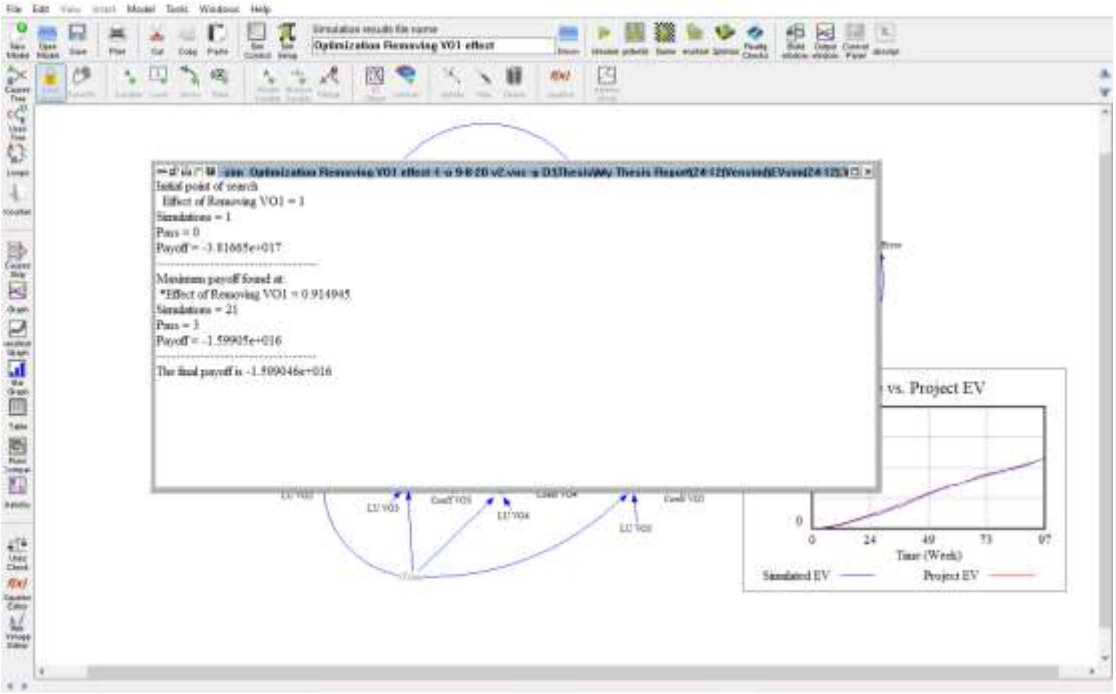

Figure 17 Effect of Removing VO1

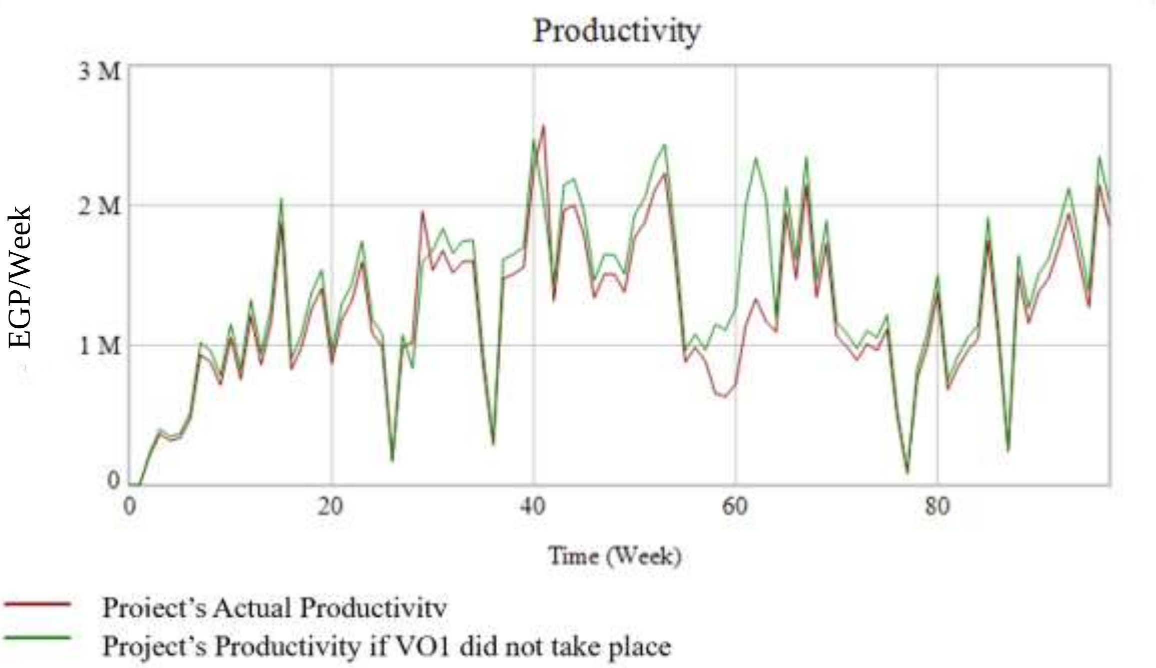

Figure 18 Productivity with Versus without VO1 Effect

4.3.2 Effect of Removing VO2

The effect of removing the second change order (VO2) on the actual project progress (Project EV) is shown below. When VO2 was removed, the simulated project curve imitated the project EV progress curve, and it showed no difference between the simulated project progress and the

EV progress as shown in figure 19. Afterwards the model was calibrated to generate the effect of removing VO2 “variable” through minimizing the square error to imitate the project EV. Figure 20 shows the independent effect of removing VO2; and showed that VO2 has no effect with a result of 1 on the manhours. Figure 21 demonstrates the productivity graph, with the presence of VO2 is similar to without its presence, and has no impact

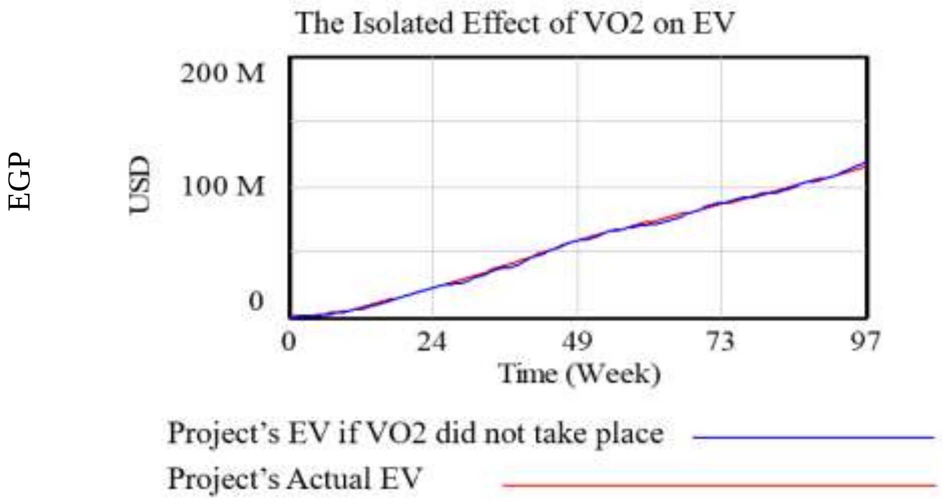

Figure 19 The Isolated Effect of VO2 on EV

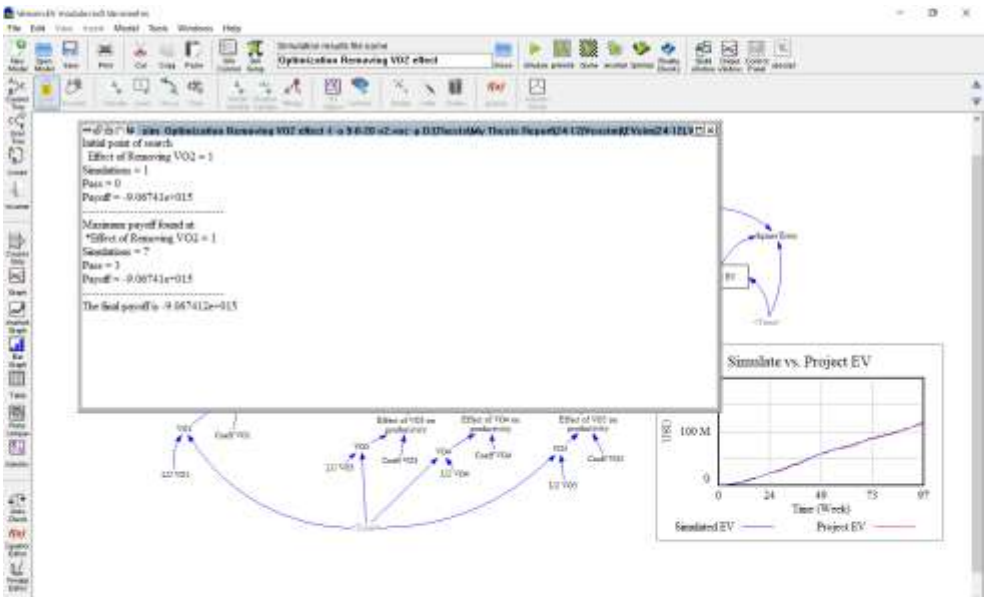

Figure 20 Effect of Removing VO2

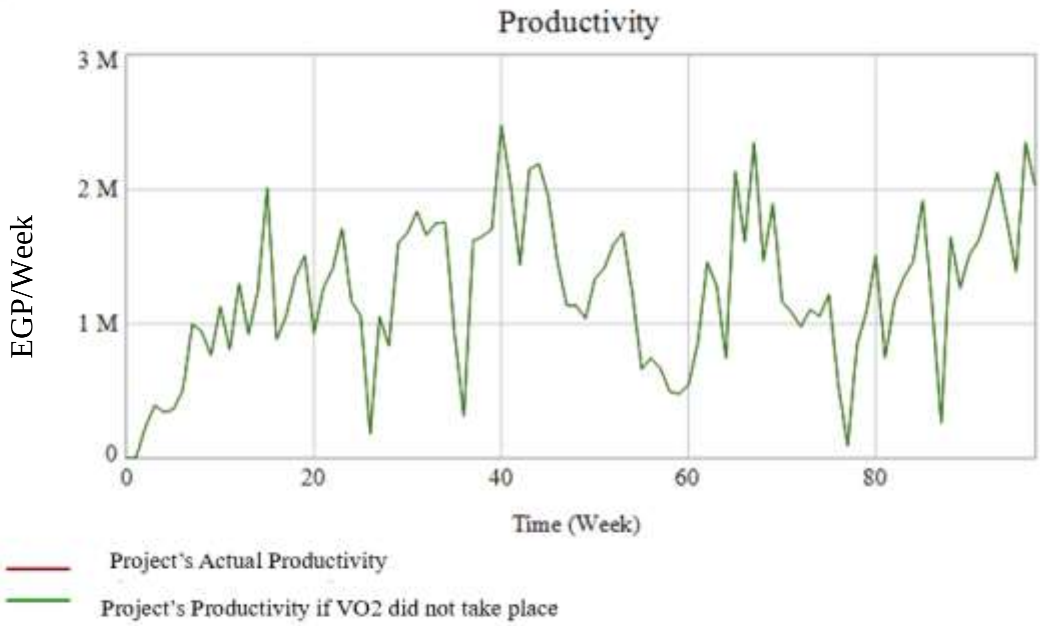

Figure 21 Productivity with Versus without VO2 Effect

4.3.3 Effect of Removing VO3

The effect of removing the third change order (VO3) on the actual project progress (Project EV) is shown below. When VO3 was removed, the simulated project curve did not imitate the project EV progress curve and it showed that the simulated project progress was faster than the EV progress as shown in figure 22. Afterwards the model was calibrated to generate the effect of removing VO3 "variable" through minimizing the square error to imitate the project EV. Figure 23 shows the independent effect of removing VO3; if VO3 has no effect the result should be 1 but, in this case, the resulted effect 0.9597; accordingly, the direct effect is (1-0.9597) *100= 4% on the manhours. Figure 24 demonstrates the productivity graph, with the presence of VO3 is lower than without its presence, and the impacts is highest between weeks 62 and 65 (the highest gap in the overall weekly productivity)

