SIMULATING CONSTRUCTION PROJECT MANAGEMENT USING SYSTEM DYNAMICS

By

Ahmad Awni Abu-Seba

Supervisor

Dr. Ghaleb Abbasi, Prof.

This Thesis was Submitted in Partial Fulfillment of the Requirements for the Master's Degree of Science in Industrial Engineering

Faculty of Graduate Studies

The University of Jordan

April, 2010

The University of Jordan

Authorization Form

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نموذج رقم (١٨)
اقرار والتزام بقوانين الجامعة الأردنية وأنظمتها وتعليماتها لطلبة الماجستير والدكتوراة

أنا الطالب: أحمد عوني فوزي أبو سباع الرقم الجامعي: 8071255
التخصص: الهندسة المدنية / إدارة الكلية: الهندسة والتكنولوجيا

عنوان الرسالة / الاطروحة

Simulating Construction Project Management Using System Dynamics.

محاكاة إدارة المشاريع الإنشائية باستخدام الأنظمة الديناميكية.

أعلن بأنني قد التزمت بقوانين الجامعة الأردنية وأنظمتها وتعليماتها وقراراتها السارية المفعول المتعلقة باعداد رسائل الماجستير والدكتوراة عندما قمت شخصيا" باعداد رسالتي / اطروحتي ، وذلك بما ينسجم مع الأمانة العلمية المتعارف عليها في كتابة الرسائل والأطاريح العلمية. كما أنني أعلن بأن رسالتي /اطروحتي هذه غير منقولة أو مستلة من رسائل أو أطاريح أو كتب أو أبحاث أو أي منشورات علمية تم نشرها أو تخزينها في أي وسيلة اعلامية، وتأسيسا" على ما تقدم فإنني أتحمل المسؤولية بأنواعها كافة فيما لو تبين غير ذلك بما فيه حق مجلس العمداء في الجامعة الأردنية بالغاء قرار منحي الدرجة العلمية التي حصلت عليها وسحب شهادة التخرج مني بعد صدورها دون أن يكون لي أي حق في التظلم أو الاعتراض أو الطعن بأي صورة كانت في القرار الصادر عن مجلس العمداء بهذا الصدد.

توقيع الطالب: .... التاريخ: ٢٦/ ٤ / ٢٠١٠

COMMITTEE DECISION

This Thesis (Simulating Construction Project Management Using System Dynamics) was Successfully Defended and Approved on 7/4/2010

Examination Committee	Signature
Dr. Ghaleb Y. S. Abbasi, (Supervisor) Prof. of Project Management	
Dr. Sameh Al-Shihabi, (Member) Assist. Prof. of Applied Operations Research	
Dr. Abbas M. Al-Refaie, (Member) Assist. Prof. of Robust Design & Quality Engineering	
Dr. Adnan M. A. Mukattash, (Member) Assoc. Prof. of Modern Production Systems (The Hashemite University)	

Dedication

To my father for his guidance and support

To the lady who never had time to do anything else but be my mother

To my wife for helping me to concentrate on my research

To my brother and sister for their endless support and help

To all my relatives and friends for their encouragement

Acknowledgment

Many people have contributed to the work which culminates in this Thesis. Primarily among them is my advisor, Prof. Ghaleb Abbasi. I would like to express my appreciation for his encouragement, valuable comments, and professional feedback through my journey in the Industrial Engineering Department and who directed me to the System Dynamics work at the University of Jordan.

I would like to thank the committee members for their time, useful feedback and comments on the Thesis. Furthermore, my sincere thanks go to the academic and administrative staff within the same department.

Finally, my sincere appreciation goes to my family for their patience, continuous love, support and encouragement; this Thesis would not have been possible without them.

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Dr. Ghaleb Abbasi, Prof.

ABSTRACT

Whereas the traditional Project Management (PM) tools provide useful support, their underlying models often seem to bear little relation to actual projects. Experience suggests that the interrelationships between the project's components are more complex than is suggested by the traditional Work Breakdown Structure (WBS) of project network. An alternative view of the project is offered by System Dynamics (SD) which concentrates on the whole project.

The main objective of this research was to find out which parameter has the most influence on the output of the SD model. A SD model was built to look at the effects of various events and effects on project using computer simulation software. This research used four feedback structures (Rework, Human Resource, Client Behavior and Scope) that represent existing SD models of construction projects. One-way and multi-way sensitivity analysis was applied to the model to show which parameter was significant to the system behavior.

Fifty sets of project input data were generated to test the sensitivity of the model behavior. Eight parameters, which are (Time to Average Added Rework, Time to Correct Amount of Work, Average Quitting Time, Time in Training, Average Hiring Delay, Available Workers, Time to Correct Workers and Productivity), were found affecting the time to reach the equilibrium value. Five of these eight parameters (Time to Average Added Rework, Time to Correct Amount of Work, Available Workers, Time to Correct Workers and Productivity) were significant to study in multi-way sensitivity phase. A factorial design was chosen for this research with two levels for the five factors. It was found that 35 projects were significantly affected by changing in Time to Average Added Rework.

The research found that development processes significantly impact the dynamic behavior of projects through the feedback, delays and nonlinear relationships which are not used in traditional project models but are important descriptors of project complexity. For effective PM, both operational and strategic issues have to be handled properly.

CHAPTER ONE

INTRODUCTION

Chapter One Introduction

1.1 Context

Project success is a primary factor for the survival and prosperity of organizations. The increasing rate of change and the complexity of the new technologies and markets impose the need for quick and effective responses. As a consequence, many organizations are now adopting *Management by Projects* as a general approach (Turner et al., 1990). However, projects also become more complex and project failure is unfortunately another major trend. Many projects are often completed later or over budget and do not perform in the way expected. Also, over-runs of 40% to 200% are common (Morris and Hough, 1987) hence the question of how appropriate the traditional approach, such as Work Breakdown Structure (WBS), Gantt charts, Program Evaluation and Review Technique/Critical Path Method networks (PERT/CPM), Project Crashing Analysis, Trade-off Analysis, Earned Value Management (EVM), is for the management of modern large scale projects.

Assuming a holistic view of the organization, the System Dynamics (SD) approach focuses on the behavioral trends of projects and their relation to managerial strategies. The need for the development of models capable of assessing the strategic issues has also been identified by Morris and Hough (1987): "…. (traditional) project management has not addressed itself the factors which often really cause projects to fail.… We feel compelled to agree that the need for such a (strategic management) model is real.". Davidson and Hout (1991) state: "It is difficult or even impossible, (to rely) solely on traditional PERT/CPM system approaches… the solutions require a new paradigm for the control of large projects…

(based on) a framework of open and dynamics system theories as opposed to the traditional approaches that are static and closed.".

This research addresses the need for a better understanding of the nature, differences, similarities and purposes of traditional Project Management (PM) and SD approaches. If SD models are to play a core role in the future developments of PM, it is important to understand their distinctive contribution to the current body of knowledge and their place in a future methodology.

1.2 Motivation of Research

Competitive forces such as intense global competition, fragmented and demanding markets and diverse and rapidly changing technologies cause Engineering and Construction companies to view improved PM as a competitive imperative. These forces have increased the complexity and uncertainty of heavy construction projects. The PM processes and organizations created for relatively stable markets, long project durations, and technology-based competition are often no longer capable of producing projects fast enough, inexpensive enough and of high enough quality to remain competitive (Rodrigues and Bowers, 1996).

Therefore, improving project performance may not be as simple. There is a growing uncertainty in construction projects. Both the internal and external environments of construction projects are dynamic and relatively unstable. Changes that occur during a project's development may have significant and often unpredictable effects on its organization and management. In this context, changes are basically the unplanned disturbances that (typically) interfere with the intended progression of work and can impact badly on the PM system. Thus, project managers must react appropriately to 'change' and understand how it can influence the behavior of the project system. Only then can changes be managed effectively.

Typically, project organizations comprise of team members from different organizations who engage the project at different points in time to form a temporary multi-organization (Cherns and Bryant, 1984), or an ephemeral shifting coalition (Love et al., 1998). Relationships between team members are governed formally by the contract(s) but are supplemented and moderated by informal understandings and protocol that have evolved over time; very often to cope with unforeseen difficulties. The latter characterises construction and numerous studies have identified these uncertainties. The nature of relationships within a project team is one of 'independent autonomy' with interdependence and uncertainty being inherent characteristics (Love et al., 2002).

1.3 The Problem

Static features and impacts of projects have been extensively researched and applied to PM practice (Barrie and Paulson, 1984; Moder et al., 1983; Halpin and Woodhead, 1980). In contrast, project managers do not effectively understand or utilize the dynamic features of construction project structures. These dynamic features include feedback systems, time delays and nonlinear cause-effect relationships among project components. These features combine to cause project systems to behave in complex ways which are difficult to understand, predict and manage (Cooper, 1994, 1993a, b, c, 1980; Cooper and Mullen, 1993; Sterman, 1992; Reichelt, 1990; Brooks, 1978).

The underlying problem addressed by this research is the failure of project managers to fully recognize and utilize the dynamic features of projects which often drive project performance. Managers cannot effectively manage projects without understanding the impacts of dynamic features. The understanding and use of project dynamics which are currently used remains trapped in the intuition of experienced managers. An improved understanding of project dynamics is a first step in improving project mental models, decision heuristics and project performance. This research seeks to improve that understanding by increasing the knowledge of how project management process and coordination policy impact project performance. Developing a tool for an improved understanding of these impacts is the focus of this work. Therefore, the research question is *"How Does Development Project Structure Impact Project Performance?"* This question will be investigated through the building of a dynamic simulation model of the key project parameters and the use of that model to investigate a coordination policy for improved project performance using sensitivity analysis.

1.4 Research Objectives

The objectives of this research are to: (1) find out which parameter has the most influence on the output of the SD model; (2) figure out which parameter affect the equilibrium value and which affect the time to reach it; (3) investigate the impact of development project on project performance using a dynamic computer simulation model; and (4) compare the SD approach with the Traditional approach.

1.5 Research Approach

The purpose of this research is to increase the understanding of development projects. This improved understanding can act as the basis for improved project mental models, management heuristics and decisions and project performance. While no single approach or model can provide a complete understanding of development projects, this Thesis will contribute by identifying feedback relationships and other dynamic features which significantly impact project performance and by evaluating the nature of those impacts. This will be done by applying the SD approach in a realistic construction projects and analyzing the behavior sensitivity of the SD model to find out which parameter is significant to the model using Design of Experiment (DOE).

This Thesis uses dynamic computer simulation to model and investigate the impact of development project on project performance. A computer simulation model provides several advantages. First, the many and various project parameters and relationships can be modeled more comprehensively with the flexible representation available than with manual modeling methods. Second, assumptions are made explicit and unambiguous by their representation as formal equations. Third, consequences of assumptions and policies over time can be revealed through the simulation under safe experimental conditions. Finally, the model's reflection of actual project structures provides an effective means of communicating research work and results.

The SD methodology (Lyneis and Ford, 2007) for modeling complex systems has been adopted. SD assumes a holistic view of the organization focusing on the behavioral trends of projects and their relation to managerial strategies. The approach contrasts with the traditional methods which rely on detailed models of the components of the project with the main objective of providing tactical advice about the resourcing and scheduling of activities (Rodrigues, 1996). Concentrating on the details all the time ignores many of the major, but not readily quantified, influences that cause project failure and that a new approach is needed taking a more systemic view. SD provides such an alternative view considering these major influences on a project and dispensing with much of the details to ensure that the key behavior of the project is not obscured.

The most significant aspect of SD is the feedback perspective which is particularly relevant to understand, explain and act upon the behavior of complex project systems. Its added value for focusing on the project dynamics, which can generate risks, is very important. The understanding of risks is crucial for better identifying, assessing, monitoring and controlling the overall project performance. No single factor can be blamed for generating a risk nor can management find effective solution by acting only upon individual factors. To understand why risks emerge and devise effective solution, management needs to look at the *whole* (Rodrigues, 2001).

1.6 Thesis Structure

This section briefly describes the general structure of this Thesis. The research consists of Five Chapters.

After concluding this Introductory Chapter, Chapter Two is a summary of the literature review regarding construction project features, the nature of project failure, the dynamics of PM in construction and the need to manage project dynamics, characteristics of traditional tools of PM, SD methodology and the conceptualizations of SD.

Chapter Three is about model description. It describes the feedback structures in SD models using four key feedback structures. The effect of each feedback element will be determined in this Chapter to show the impact of these feedbacks on the project's performance throughout the life cycle of the project.

Chapter Four describes the sensitivity of the SD model using computer software, iThink 9.0.2. Also it contains the simulation results and the sensitivity analysis for the model behavior using DOE.

Chapter Five represents the conclusion of the research and the recommendations for future researches regarding the SD methodology.

1.7 Summary

The successful performance of development projects is critical to competitiveness in many companies. Recent market and technology changes have increased the importance and difficulty of improving project performance. Although understanding the impacts of the dynamic aspects of development projects is increasingly important for improvement, these features are typically unrecognized, ignored or used inappropriately. An improved understanding of dynamic project features is needed to improve project mental models, decision heuristics and thereby performance. The overall idea is to focus on a dynamic engagement of SD within the established traditional PM process. The approach will try to emphasize on the interrelationships that may be responsible for unexpected overrun and suggests the use of right control tools to simulate a computer PM model for managing complex construction projects.

CHAPTER TWO

LITERATURE REVIEW

Chapter Two Literature Review

This chapter describes and evaluates the literature as it pertains to this research. Construction project features are described followed by the dynamics of PM in construction. These descriptions provide the evaluation of PM models for investigating the dynamic impacts of project structure on performance. Finally, a more detailed evaluation of existing traditional tools of PM is described.

2.1 Construction Project Features

Generally, a large construction project might be complex, made up of a large number of interconnected sub-systems and components, requiring considerable human efforts and financial commitments. Typically, such project organizations comprise of team members from different organizations like client, contractor, sub-contractor(s) and supplier(s). They are engaged in the project at different points in time to form a temporary multi-organization. Relationships between team members are governed formally by the contract, but they are supplemented and moderated by informal understanding and protocol that have evolved over time, very often to cope with unforeseen difficulties. The nature of relationships within a project team is one of 'independent autonomy' (Love et al., 2002), with interdependence and uncertainty being inherent characteristics.

A typical construction project consists of three main phases: Engineering/Design, Procurement and Construction. All three phases should coordinate and work perfectly for successful completion of a project. Engineering/Design is a very crucial phase of such projects where the needs of the owner/developer are defined, quantified and qualified into clear requirements which are further communicated to the contractors and sub-contractors. The engineering phase has a highest level of influence on the project, as many key decisions and planning of activities will be made during this phase. These decisions further lead to commitments of a large sum of the funds and other resources necessary for the completion of the project (Yeo and Ning, 2002).