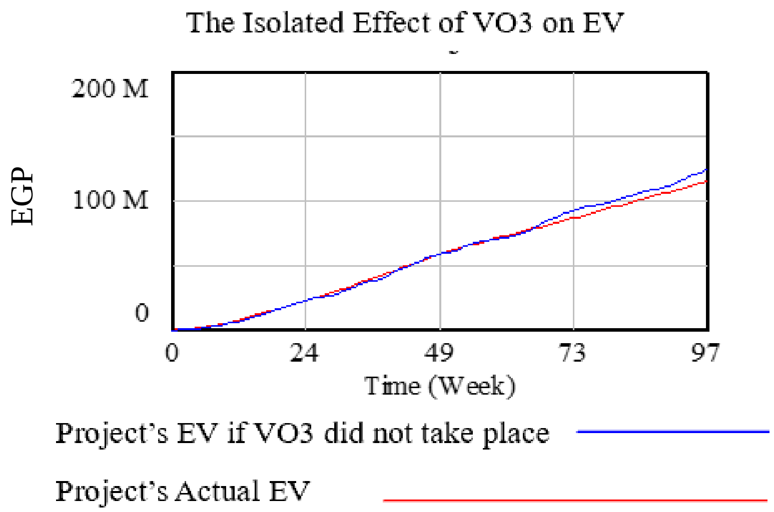

Figure 22 The Isolated Effect of

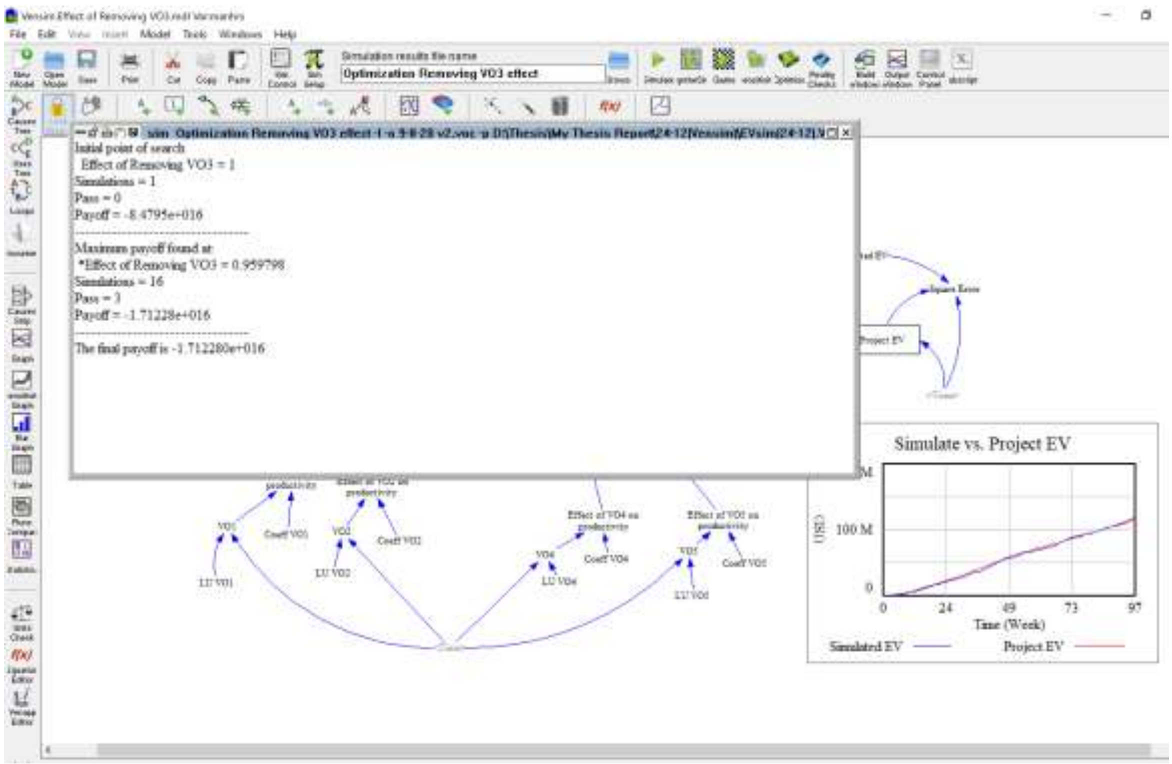

Figure 23 Effect of Removing VO3

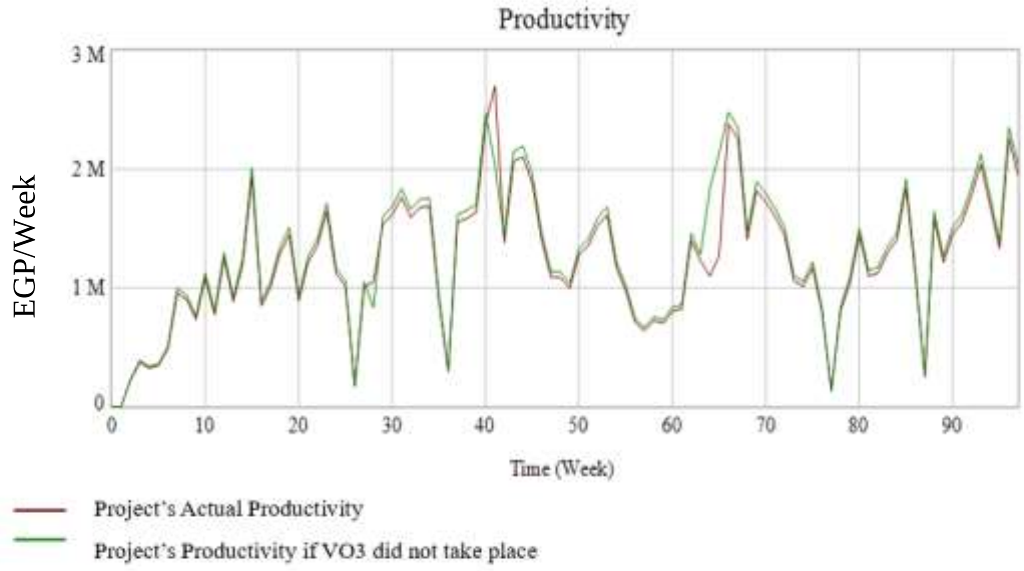

Figure 24 Productivity with Versus without VO3 Effect

4.3.4 Effect of Removing VO4

The effect of removing the fourth change order (VO4) on the actual project progress (Project EV) is shown below. When VO4 was removed, the simulated project curve imitated the project EV progress curve, and it showed no difference between the simulated project progress and the EV progress as shown in figure 25. Afterwards the model was calibrated to generate the effect of removing VO4 "variable" through minimizing the square error to imitate the project EV. Figure 26 shows the independent effect of removing VO4; and showed that VO4 has no effect with a result of 1 on the manhours. Figure 27 demonstrates the productivity graph, with the presence of VO4 is similar to without its presence and has no impact.

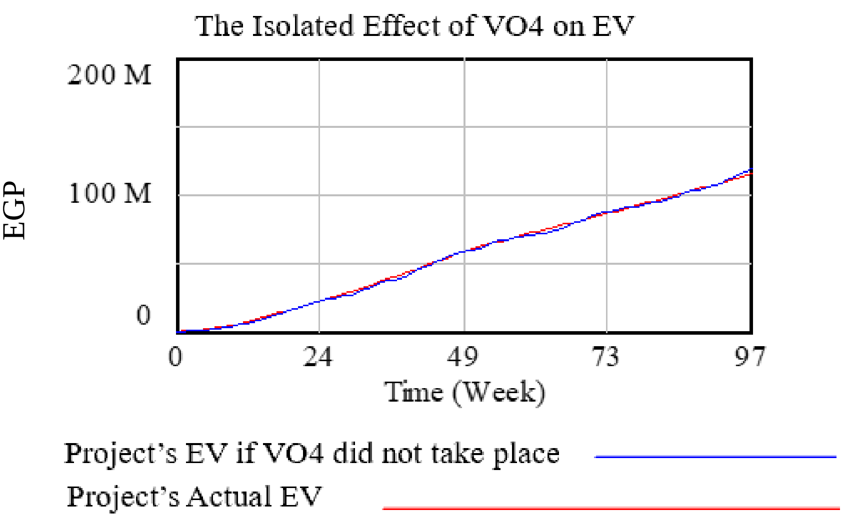

Figure 25 The Isolate Effect of VO4 on EV

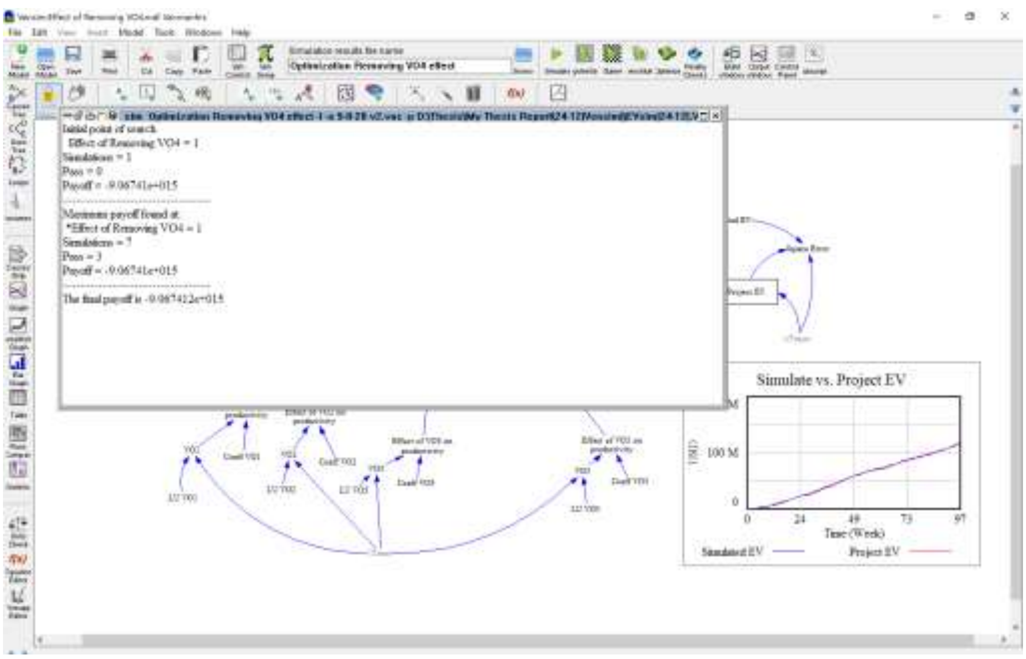

Figure 26 Effect of Removing VO4

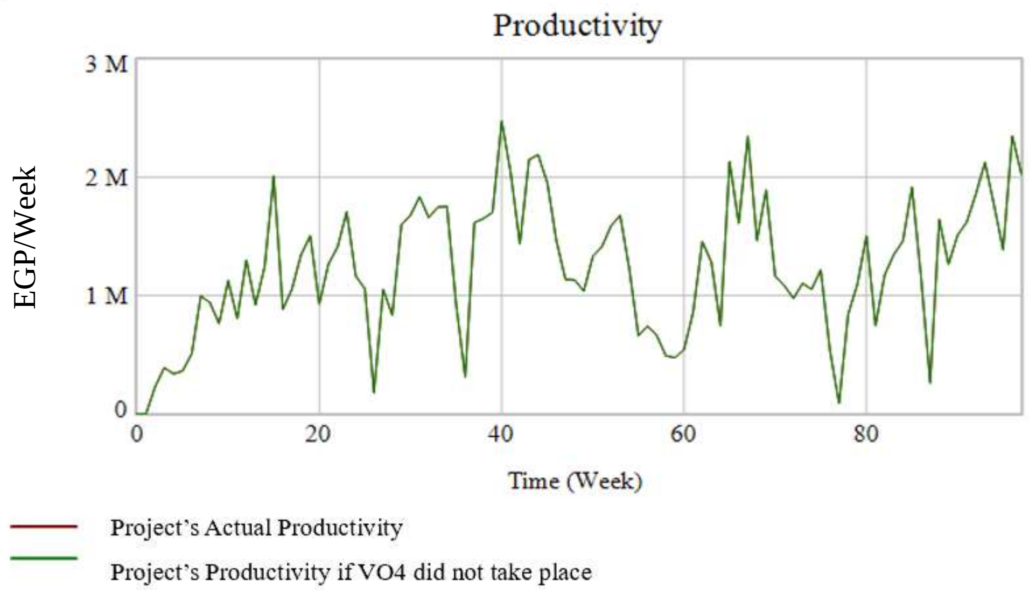

Figure 27 Productivity with Versus without the VO4 Effect

4.3.5 Effect of Removing VO5

The effect of removing the fifth change order (VO5) on the actual project progress (Project EV) is demonstrated. When VO5 was removed, the simulated project curve imitated the project EV progress curve, and it showed no difference between the simulated project progress and the EV progress as shown in figure 28. Afterwards the model was calibrated to generate the effect of removing VO5 "variable" through minimizing the square error to imitate the project EV. Figure 29 shows the independent effect of removing VO5; if VO5 has no effect the result should be 1 but, in this case, the resulted effect 0.988; accordingly, the direct effect is (1-0.988) *100= 1.2% on the manhours. Figure 30 demonstrates the productivity graph, with the presence of VO5 is lower than without its presence, and the impacts is highest in week 63 (the highest gap in the overall weekly productivity)