A contractor/sub-contractor begins to procure project equipment and construction materials upon receipt of engineering drawings/specifications and other relevant documents. The entire construction phase activities are being planned and scheduled along with their resources based on Engineering and Procurement inputs. The construction works according to work packages prepared during engineering phase and uses equipment and materials obtained in the procurement phase. The sequence and schedule of construction activities will be initially planned to reflect the most logical and cost effective approach to meet the due dates. But, there are constant dynamics involved in this entire engineering, procurement and construction phase which affect the project's performance. There is a tremendous amount of interdependence of all the activities/phases for the entire project. Phase overlaps of engineering, procurement and construction increases the risk of project overruns in schedule and cost. This result mainly due to lack of complete information and frequent changes especially those attributed to Engineering/Design.

Many of these project changes and variations are critical factors that can delay the whole project resulting in its failure. At certain point, the changes and rework becomes inevitable and uncontrollable even by the engineering team. Hence, when all the unexpected changes do occur during the project’s life cycle, the planning, organizing, motivating, scheduling and controlling of construction becomes a problematic task in this dynamic environment. All these further results in project schedule slippage foe all the parties involved in the project (client/contractor/sub-contractor) causing overtime work, loss of productivity and claims from contractors/sub-contractors.

2.2 The Nature of Project Failure

Many factors can be considered as responsible for project failure. Uncontrollable external forces are often blamed. However, the real cause may be bad PM which is the result of a defective PM system organizations, practices and procedures (Nicholas, 1990). Despite the enormous attention devoted to this field during the last years, why do organizations continue to practice bad PM? Morris and Hough (1987) suggest that the main causes are to be found in areas which have traditionally not been the concern of PM. Such factors arise from circumstances which are external to the project. They have classified and grouped these critical factors in the following categories: project definition, planning, design and technology management, politics/social factors, schedule duration, schedule urgency, finance, legal agreements, contracting, project implementation and human factors.

As an example, the estimated duration of project activities is based on the assumption that the staff employed will work at a certain productivity level. On making this estimation, the project manager naturally considers subjective factors like workforce motivation, schedule pressure, workforce experience and possible errors. However, if in practice this informal analysis fails, all the effort employed in the development of the work schedule plan will be wasted. Another typical case relates to project monitoring, the project control process is based on human perceptions of the project status. In the real world, errors tend to remain unperceived and as a consequence the real progress differs from the perceived progress. Factors of political nature have motivated a generalized trend to reject errors in the early development stages of projects (Abdel-Hamid and Madnick, 1990). Detailed plans based on these illusive perceptions direct useless or even counterproductive efforts. In the later stages of the project considerable, effort is then spend in correcting errors. Managers tend to feel that the work never goes beyond the 90% perceived progress, this phenomenon is usually referred as the "90% syndrome" (Abdel-Hamid, 1988).

A project is a man-made, goal-oriented and open system and as such it tends to be scientifically unpredictable, disruptive and unstable. The complexity of projects and of their environment has increased the disruptive effect of subjective factors. Personal judgment based on past experience is no longer sufficient to cope with this problem. There is a need for better understanding of the strategic issues of PM and this can only be achieved through systematic analysis. While traditional tools and techniques were not developed with that purpose, SD models gather all the requisites to provide such approach.

2.3 Dynamics of PM in Construction

The dynamics that impinge upon a project system are derived from two basic sources: *planned activities* and *uncertainties*. Planned activities include the established operation program, schedule with resource and due dates for activities, the arrangements of daily duties, planned material and plant operations, etc. These activities are designed to initiate change, that is, the progress of construction works (Coyle, 1996).

The dynamics of planned activities are called "*attended dynamics*", which is synonymous with "*intended dynamics*", a description often-used in SD literature. The term "*attended dynamics*" is preferred because it assumes that an observed behavior is the direct result of active interventions. Attended dynamics mainly include: decision making, techniques and technology, behavioral responses, project structure, etc. They can affect a project's objectives in either a positive or negative way. Positive influences would indicate that through policy intervention, progress had been made towards achieving a project's objectives. Conversely, negative influences would indicate that progress toward project objectives had been hindered. Similarly, "*unattended dynamics*", also known as "*unintended dynamics*", places emphasis on factors beyond the control of project managers. Unattended dynamics include: project related uncertainties (uncertain durations, costs, resources, etc), organization related uncertainties, interest related uncertainties, human related uncertainties, legal and social uncertainties, etc. Like attended dynamics, unattended dynamics can also have positive and negative influences.

Uncertainties or unexpected events can significantly affect the operation of a project; such events either improving or hindering project performance. Both attended and unattended dynamics coexist throughout a project's life cycle (Coyle, 1996).

2.4 The Need to Manage Project Dynamics

To manage attended dynamics, various PM techniques have been developed and applied over the years. The management of unattended dynamics is, however, much more complicated. This requires identification of uncertainties source, assessment of nature (i.e. whether positive or negative) and to conceive methods to enhance the positive impacts while at the same time reducing negative impacts.

In managing unattended dynamics, it is crucially important to select and use the most effective management methods. When changes occur, they should be dealt with as soon as possible. At the initial stages of a project, gross development value, overhead cost, construction cost, time and profit are the main concerns of all the parties involved in the project (client/contractor/sub-contractor). When the economic environment changes, the owner/client may change the plan or strategy so as to reduce or eliminate the negative impacts of any change that is incurred. Furthermore, these changes may affect in a positive or negative way the contractor/sub-contactor and their activities (Richardson and Pugh, 1981).

Methods used in a risk management approach can be applied in dynamic approach. For example, risk identification techniques can be applied to identify unattended dynamics.

However, the dynamic approach is much more comprehensive compared with risk management. The dynamics approach is to consider all attended dynamics and all risks during the whole construction process. It requires prompt decisions regarding changes. This indicates that managers consider experience; and prompt subjective judgments are essential for arriving at a correct response. Contractors should use recognized construction PM techniques to adjust to the changes and to forecast problems ahead. Based on these findings, it is suggested that the dynamics of a project system should be monitored and evaluated by project managers in accordance with the following functions: planning, organizing, commanding, and controlling and further emphasis should also be placed on how particular dynamics can hinder the performance of PM system so that appropriate actions can be taken.

2.5 Characteristics of Traditional Tools of PM

Numerous techniques have been developed to help manage project schedules and costs, such as WBS, Gantt charts, PERT/CPM, Project Crashing Analysis, Trade-off Analysis, EVM, etc. These techniques were founded on the premises that whereas a project may be unique, many of its constituent elements have been experienced before. The project work is therefore decomposed into elements, for example activities, which can be individually related to previous experience. Then, it is possible to produce reasonable estimates of the duration, cost and resource requirements for each element. The logic of the project, such as represented in a network, supplies the basis for reconstructing the project from its elements and calculating the duration, cost and resource requirements of the whole project from those of its elements. One of the concerns about such an approach is that, whereas the estimates for the individual elements may be very accurate, the reconstruction of the project may ignore important intra-project forces, the whole may be much greater than the sum of the parts (Williams et al., 1995).