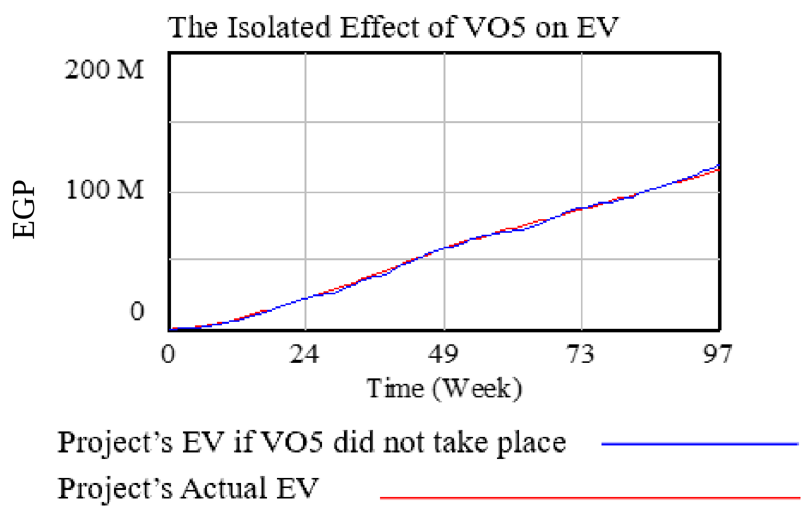

Figure 28 The Isolated Effect of VO5 on EV

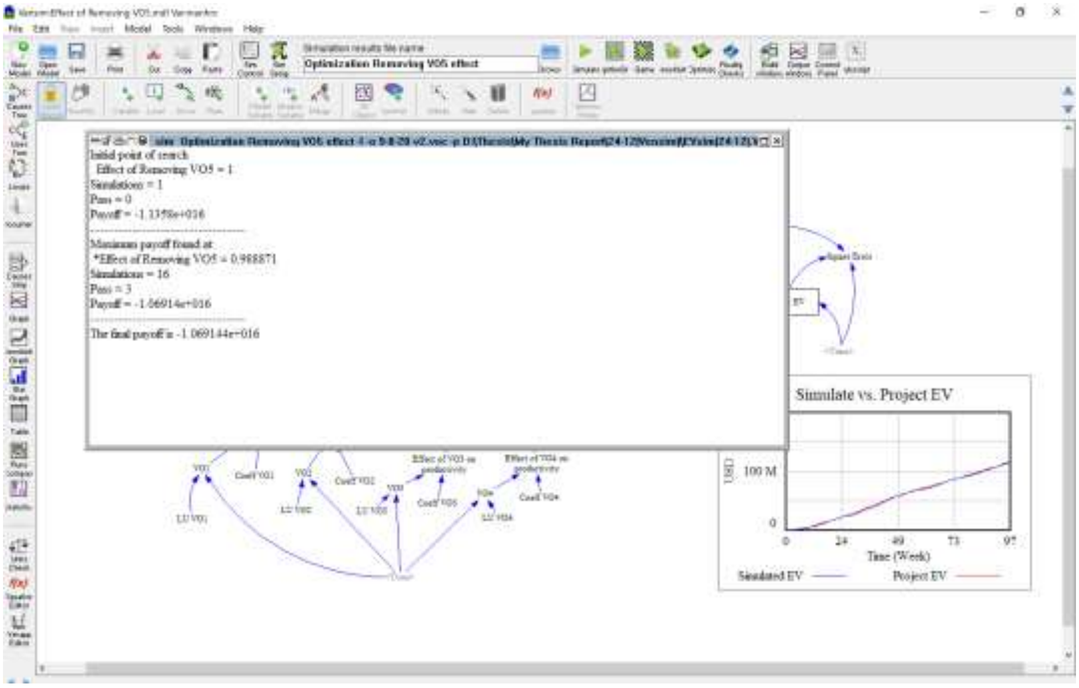

Figure 29 Effect of Removing VO5

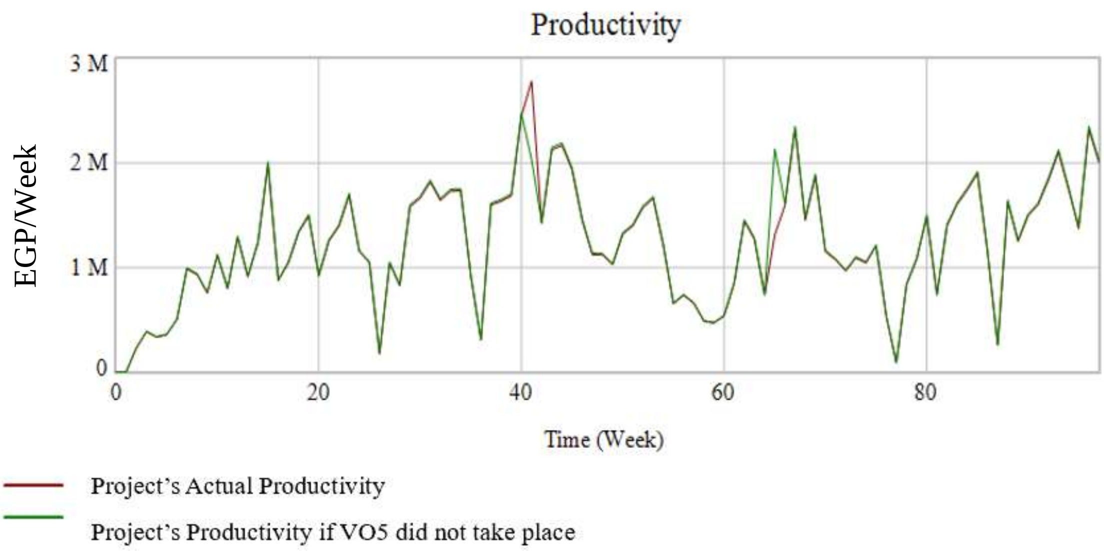

Figure 30 Productivity with Versus without VO5 Effect

4.3.6 Effect of Removing VO1 and VO2

The effect of removing the first and second change orders (VO1& VO2) on the actual project progress (Project EV) is shown below. When VO1&VO2 were removed, the simulated project curve did not imitate the project EV progress curve and it showed that the simulated project progress was faster than the EV progress as shown in figure 31. Afterwards the model was calibrated to generate the effect of removing VO1&VO2 "variable" through minimizing the square error to imitate the project EV. Figure 32 shows the independent effect of removing VO1&VO2; if VO1&VO2 has no effect the result should be 1 but, in this case, the resulted effect 0.9153; accordingly, the direct effect is (1-0.9153) *100= 8.5% on the manhours. Figure 33 demonstrates the productivity graph, with the presence of VO1&VO2 is lower than without its presence, and the impacts is highest between weeks 59 and 63 (the highest gap in the overall weekly productivity)

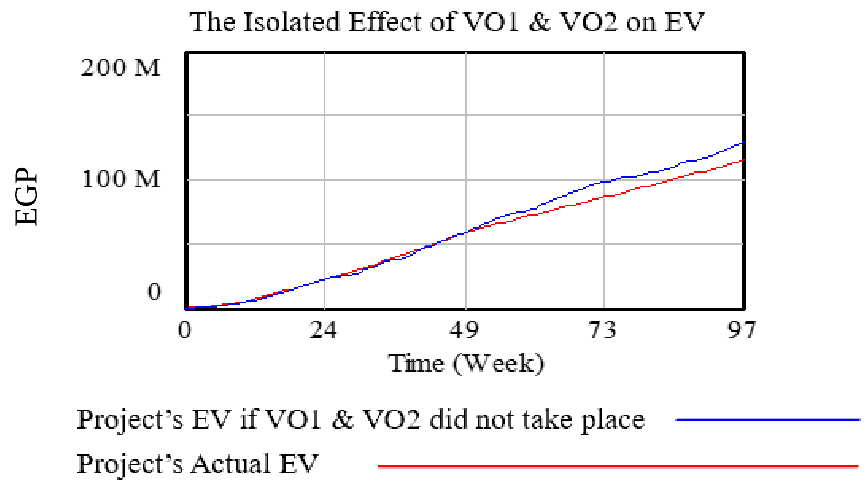

Figure 31 The Isolated Effect of VO1 & VO2

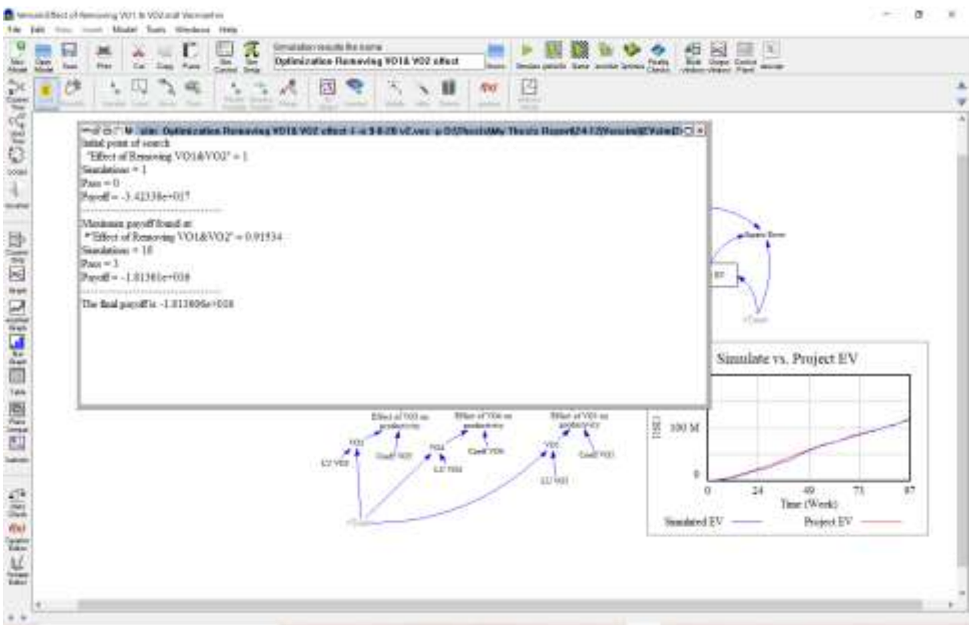

Figure 32 Effect of Removing VO1 and VO2

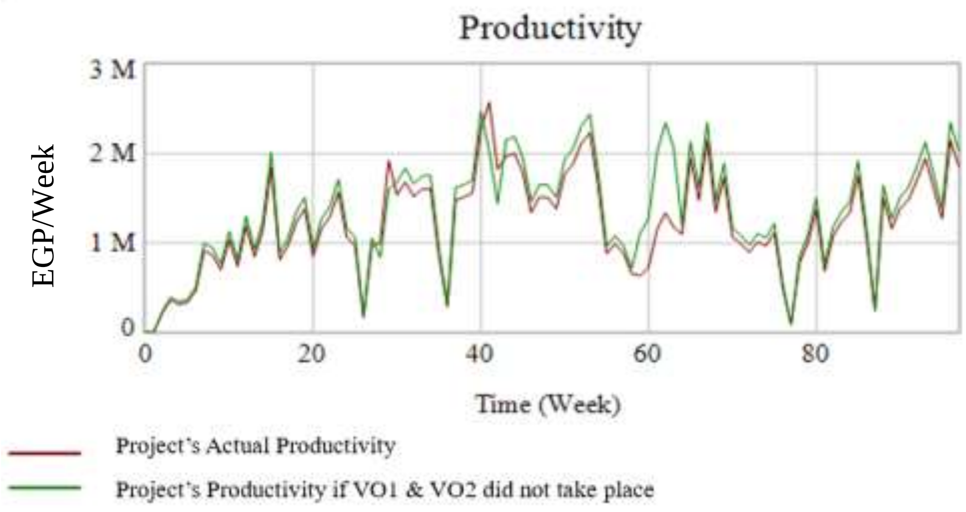

Figure 33 Productivity with Versus without VO1 and VO2 Effect

4.3.7 Effect of Removing VO1 and VO3

The effect of removing the first and third change orders (VO1&VO3) on the actual project progress (Project EV) is shown below. When VO1&VO3 were removed, the simulated project curve did not imitate the project EV progress curve and it showed that the simulated project progress was faster than the EV progress as shown in figure 34. Afterwards the model was calibrated to generate the effect of removing VO1&VO3 "variable" through minimizing the square error to imitate the project EV. Figure 35 shows the independent effect of removing VO1&VO3; if VO1&VO3 has no effect the result should be 1 but, in this case, the resulted effect 0.869; accordingly, the direct effect is (1-0.869) *100= 13.1% on the manhours. Figure 36 demonstrates the productivity graph, with the presence of VO1&VO3 is lower than without its presence, and the impacts is highest between weeks 42 and 78 (the highest gap in the overall weekly productivity)

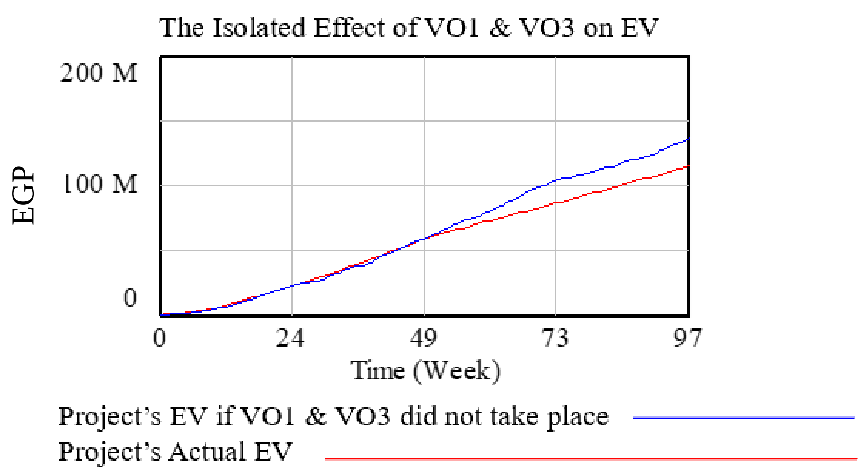

Figure 34 The Isolated Effect of VO1 and VO3

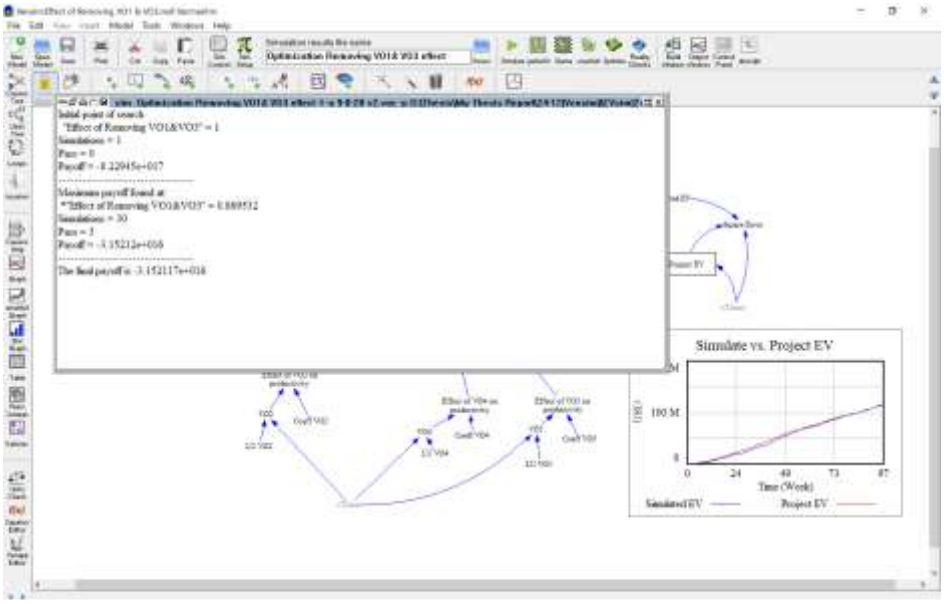

Figure 35 Effect of Removing VO1 and VO3

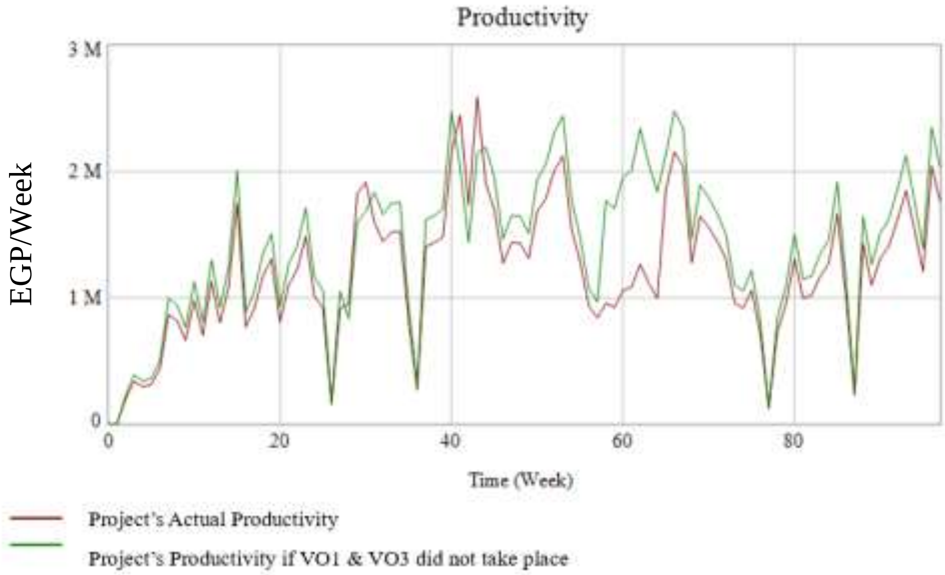

Figure 36 Productivity with Versus without VO1 and VO3

4.3.8 Effect of Removing VO1 and VO4

The effect of removing the first and fourth change orders (VO1&VO4) on the actual project progress (Project EV) is shown below. When VO1 were removed, the simulated project curve did not imitate the project EV progress curve and it showed that the simulated project progress was faster than the EV progress as shown in figure 37. Afterwards the model was calibrated to generate the effect of removing VO1&VO4 "variable" through minimizing the square error to imitate the project EV. Figure 38 shows the independent effect of removing VO1&VO4; if VO1&VO4 has no effect the result should be 1 but, in this case, the resulted effect 0.915; accordingly, the direct effect is (1-0.915) *100= 8.5% on the manhours. Figure 39 demonstrates the productivity graph, with the presence of VO1&VO4 is lower than without its presence, and the impacts is highest between weeks 58 and 63 (the highest gap in the overall weekly productivity)

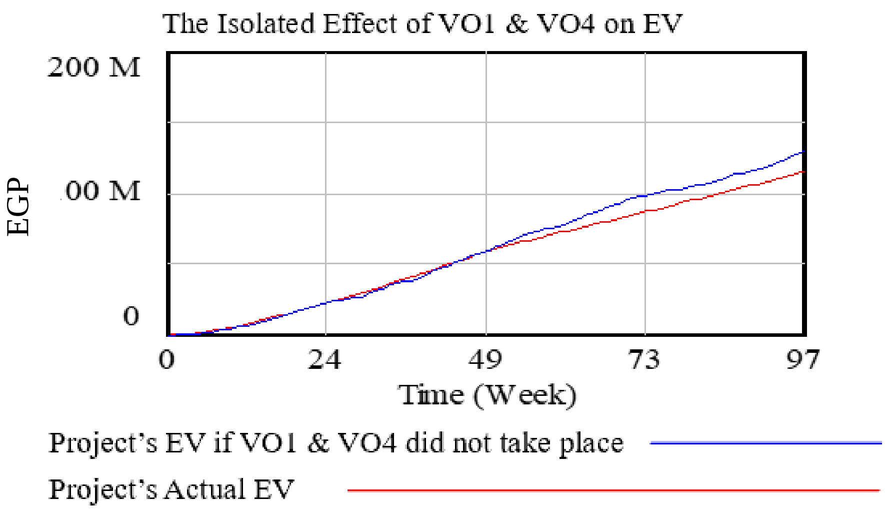

Figure 37 The Isolated Effect of VO1 and VO4 on EV

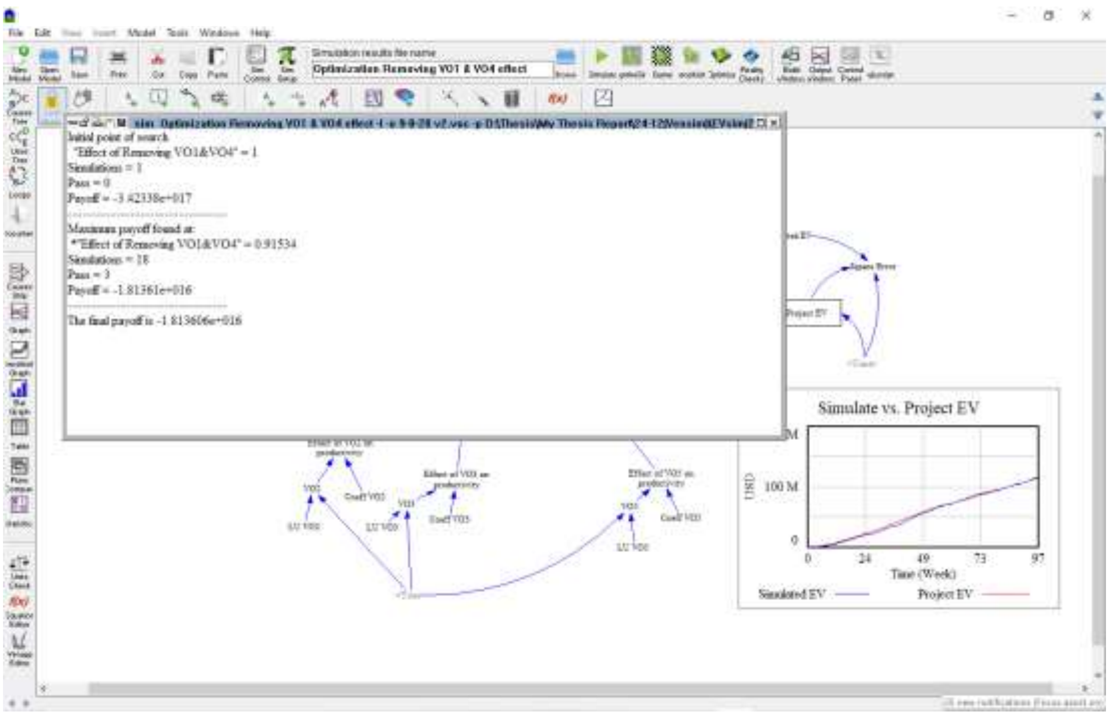

Figure 38 Effect of Removing VO1 and VO4

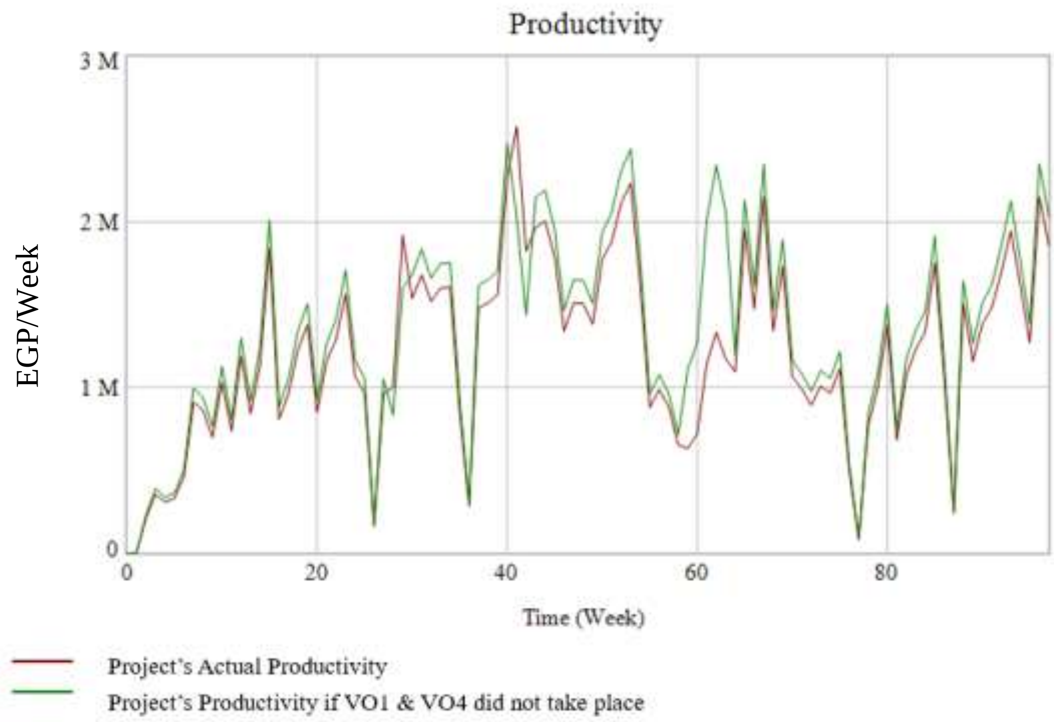

Figure 39 Productivity with Versus without VO1 and VO4

4.3.9 Effect of Removing VO1 and VO5

The effect of removing the first and fifth change orders (VO1&VO5) on the actual project progress (Project EV) is shown below. When VO1&VO5 were removed, the simulated project curve did not imitate the project EV progress curve and it showed that the simulated project progress was faster than the EV progress as shown in figure 40. Afterwards the model was calibrated to generate the effect of removing VO1&VO5 "variable" through minimizing the square error to imitate the project EV. Figure 41 shows the independent effect of removing VO1; if VO1 has no effect the result should be 1 but, in this case, the resulted effect 0.912; accordingly, the direct effect is (1-0.912) *100= 8.8% on the manhours. Figure 42 demonstrates the productivity graph, with the presence of VO1&VO5 is lower than without its presence, and the impacts is highest between weeks 59 and 63 (the highest gap in the overall weekly productivity)