The traditional analyses of projects have been described as linear or as "static and closed”, suggesting an assumption of a strictly ordered project that progresses in well defined, predictable stages to completion. This includes an assumption that all the information is available at the start of the project, allowing the design of an optimal plan and the only concern of management is to keep the project on the specified track. However, in practice, management needs to be dynamic, responding to new information and adapting the plan rather than keeping rigidly to the original. When implemented properly, the traditional methods are used in a more responsive manner, deployed within the dynamic environment of the classical control feedback loop. The original plan is used to set targets which are then compared to progress and where there is significant deviation, action is taken including revisions of the project plan. Whereas individual tools might be very linear in nature, the overall framework of traditional project control exhibits the classic characteristics of a dynamic system.

However, the traditional tools struggle to incorporate many of the important non-linear project dynamics. While the tools can be adapted, they do not encourage managers to examine the feedback loops which rule a project's dynamics. There are many accounts of problems in projects escalating with the knock-on effects producing unexpected dramatic overrun and overspend, these are examples of undesirable positive feedback. The failure to consider these project dynamics may be one reason for the general record of project overruns. Thus, there is an urgent need to support the traditional techniques with a different approach that focuses on the whole project and the valuable intra-project dynamics.

The traditional approach to PM is based on a typical set of techniques and procedures intended to help the project manager to define and direct the project work. Over the years, a wide collection of methods have been developed in response to the need of managing with the real problems of project implementation. These methods focus on the definition of the project work structure, scheduling and budgeting project activities and monitoring and controlling project performance while the work is being undertaken, evaluating and reporting project status along the project life cycle (Nicholas, 1990).

Table 2-1 briefly describes the most important tools and techniques used in the traditional approach. To assess the project status and keep the interested parties informed, several procedures are followed for collecting and communicating project evaluation information like graphical representations, reports, observations and review meetings (Nicholas, 1990).

Table 2-1: Overview of Traditional PM Techniques and Tools.

Technique/Tool	Purpose
Work Breakdown Structure- WBS	Basic definition of the project work. Precedes the project schedule and cost estimations.
Responsibility Matrixes	Integration of the project organization with the WBS- assignment of responsibilities.
Bar Chart or Gantt Charts	Simple representation of the project schedule. Does not show the precedence relationships among activities.
Project Network Techniques: PERT, CPM, PDM, GERT, and others	Network techniques for work scheduling. Provide the analysis of the scheduling impacts that activities have on each other and the determination of critical activities and float times. Base of cost estimation, resources allocation and management, and risk analysis.
Cost Schedules	Identification of the capital requirements for resources. Estimation of realistic budgets that provide standards against which project performance is measured.
Project Control: variance analysis, PERT/cost, Earned Value, and others	Assessment of project performance with the generation of performance indices. Provide for the detection of project overruns and the need for corrective actions. The WBS, Gantt Charts and other scheduling techniques are usually incorporated in the project control process.

The CPM and PERT are two traditional tools which are widely used to manage development projects. Although initially developed for schedule control, they have been expanded to manage resources (and therefore costs). They are based upon the traditional paradigm of development. The CPM disaggregates the development process into activities which are related through their temporal dependencies. Each activity is treated as a monolithic block of work described only by its duration. The temporal dependencies describe the constraints which earlier (upstream) activities impose on later (downstream) activities. The constraints are described with relationships between the beginnings and completions of activities. The logic of the schedule can be represented in a network diagram. Two simple examples of a network diagram using Activity on Arrow (AOA) and Activity on Node (AON) are shown in Figure 2-1 and Figure 2-2, respectively.

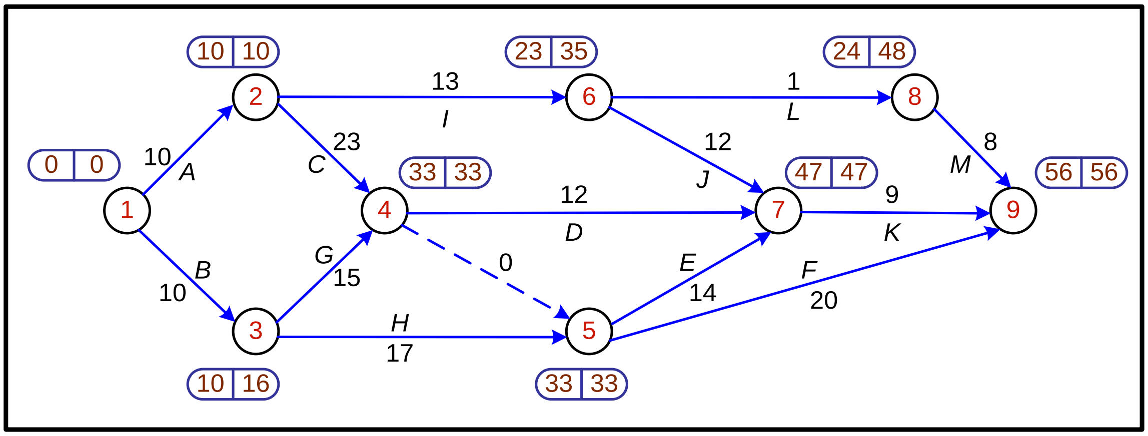

Figure 2-1: Example of AOA Network (Halpin and Woodhead, 1980).

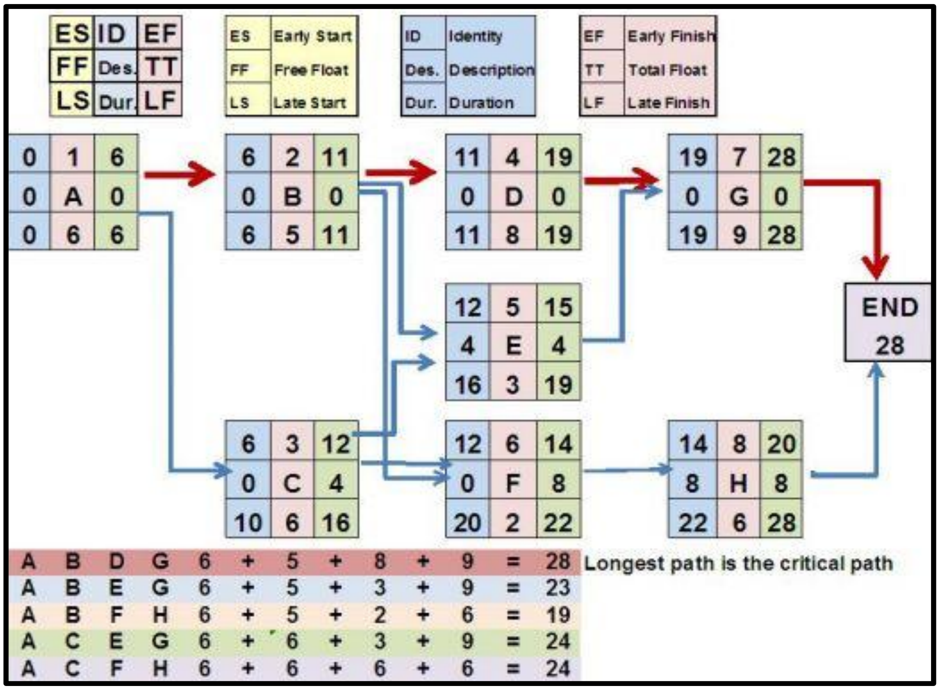

Figure 2-2: Example of AON Network.

CPM calculations identify a project's critical path which is the sequence of tasks whose combined durations define the minimum possible completion time for the entire set of tasks. Earliest and latest possible start and finish dates of all activities within a schedule determined by the critical path can be calculated as can the available slack times. The results of this planning and analysis can be presented for broader communication with a Gantt chart. An example of a Gantt chart is shown in Figure 2-3.