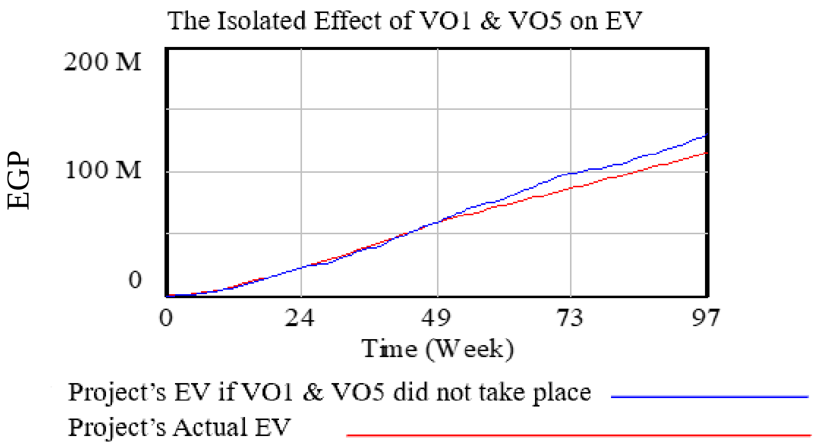

Figure 40 The Isolated Effect of VO1 and VO5

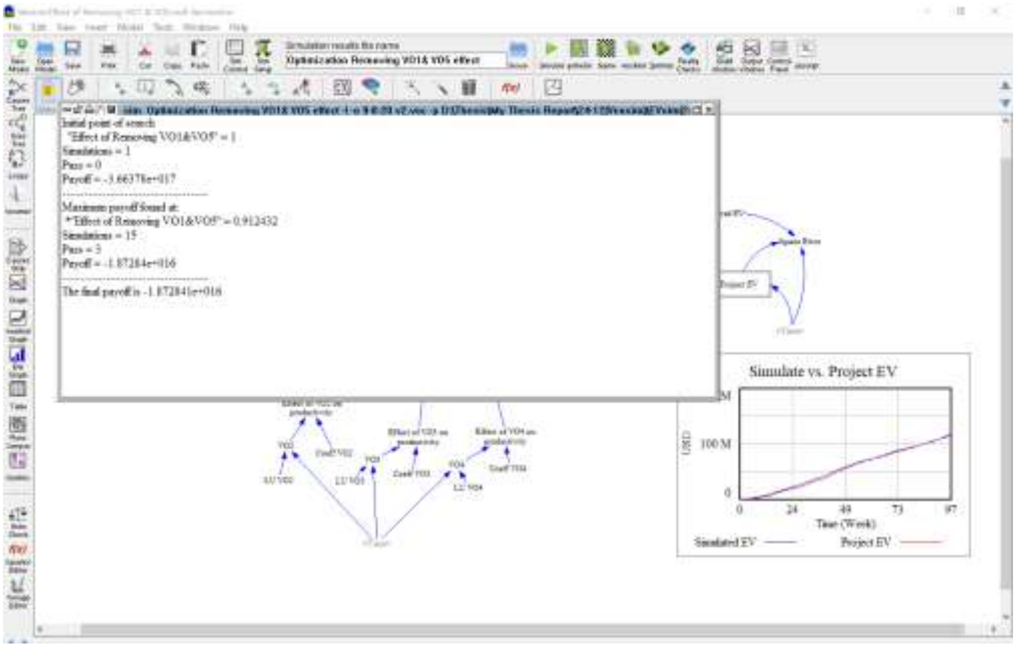

Figure 41 The Effect of Removing VO1 and VO5

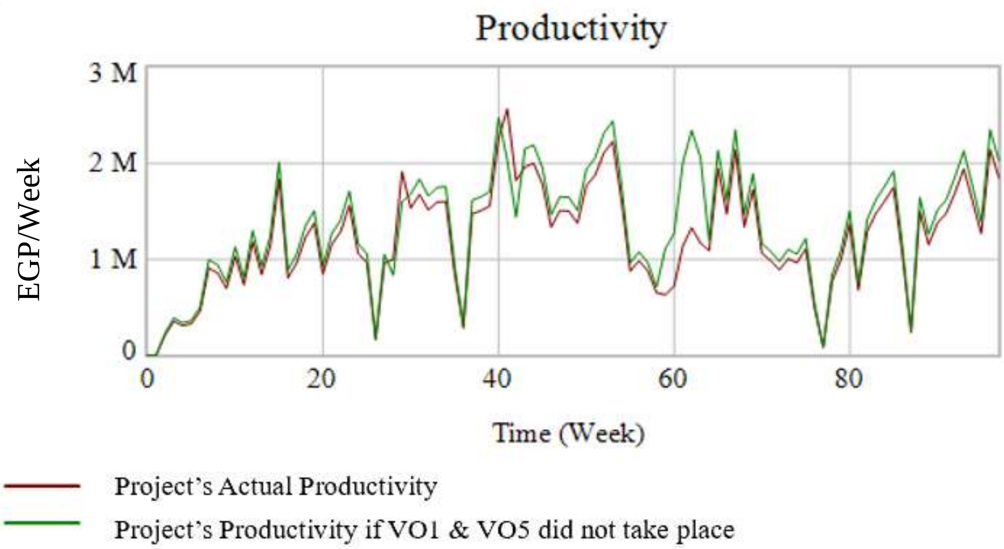

Figure 42 Productivity with Versus without VO1 and VO5

4.3.10 Effect of Removing VO2 and VO3

The effect of removing the second and third change orders (VO2&VO3) on the actual project progress (Project EV) is shown below. When VO2&VO3 were removed, the simulated project curve did not imitate the project EV progress curve and it showed that the simulated project progress was faster than the EV progress as shown in figure 43. Afterwards the model was calibrated to generate the effect of removing VO2&VO3 "variable" through minimizing the square error to imitate the project EV. Figure 44 shows the independent effect of removing VO2&VO3; if VO1 has no effect the result should be 1 but, in this case, the resulted effect 0.959; accordingly, the direct effect is (1-0.959) *100= 4.1% on the manhours. Figure 45 demonstrates the productivity graph, with the presence of VO2&VO3 is lower than without its presence, and the impacts is highest between weeks 62 and 64 (the highest gap in the overall weekly productivity)