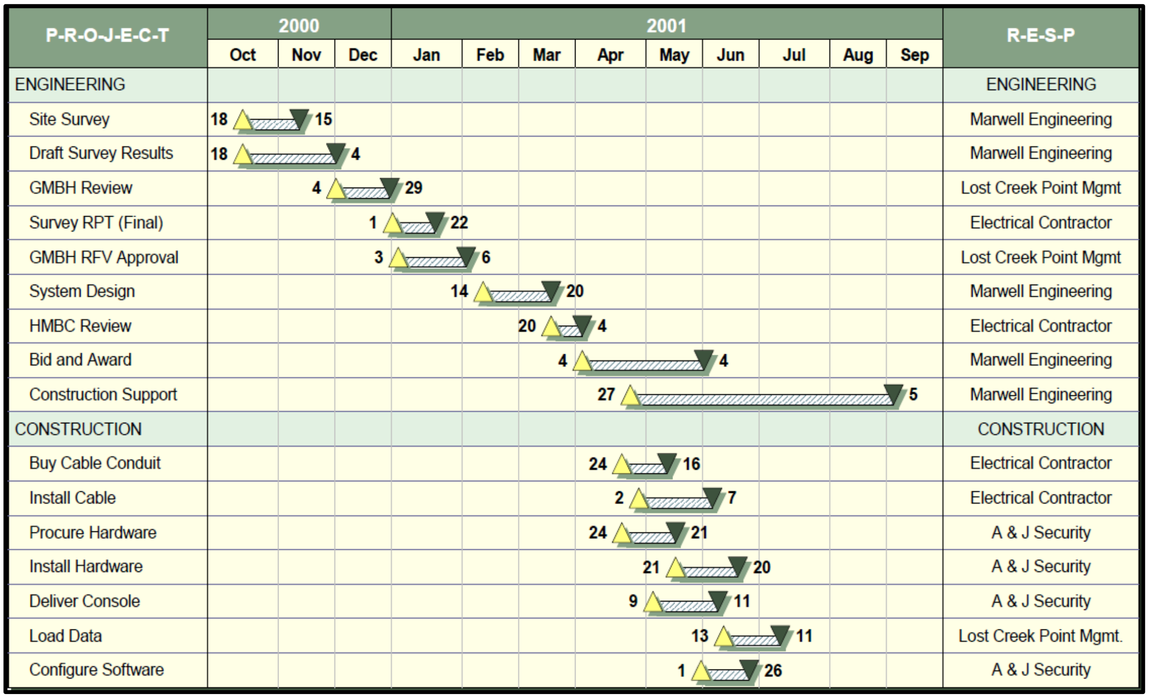

Figure 2-3: Example of Gantt Chart Representation of a Project Schedule.

The CPM provides several tools for trading away good performance in one measure for improved performance in another. For example, durations of activities along the critical path can be shortened by adding more resources (Moder et al., 1983). The CPM provides a time-cost trade-off method for analyzing the effectiveness of accelerating alternative activities. The effects of altering activity dependencies among activities to shorten the critical path can be investigated (Barrie and Paulson, 1984; Moder et al., 1983).

The CPM is easily understood and applied. It provides a set of fundamental tools for characterizing and managing a development project in temporal terms. However, the method has critical limitations. The method assumes no rework of errors which are undiscovered when the phase is "completed" and that the rework of errors discovered within a phase's duration is incorporated into the phase duration estimate. The method cannot explicitly represent bilaterally coupled activities and therefore cannot describe loops, feedback or iteration in a system. It also assumes that the development project remains unchanged over time. This prevents the method from modelling time-varying and endogenous factors such as developer skill, training and coordination issues. Therefore, the CPM is unable to model the highly coupled aspects and dynamic nature of the product development process. Finally, the CPM cannot describe the rational which underlies the structure description and therefore lacks depth of information content.

PERT uses an approach to schedule management which is similar to the CPM. This method was developed for processes such as product development (Moder et al., 1983). PERT addresses one of the limitations of the CPM by incorporating the uncertainty inherent in the estimates of the durations of development activities into a scheduling tool. Three estimates of project duration are used for each activity to model the variability of durations. The PERT method calculates the probabilities of a project meeting specific schedule objectives.

PERT incorporation of duration uncertainty makes it more valuable in managing less certain processes such as product development. However, PERT requires lots of data and is limited in accuracy by the estimates of variability of activity durations. Like the CPM and PERT cannot explicitly represent coupled loops or feedback, assumes the project is static, and cannot model causes of process behavior.

2.6 Conceptualizations of SD

2.6.1 Description of SD Approach

SD was introduced by Forrester (1961), as a method for modeling and analyzing the behavior of complex social systems, particularly in an industrial context. It has been used to examine various social, economic and environmental systems, where a holistic view is important and feedback loops are critical to understanding the interrelationships. The approach has attracted particular attention in recent years since computer software has become readily available to help communicate the key dynamics of systems to the managers responsible.

The models of SD can be used in PM to mange projects more effectively and to assess the magnitude and sources of cost and schedule overruns. The modeling approach focuses on an understanding of feedback and feedforward relationships considering both "soft" as well as "hard" aspects of a system's behavior and information flows. SD models are usually prepared using a computer package based on a diagrammatic interface. Model construction requires the analyst to construct the relationships between the variables, with equations for these relationships being embedded within the variables on the diagram.

Three packages are in popular use: STELLA/iThink (High Performance Systems Inc.), POWERSIM (Modeldata AS, Bergen, Norway) and VENSIM (Ventane Systems Inc.). But all of these use the same modeling logic, using three types of variables. Their actual representation on diagram depends on the package used, the diagrams used here and the computer package used for this Thesis is iThink 9.0.2.

2.6.2 A Structured SD Approach

The SD analysis has a four stage approach for its application. The First Stage is to recognize the problem and to find out which people care about it and why. It is rare for the right answers to be found at this stage and one of the attractive features of SD as a management science methodology is that one is often led to reexamine the probability that one is attempting to solve.

Secondly, comes the description of the system by means of a causal loop diagram also referred to as "influence diagram". This is a diagram of the forces at work in the system which appear to be connected to the phenomena underlying people's concerns about it. Causal loop diagrams can be most useful during the early stage of model conceptualization as they help to identify and organize the principal components and feedback loops of the system under study. Having developed an initial diagram, attention moves to Stage Three, qualitative analysis. The term simply means looking closely at the causal loop/influence diagram in the hope of understanding the problem better. This is a most important stage which often leads to significant results.

If qualitative analysis does not produce enough insight to solve the problem, work finally proceeds to Stage Four, the construction of a simulation model. There are different software and simulation languages available for SD simulation. The simulation model basically consists of flow diagram and set of equations. Flow diagrams yield considerably more information than causal loop diagram about system structure and behavior and equations further provide a powerful aide to thinking about and understanding the problem.

2.6.3 SD Application to PM

Figure 2-4, illustrates the main features of an influence diagram (causal loop diagram), the core of the SD model (Rodrigues and Bowers, 1996). The arrows represent influences between the different factors; the plus or minus sign indicates whether a positive change in the preceding factor has a positive or negative effect on the next. Thus, a higher resource level results in a greater progress rate, which in turn causes the perceived progress to grow. The arrows suggest a complete balanced cycle. If there is a perceived schedule slippage, there should be an appropriate change in resource level. This example contains one main and two subsidiary balancing feedback loops, as emphasized by the "B-" loops. In practice, the balance is not so easily achieved and there may be a number of disruptive factors, as summarized in the boxes of Figure 2-4.