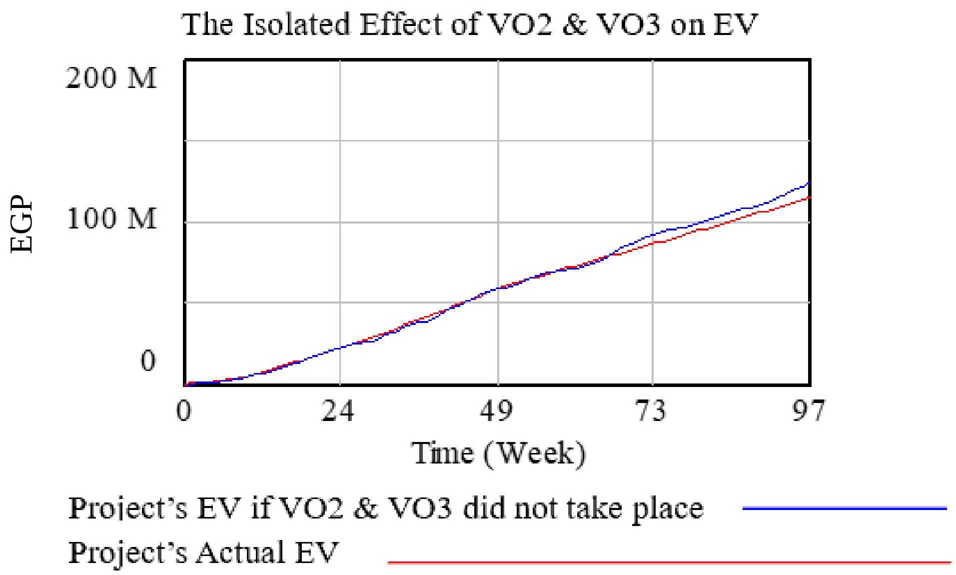

Figure 43 The Isolated Effect of VO2 and VO3

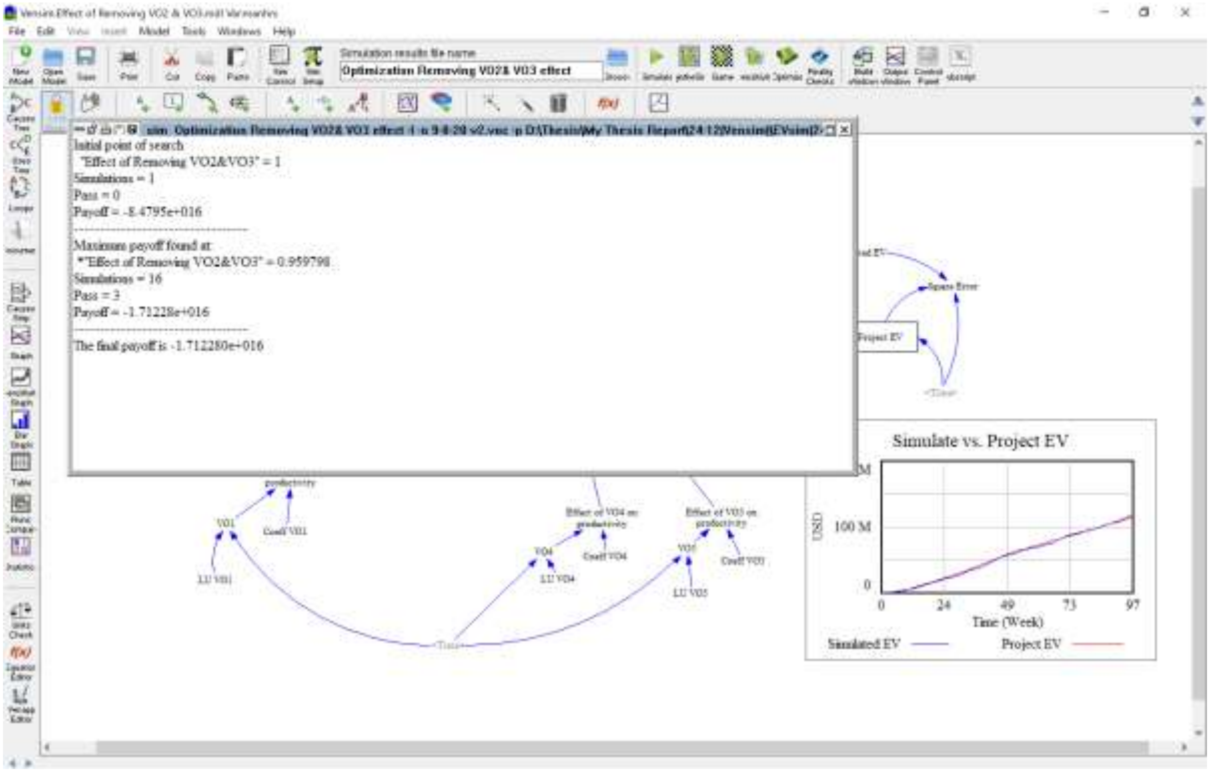

Figure 44 The Effect of Removing VO2 and VO3

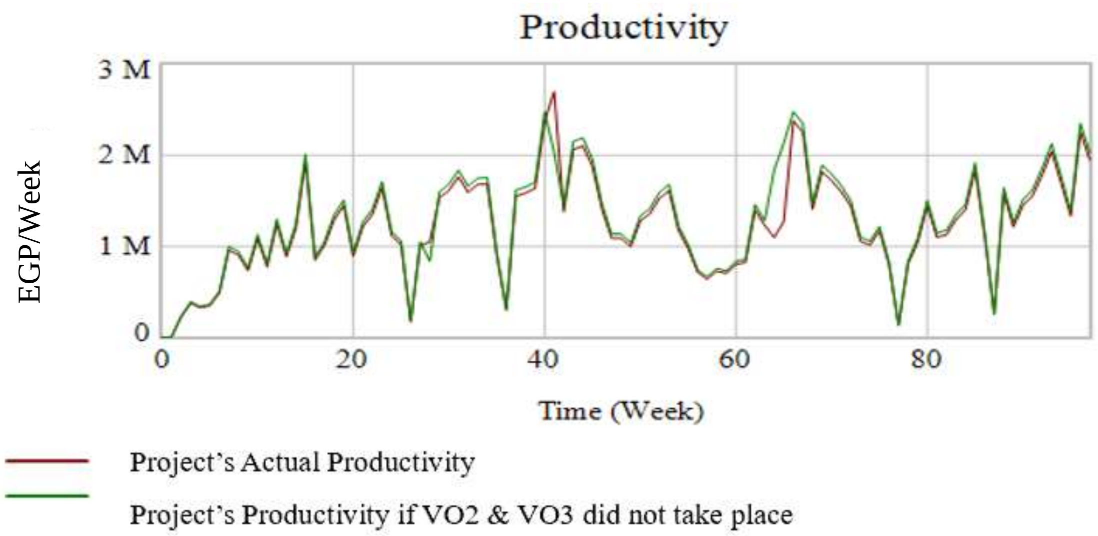

Figure 45 Productivity with Versus Without VO2 and VO3

4.3.1 Effect of Removing VO2 and VO4

The effect of removing the second and fourth change order (VO2&VO4) on the actual project progress (Project EV) is shown below. When VO2&VO4 were removed, the simulated project curve imitated the project EV progress curve, and it showed no difference between the simulated project progress and the EV progress as shown in figure 46. Afterwards the model was calibrated to generate the effect of removing VO2&VO4 "variable" through minimizing the square error to imitate the project EV. Figure 47 shows the independent effect of removing VO2&VO4; and showed that VO2&VO4 has no effect with a result of 1 on the manhours. Figure 48 demonstrates the productivity graph, with the presence of VO2&VO4 is similar to without its presence and has no impact.

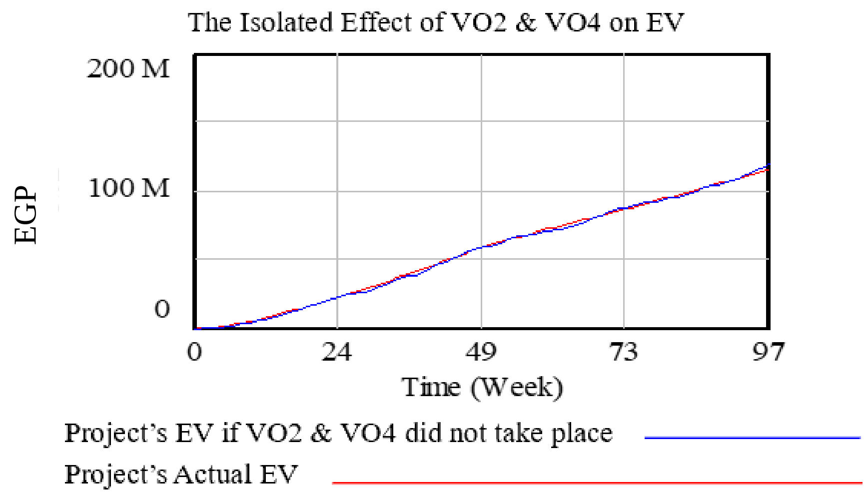

Figure 46 The Isolated Effect of VO2 and VO4

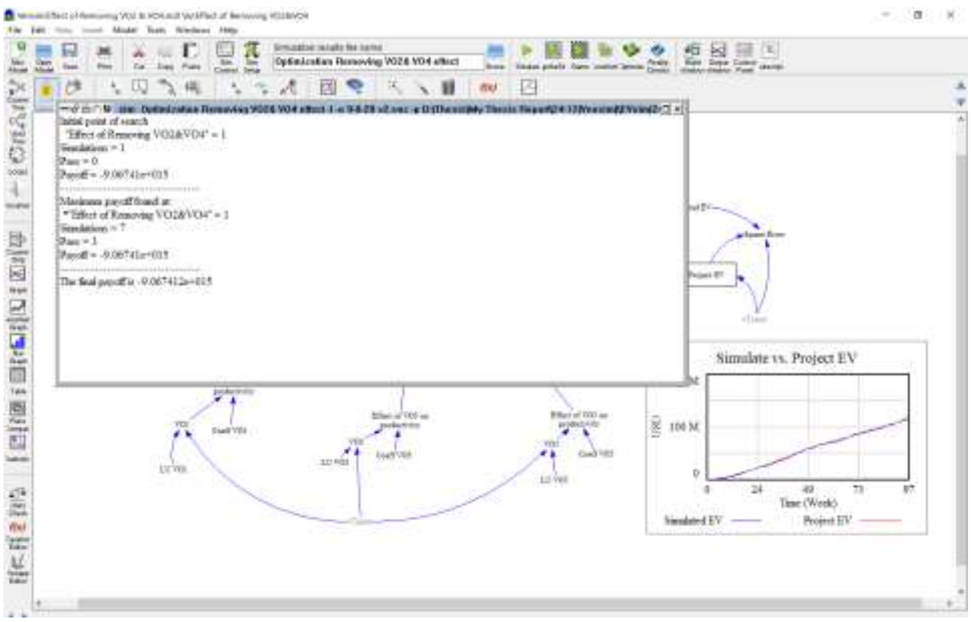

Figure 47 Effect of Removing VO2 and VO4

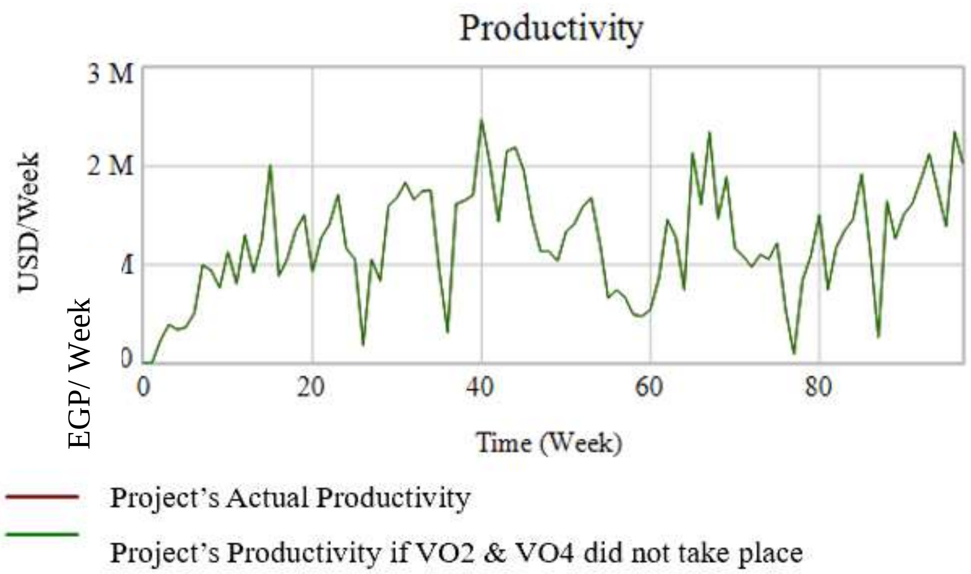

Figure 48 Productivity with Versus without VO2 and VO4

4.3.11 Effect of Removing VO2 and VO5

The effect of removing the second and fifth change order (VO2&VO5) on the actual project progress (Project EV) is shown below. When VO2&VO5 were removed, the simulated project curve imitated the project EV progress curve, and it showed no difference between the simulated project progress and the EV progress as shown in figure 49. Afterwards the model was calibrated to generate the effect of removing VO2&VO5 "variable" through minimizing the square error to imitate the project EV. Figure 50 shows the independent effect of removing VO2&VO5; if VO2&VO5 has no effect the result should be 1 but, in this case, the resulted effect 0.988; accordingly, the direct effect is (1-0.988) *100= 1.2% on the manhours. Figure 51 demonstrates the productivity graph, with the presence of VO2&VO5 is lower than without its presence, and the impacts is highest in weeks 63 and 64(the highest gap in the overall weekly productivity)

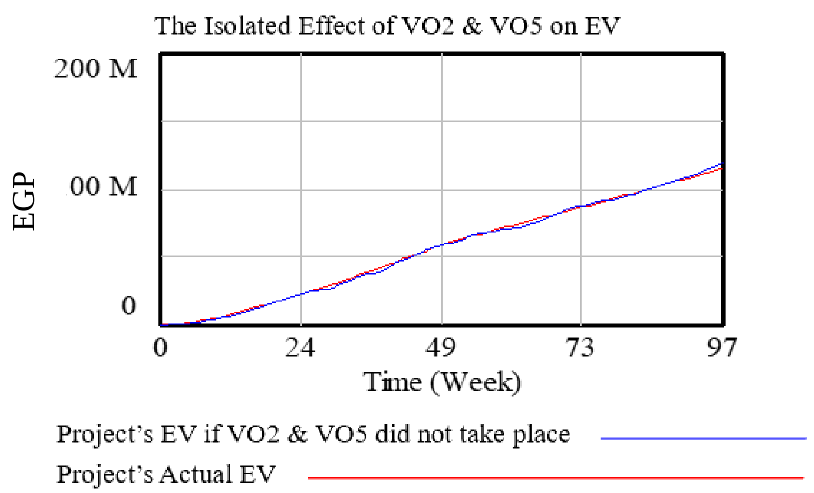

Figure 49 The Isolated Effect of VO2 and VO5

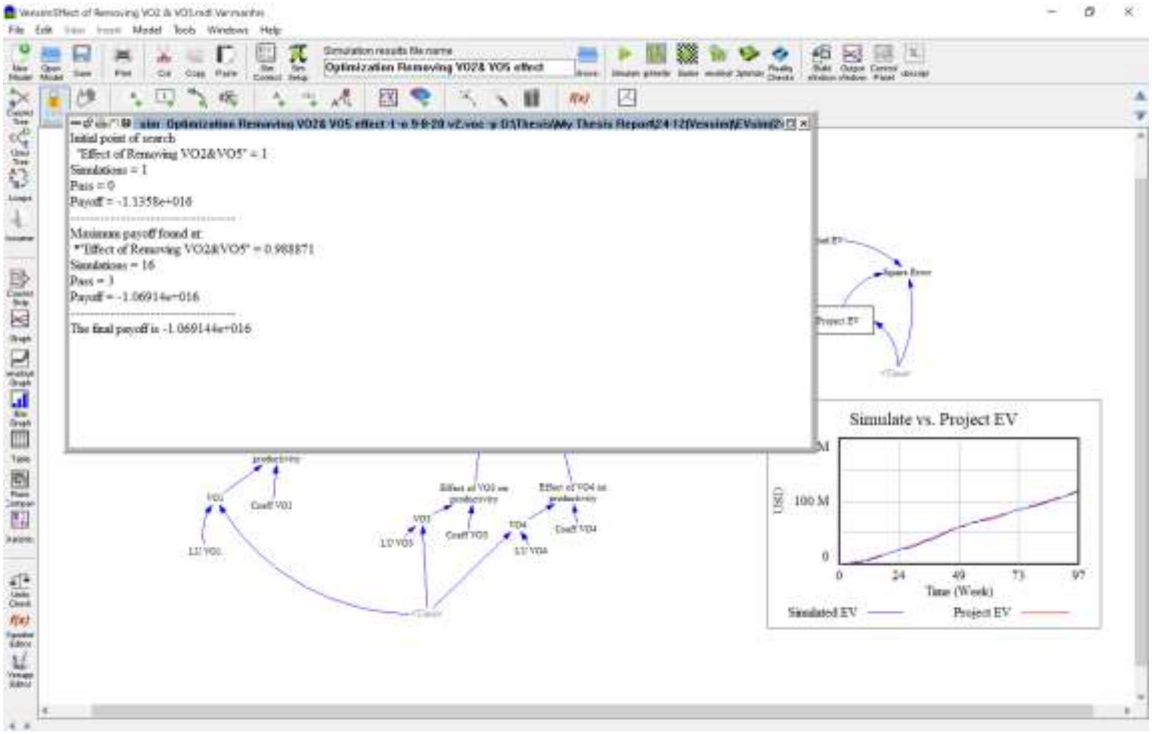

Figure 50 Effect of Removing VO2 and VO5

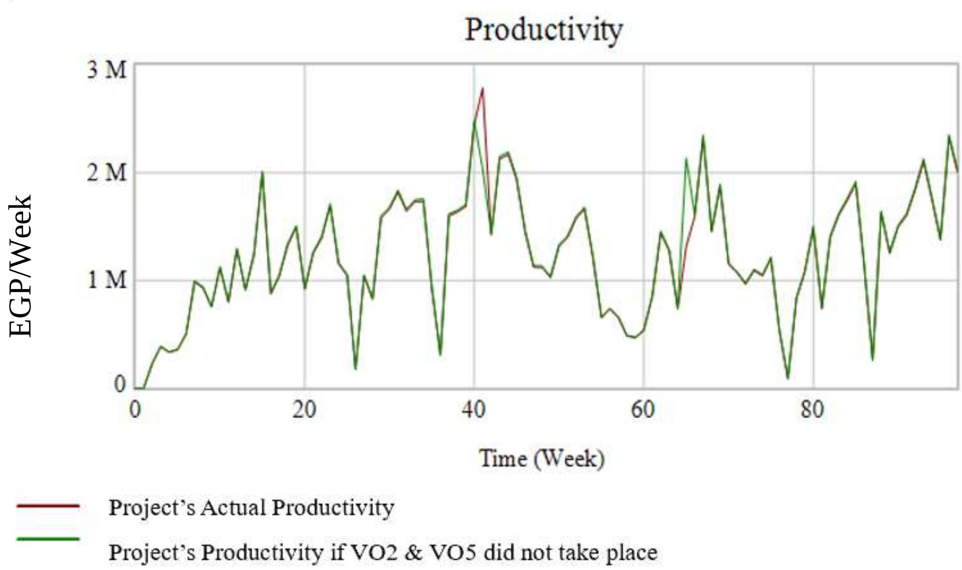

Figure 51 Productivity with Versus without VO2 and VO5

4.3.12 Effect of Removing VO3 and VO4

The effect of removing the third and fourth change orders (VO3&VO4) on the actual project progress (Project EV) is shown below. When VO3&VO4 were removed, the simulated project curve did not imitate the project EV progress curve and it showed that the simulated project progress was faster than the EV progress as shown in figure 52. Afterwards the model was calibrated to generate the effect of removing VO3&VO5 “variable” through minimizing the square error to imitate the project EV. Figure 53 shows the independent effect of removing VO3&VO5; if VO2&VO5 has no effect the result should be 1 but, in this case, the resulted effect 0.959; accordingly, the direct effect is (1-0.959) *100= 4.1% on the manhours. Figure 54 demonstrates the productivity graph, with the presence of VO3&VO5 is lower than without its presence, and the impacts is highest in weeks 63 and 64 (the highest gap in the overall weekly productivity)

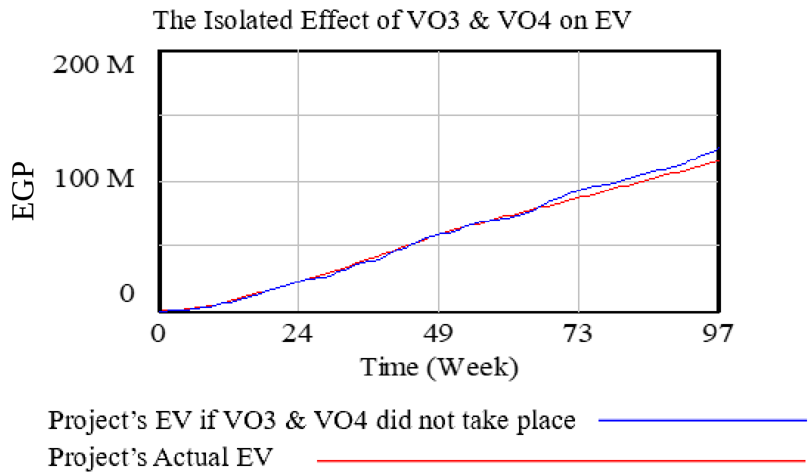

Figure 52 The Isolated Effect of VO3 and VO4

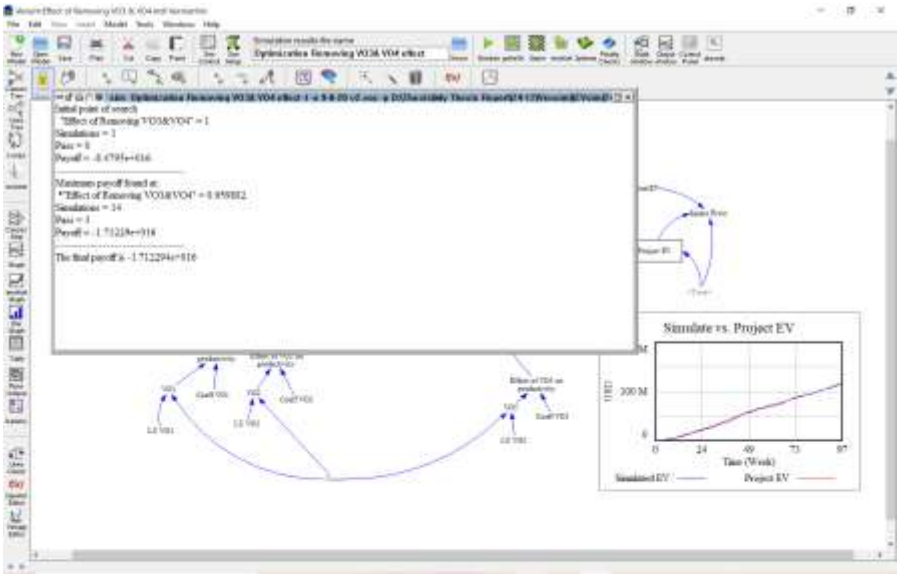

Figure 53 Effect of Removing VO3 and VO4

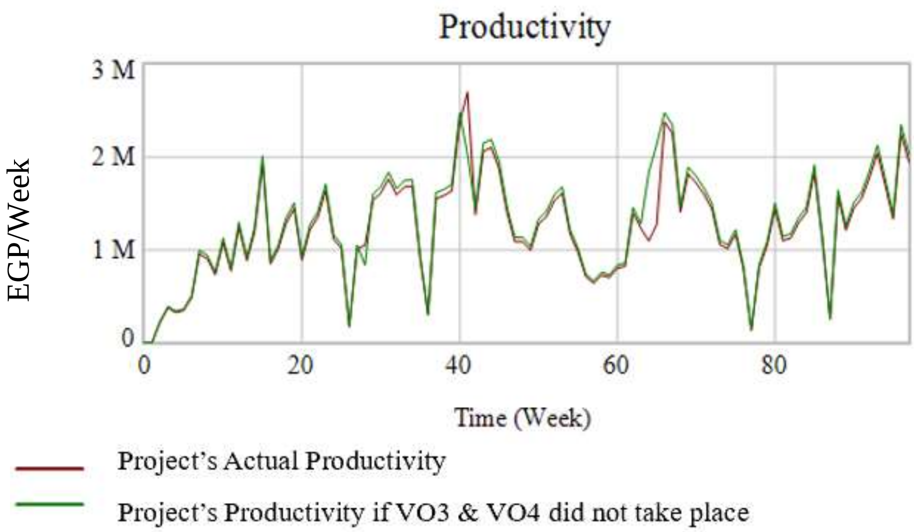

Figure 54 Productivity with Versus without VO3 and VO4

4.3.13 Effect of Removing VO3 and VO5

The effect of removing the third and fourth change orders (VO3&VO5) on the actual project progress (Project EV) is shown below. When VO3&VO5 were removed, the simulated project curve did not imitate the project EV progress curve and it showed that the simulated project progress was faster than the EV progress as shown in figure 55. Afterwards the model was calibrated to generate the effect of removing VO3&VO5 "variable" through minimizing the square error to imitate the project EV. Figure 56 shows the independent effect of removing VO3&VO5; if VO3&VO5 has no effect the result should be 1 but, in this case, the resulted effect 0.956; accordingly, the direct effect is (1-0.956) *100= 4.4% on the manhours. Figure 57 demonstrates the productivity graph, with the presence of VO3&VO5 is lower than without its presence, and the impacts is highest in week 42 (the highest gap in the overall weekly productivity)