Also, the basic cycle of the project control model is shown in Figure 2-4. Management responds to a perceived slippage in the schedule by deploying more resources, typically staff, in the hope of increasing the progress rate. This action should reduce the perceived effort remaining and eventually bring the forecasted completion date forward and eliminate the slippage. An alternative response to a perceived slippage is simply to adjust the schedule, as suggested by the top cycle of Figure 2-4. However, there are many disruptive factors which might prevent the effective employment of more resources; some of the factors influencing the employment of human resources are discussed below. Other disruptive factors can influence other stages of the cycle, political factors can be particularly important, encouraging a too optimistic view of the project's useful progress and restricting adjustments to the schedule. SD provides a language for expressing these influences and given numerical estimates of their effects, a quantitative analysis of the impact on the project's likely progress. There is no pretence that a quantitative analysis is easy, but at least SD can make all the factors explicit.

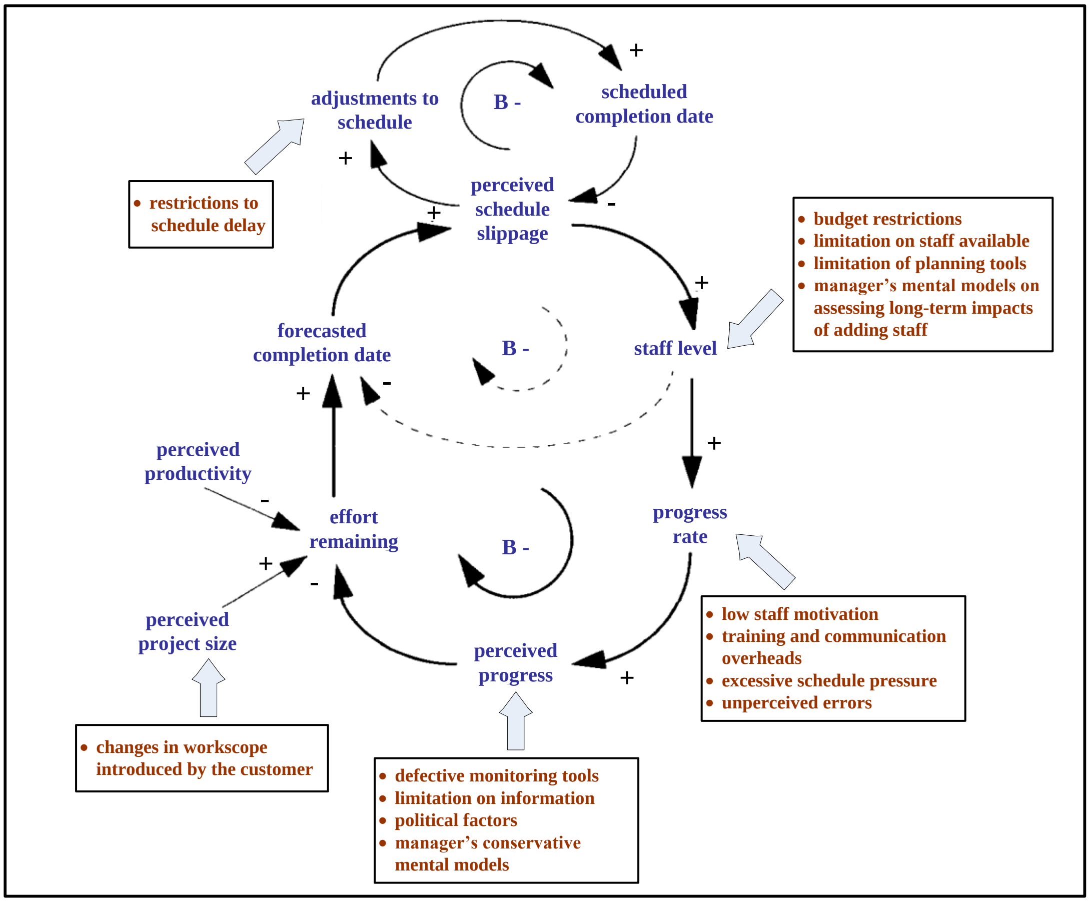

Figure 2-4: Example of the Project Control Cycle (Rodrigues and Bowers, 1996).

Having identified the key feedback loops and various disruptive factors, quantitative estimate of the different effects are elicited, either from data describing past projects or in discussions with various project participants. A computer based SD simulation model can then be built using the simulation software's available. The graphics of such models allow the effects of the feedback dynamics to be observed, leading to a greater understanding of the system and encouraging experiments to explore new management options.

The application of SD to PM has been motivated by various factors:

- A concern to consider the whole project rather than a sum of individual elements (the holistic approach).
- The need to examine major non-linear aspects typically described by balancing or reinforcing feedback loops.
- A need for a flexible project model which offers a laboratory for experiments with management's options.
- The failure of traditional analytic tools to solve all PM problems and the desire to experiment with something new.

Thus, SD model of a project aims to capture all the major feedback processes responsible for the system behavior. Then the second stage is developing quantitative simulation models based on these feedbacks to show different scenarios, predicting the impacts of dynamics and thus guide the PM team, to improve the decision making ability on important project factors (Love et al., 2002).

2.7 SD Literature Review

Several models using the SD methodology (Forrester, 1961) incorporate dynamic features into models of project development. The feedback structures of SD models describe the modeler's hypotheses about the dynamic behavior of the project and form a framework for describing their investigations of project behavior. As far as the Construction PM is concerned, there are four main elements identified as the dynamics, which can affect the project's performance throughout the life cycle of the project. These dynamic elements of the project form the key loops and are aggregated in the form of four feedback structures.

2.7.1 Four Key Feedback Structures in SD Construction Models

1. The Project Rework Structure.
2. The Project Human Resource Structure.
3. The Client Behaviour Structure.
4. The Project Scope Structure.

There are number of elements of the construction project, but these four key feedback structures are the most important elements worth looking, as they recur frequently in the project models.

Each feedback structure is studied in details along with the various factors acting on it during the project's life, in order to develop causal loop diagrams for each of them. Furthermore, an attempt is made to show the positive as well as negative impacts of each structure on the project performance, by developing simulation models.

A simple example demonstrates the potential effects of feedback, time delays and nonlinear relationships in project structures. Consider a project in which the expected completion date exceeds the deadline, creating a schedule gap. A common managerial response is to increase headcount (number of designers or crews) to increase output, move up the completion date and thereby reduce the schedule gap. This simple feedback structure can be described with the causal loop diagram (Richardson and Pugh, 1981) that is shown in Figure 2-5. In causal loop diagrams, causal links (arrows) are labeled as those which cause the variable at the arrowhead to move in the same (+) or opposite (-) direction as the variable at the arrow's tail when other factors are held constant. Feedback loops are labeled as balancing (B) if variable values tend to be goal-seeking over repeated passes around the loop or reinforcing (R) if repeated passes accelerate movement in a single direction.

The feedback structure in Figure 2-5 describes how the project condition (the size of the schedule gap) influences the managerial response to the system (change in headcount), which in turn effects the condition of the system (reduced schedule gap). In isolation, the feedback structure in Figure 2-5 would restrain the project's schedule gap. But the feedback inherent in complex project systems often has many unintended side effects.

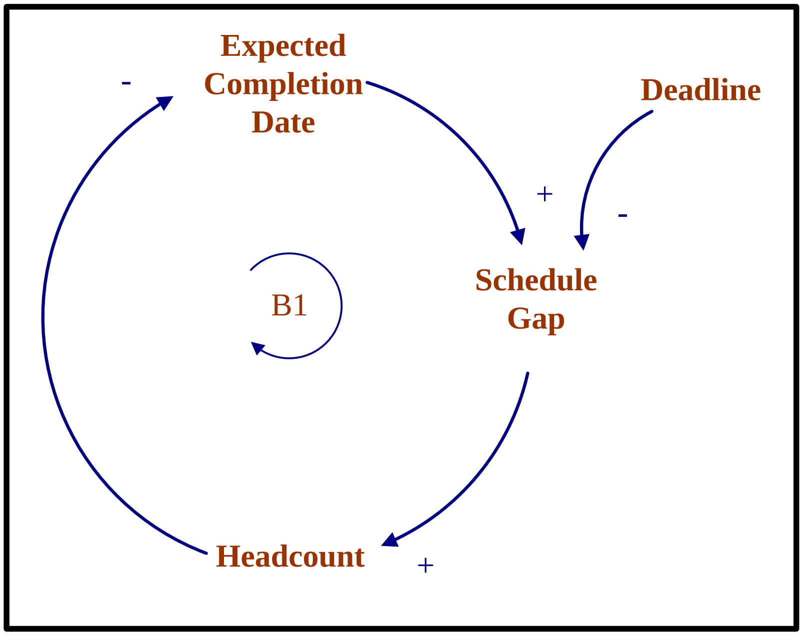

Figure 2-5: Example of a Construction Project Feedback Structure.
(Richardson and Pugh, 1981)

For example, Thomas and Napolitan (1994) identified fourteen secondary impacts of changes in construction development projects caused by three primary impacts (increased costs, schedule delays and rework). These fourteen secondary impacts are:

- Decreased worker productivity.
- Lowered design team morale and productivity.
- Relocation of labor.
- Increased planning, coordination and rescheduling activities.
- Possible out-of-sequence work.
- Demobilization or remobilization.
- Overtime (fatigue) due to acceleration.
- Crowding due to acceleration.

- Possible delays due to seasonal/weather related impacts.
- Increased effort to price out and negotiate the changes.
- Learning curve associated with a change.
- Inadequate coordination of changes.
- Additional value engineering due to increased costs.
- Possible litigation.

An unintended side effect of increased time required to coordinate larger headcounts can be described with the reinforcing causal loop shown in Figure 2-6. The unintended side effect counteracts the intended impact of the balancing loop. This is because some of the increased headcount is used to address the increased coordination need instead of increasing output. If the unintended side effect is larger than the intended effect, it can extend the "Expected Completion Date" and increase the "Schedule Gap". This could occur immediately after implementation of the increased headcount policy. The relative strength of the balancing and reinforcing loops at any given time determines whether the "Schedule Gap" is increasing or decreasing and which feedback loop dominates the system behavior is strongly influenced by another characteristic of dynamic systems and time delays. For example, a delay in the direct influence of "Headcount" on "Expected Completion Date" can cause the reinforcing loop to dominate soon after the headcount increases and the balancing loop to dominate later. Shifts of dominance among the feedback loops in a project structure cause project behavior to oscillate and can magnify impacts (Forrester, 1961).

A nonlinear relationship among components is one of the most important characteristic of dynamic systems. An exponential relationship between "Headcount" and "Percent of Time Required for Coordination" is shown in Figure 2-6. Nonlinear relationships make systems difficult to predict and manage by causing the system to respond differently to the same managerial action depending upon the system's current condition.

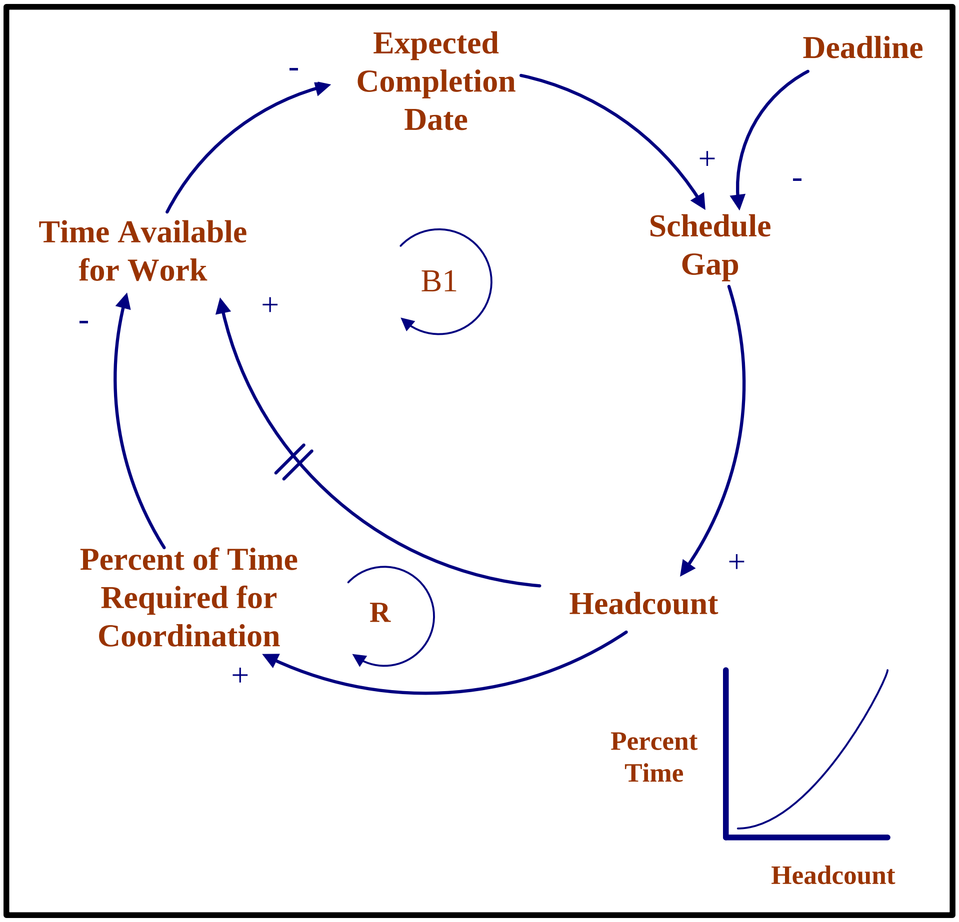

Figure 2-6: Example of a Delay and a Nonlinear Relationship in a Project System. (Richardson, 1995)

For example, an increase in "Headcount" by 10% would generate a very small increase in "Percent of Time Required for Coordination" if the "Headcount" was small (left side of the "Headcount" versus "Percent Time" curve). But the same 10% increase in

"Headcount" would generate a large increase in the "Time Required for Coordination" if the "Headcount" was high (right side of the "Headcount" versus "Percent Time curve").

When project structures are described with causal loop diagrams, management policies can be viewed as plans which attempt to alter the strength of causal link relationships between variables or create or delete feedback mechanisms represented by loops. In this way, management policies can influence the relative dominance of different feedback loops.