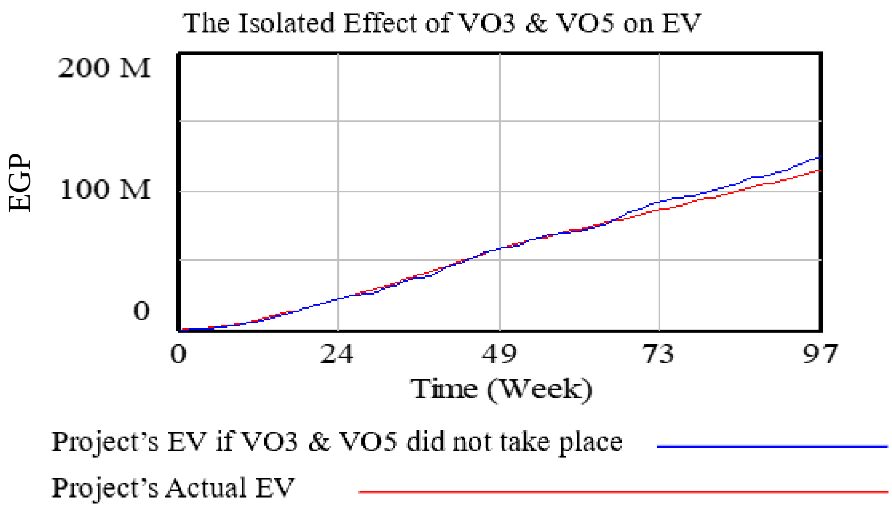

Figure 55 The Isolated Effect of VO3 and VO5

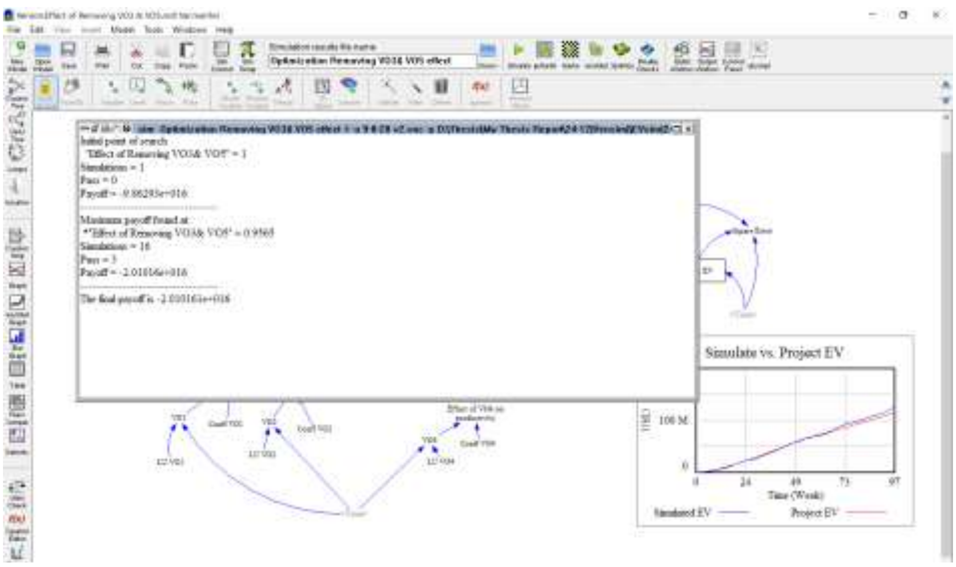

Figure 56 Productivity with VS without VO3 and VO5

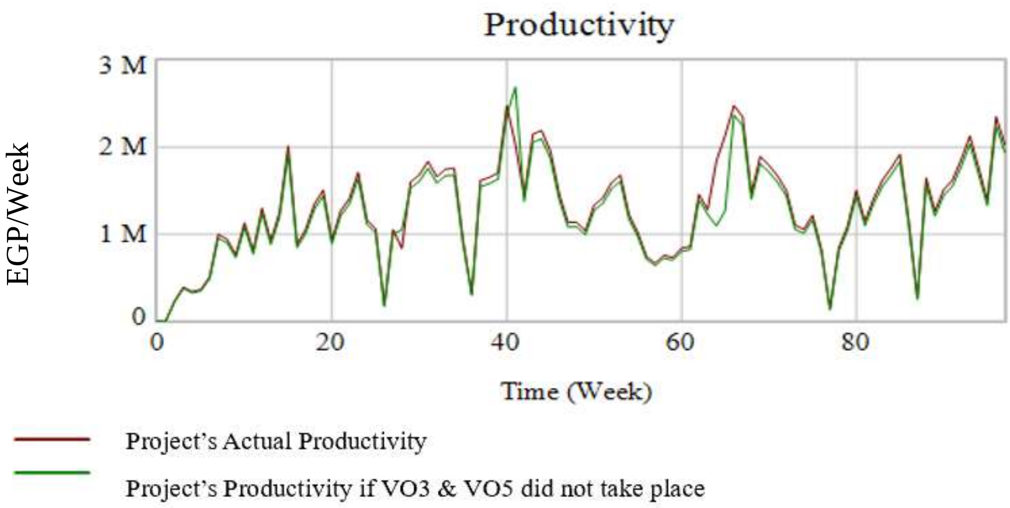

Figure 57 Productivity with Versus without VO3 and VO5

4.3.14 Effect of Removing VO4 and VO5

The effect of removing the fourth and fifth change order (VO4&VO5) on the actual project progress (Project EV) is shown below. When VO4&VO5 were removed, the simulated project curve, imitated the project EV progress curve, and it showed no difference between the simulated project progress and the EV progress as shown in figure 58. Afterwards the model was calibrated to generate the effect of removing VO4&VO5 "variable" through minimizing the square error to imitate the project EV. Figure 59 shows the independent effect of removing VO4&VO5; if VO4&VO5 has no effect the result should be 1 but, in this case, the resulted effect 0.988; accordingly, the direct effect is (1-0.988) *100= 1.2% on the manhours. Figure 60 demonstrates the productivity graph, with the presence of VO4&VO5 is lower than without its presence, and the impacts is highest in weeks 62 and 64 (the highest gap in the overall weekly productivity)

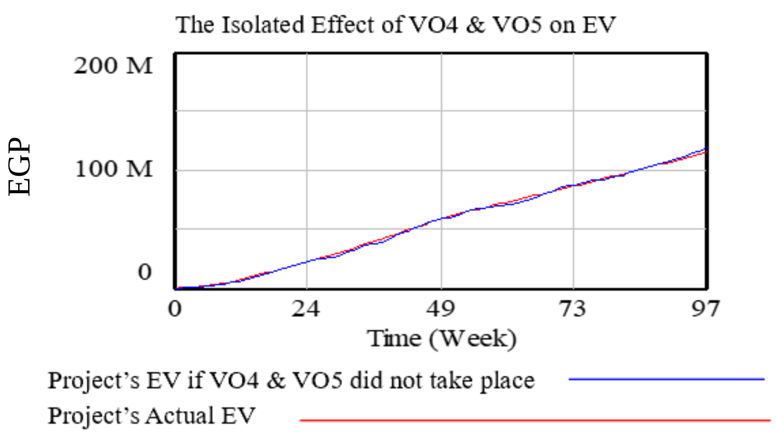

Figure 58 The Isolated Effect of VO4 and VO5

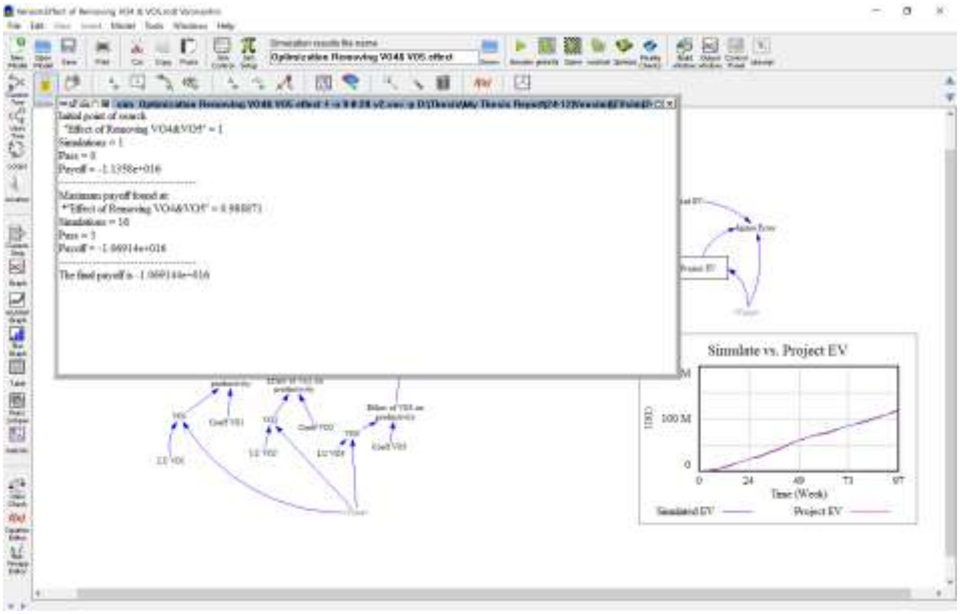

Figure 59 Effect of Removing VO4 and VO5

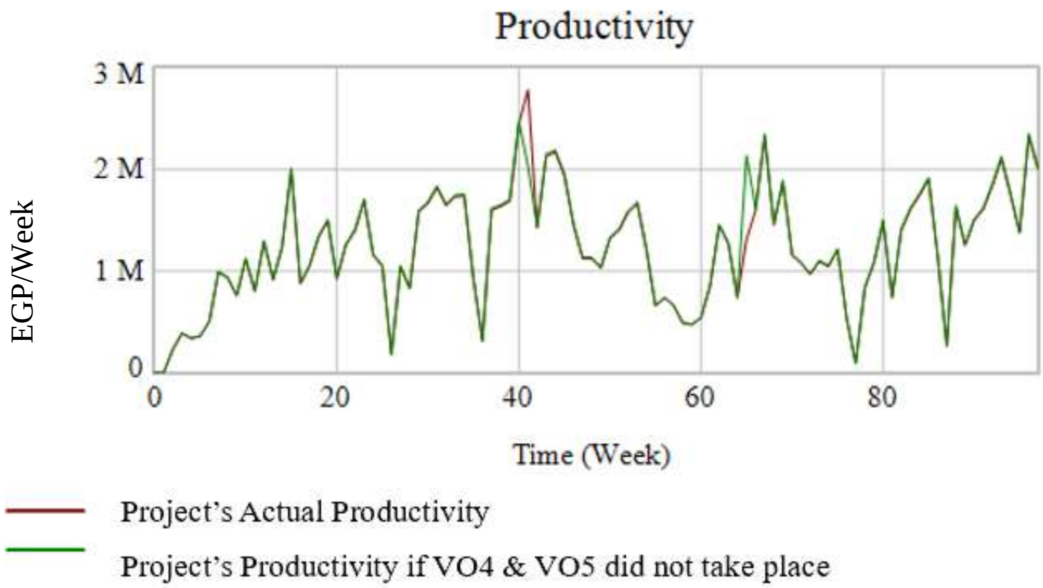

Figure 60 Productivity with VS without VO4 and VO5

Table 6 shows the different applied what-if-scenarios, for each scenario there is a corresponding change order removed from the project, the effect of it removal on manhours and the corresponding cost are shown. There are fifteen different scenarios, each change order occurrence data is represented in the date of occurrence column and represented in weeks. The results showed an increase effect of change order on the manhours when the change order takes place in the middle of the project duration rather than the change orders that comes in the end. Change orders that occurs in the end have either no effect or minimal as shown in table 6

Table 7: What-if Scenarios (The VOs and their corresponding date and effect)

Scenario #	Date of Occurrence	Removing VOs Effect on man hours	Corresponding VO Cost
VO1	Week 47 to Week 61	8.5%	691,580.23 EGP
VO2	Week 77 to Week 97	Zero	1,004,560 EGP
VO3	Weeks 54-55-58-59-64-65-66-70-71-72-76-77-81-82	4%	61,478.7 EGP
VO4	Week 78 to Week 84	Zero	9,938 EGP
VO5	Week 78 to Week 97	1.1%	81,569.42 EGP
VO1 VO2	Week 47 to Week 61 Week 77 to Week 97	8.46%	1,696,140.23 EGP
VO1 VO3	Week 47 to Week 61 Weeks 54-55-58-59-64-65-66-70-71-72-76-77-81-82	13.05%	753,058.93 EGP
VO1 VO4	Week 47 to Week 61 Week 78 to Week 84	8.46%	701,518.23 EGP
VO1 VO5	W 47 to W 61 Week 78 to Week 97	8.8%	773,149.65 EGP
VO2 VO3	W 77 to W 97 Weeks 54-55-58-59-64-65-66-70-71-72-76-77-81-82	4%	1,066,038.7 EGP

VO2 VO4	Week 77 to Week 97 Week 78 to Week 84	Zero	1,014,498 EGP
VO2&VO5	W 77 to W 97 & Week 78 to Week 97	1.1%	1,086,129.42 EGP
VO3 VO4	Weeks 54-55-58-59-64-65-66-70-71-72-76-77-81-82Week 78 to Week 84	4%	71,416.7 EGP
VO3 VO5	Weeks 54-55-58-59-64-65-66-70-71-72-76-77-81-82 Week 78 to Week 84	4.35%	143,048.12 EGP
VO4 VO5	Week 78 to Week 84 Week 78 to Week 97	1.1%	91,507.42 EGP

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

CHAPTER 5: CONCLUSION, LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1Conclusion

Change orders are one of the most crucial reasons of delays in construction projects. These delays mostly occur due to losses in labor productivity. Previous research has always discussed the different types of change orders and identifying the reasons behind these change orders and main effect on project duration and cost. All previously discussed methods of quantifying change orders and their impacts on labor productivity are qualitative rather than quantitative and used linear methodology.

Meanwhile, delay analysis is the main method used in studying the delays that occurred during the project as a whole. There are many available delay analysis techniques, but limited research was able to study the delays caused due to change orders and their individual impacts on these delays, which resulted in labor productivity losses. The method used in this research is system dynamics, which is a non-linear method and can study the rippled impacts of change orders.

The purpose of this study was to develop a new delay analysis technique to analyze the impacts of change orders in particular and their effect on labor productivity to be an additive to the main techniques used and help in preventing the arise of claims and any argument between the owner and the contractor by clarifying the effects of change orders.

A system dynamic model was developed to study the effect of change orders individually and identify the delays caused by each even solely. This system dynamic model was built through; first determining the exogenous and endogenous elements affecting the labor productivity; second formulating the dynamic hypothesis “causal loop diagram” to explain the interaction between the variables of the system; third developing the dynamic model architecture which was divided into two different steps by; (1) developing a model that can simulate the planned project progress, (2) developing an advanced model that can simulate the EV project progress along with adding the change orders that occurred during the project; fourth calibrating each model; fifth a set of verification tests are deployed to assure the workability of the model and prevent the existence of any errors; and sixth applying the developed model on a real case study.

The model was tested on a real case study, and it was validated since it was able to mimic the case study's planes and actual progress with high accuracy. Afterwards, different what-if scenarios were applied to study the effect of each change order individually and it was found that change orders had a high effect of the productivity of the project; some of these change orders affected the man hours as high as 13%, which affected the overall project productivity directly and caused delays. This technique can be used as an addition to the available delay analysis techniques in order to be able to quantify the effect of each any change order individually on project without taking the other causes of delay into perspective.

5.2 Limitations and Recommendations

This research was limited to change orders as the main endogenous in the model, but other elements can be taken into consideration for better analysis and more accuracy. For Future Research, The model should be calibrated on a larger number of projects. Impact of different types of change orders should be studied. Impact of more variables such as rework, design errors, severe weather conditions, and other on labor productivity has to be taken into consideration in addition to the change orders.

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