The combinations of feedback, time delays and nonlinear relationships in project structures have been shown to reduce performance and cause them to be very difficult to manage in the construction industry (Thomas and Napolitan, 1994; Reichelt, 1990). The dynamic nature of project behavior precludes the generation of a single set of decision rules which are robust in the face of all possible project conditions. Project managers must use their understanding of project systems to adjust management policies such as those for coordination to specific project circumstances and the evolution of project behavior. This requires that development managers include dynamic features in their project mental models. But the mental models used to describe, explain and predict projects do not generally include the dynamic features. Both complexity and dynamic features of projects are poorly understood by managers (Diehl and Sterman, 1995). The resulting inadequate project mental models prevent the development of decision heuristics which incorporate dynamic features into project management decisions. This deficit in decision heuristics constrains project performance.

2.7.1.1 The Project Rework Structure

Rework is the unnecessary effort of re-doing a process or activity that was incorrectly implemented the first time. It is an endemic feature of the construction procurement process and is a primary factor that contributes to time and cost overruns in the project. One of the most perplexing issues facing organization in the construction industry is their inability to become quality focused. As a result, sub-standard products and services often emanate, which inadvertently results in rework. Typically, rework is caused by errors made in the design process. These errors appear downstream in the procurement process and therefore have a negative impact on the project's performance during construction. The lack of attention to quality has meant that rework has become an inevitable feature of the project development process, and the costs have been found to be as high as 10-17% of the total project costs. Such costs could be even higher because they do not represent schedule delays, litigation costs and other intangible costs of poor quality.

To reduce the cost and effect of rework, an understanding of its causal structure is needed so that effective prevention strategies can be identified and the effects of rework reduced or eliminated. The concept of SD is used to develop a conceptual causal loop diagram to determine the overall causal structure of rework. Once an understanding of the causal structure of rework events has been acquired, effective strategies for rework prevention can be designed and implemented in order to improve project performance.

The difference between the perceived and actual progress is explored in more details in the rework cycle illustrated in Appendix A. The work rate is determined by the availability of resources and their productivity, and as time advances, the amount of work remaining should reduce. However, the quality of the work may not be perfect and errors may be generated. After sometime, these errors are detected and rework identified, increasing the amount of work remaining. The amount of rework required will also be dependent on the age of the errors; if the error is fundamental necessitating an important specification change, all the perceived progress subsequent to the error may be wasted.

The main cycle loop in this model is the reinforcing loop (indicated by R+), with more work generating more errors and more work in turn, though the two balancing loops (B-) should help counteract this accumulation of work remaining. The gap between the perceived and actual progress can be difficult to close; it may appear that all is nearly finished but the project can remain obstinately at the 90% completion level (Abdel-Hamid, 1988).

The rework cycle identifies four factors partially under management control: resource level, productivity, quality and the error discovery time. Typically, management focus on the resource level and productivity as the keys to successful implementation. However, experiments (Cooper, 1993a) with the rework cycle suggest that the quality and the error discovery rate are the more important factors. Simply, throwing resources at the project does not solve the fundamental problems; a more effective approach should be developed to reduce the number of errors or at least the time taken over their detection. Such a conclusion is not unexpected but SD provide a deeper understanding of its background and hence a greater possibility that the message will be taken more seriously by the project team.

2.7.1.2 The Project Human Resource Structure

The management of Human Resource (HR) for a project has in recent years been elevated to what some companies have begun calling managing the asset of human capital. Nowadays, one of the key functions of HR department on a project is to efficiently work alongside PM team in the hiring, training, assimilation and transferring of a project's human resources.

After breaking the entire project down into tasks and activities, there is a need to identify the available resources and allocate them to the project tasks. Human resources are one of the key elements, which play a very major role in deciding construction project's performance and overall success. It is very important to invest properly in human resources for timely completion of the project and within budget. Also, the realistic identification and allocation of human resources on the project is essential to effective PM. The major elements of a HR sub-system are manpower, employee moral and skill availability and work experience of employers. These elements to a large extent determine training needs, skill level, employee motivation and the decision-making process in both a construction and project organization.

Hiring the workforce for the project depends, to a much greater extent, on the amount of work to be completed (Work Availability) and the time available to accomplish the work (Project Completion Date). Basically, on construction projects the work is divided into three phases:

- The build-up phase.
- The peak period phase.
- The run down phase.

A simple trapezoidal diagram, illustrated in Appendix A, shows the construction duration with all three phases. A build-up phase is the beginning of the construction project, where the work available is much less initially and is in steadily growing stage. The hiring of workforce for the project actually begins during this phase, taking into consideration the workforce available. Hiring for project further keeps on increasing continuously to cover the peak period phase which results in most of the completion of project work and is the largest of construction phases. Finally, the hiring activities start reducing at the beginning of run down phase where the project is almost 90% complete.

The other important aspect that needs to be considered in the HR segment is the workforce productivity. Whereas hiring the required workforce on project can be valuable, there are secondary negative effects, which often conspire to the effectiveness of such action. Indeed, the immediate result of recruitment will be a reduction in the overall productivity of the project work. The reason being the newly hired workforce may not be equally productive as the experienced workforce on the project. All this human resources issues faced by the project managers are explained using the causal loop diagram shown in Appendix A.

The causal loop diagram shows the feedback processes that control both time allocation and recruitment of human resources. The diagram of the hiring process and its effect contain two reinforcing and one balancing feedback loop. In the hiring process diagram, B is the balancing (negative) feedback loop depicting the hiring policy. An increase in the workforce gap or difference between number of employees and desired number of employees will increase the advertisement rate for new employees that, consequently, increase the hiring rate after a delay. Hiring new employees serves to increase the total workforce and reduce the workforce gap.

R1 is the reinforcing (positive) feedback loop affecting the hiring policy that initially follows the same path as B. The difference is that as total workforce rises, the quit rate rises as well (given a constant quit factor). The quit rate increases the workforce gap and the cycle continues.

In the hiring effect diagram, R2 is the reinforcing loop displaying the allocation of human resources. An increase in newly hired workers results in more manpower applied to training and less manpower applied to actual project work. A reduction in project manpower reduces the rate at which work is completed. The work completion rate, on the other hand, reduces the time, which increases the necessary team size. An increase in necessary team size results in newly workers after the hiring delay.

2.7.1.3 The Client Behavior Structure

Current contractual relationships are mainly based on confrontational situations that reflect the level of trust (or mistrust) in the contract documents between the client and the contractor. This can be the driver to increase the total cost of a specific project and affect the overall relationships between the contracting parties. The difficulties of assessing the full impacts of client behavior on project performance derive in part from the subjectivity involved in providing a clear identification of how this behavior interferes with the implementation process. To approach the problem, we first need to identify what are the different client's actions that are likely to have a relevant impact.

The relationship between the client and the contractor while the project is on-going can be characterized by two different communication processes:

- The continuous reporting of progress regarding the major milestones and according to the contract.
- The continuous review of the system definition and its required functionality.

The first process result from the need to keep the customer confident that the contractual agreement are being fully respected by the contractor, while the second process aims to ensure that both parties have a clear common understanding of what is being developed.

It is from these two communication processes that problems with the client usually emerge. Projects are novel endeavors and hence can hardly follow a pre-planned steady path. As they grow more complex, their dependency on future events increases, thereby becoming sensitive to external disturbances. Despite the attempt to anticipate problems before contract negotiations, unpredictable events will inevitably emerge, making the project deviate from the ideal route. As the contractor eventually fails to meet the agreed milestones, the client feels the legal (not necessarily moral) right to compensation while reducing his trust in the contractor's competence. Alternatively, contractor's finding ways to recover the short-term milestones might be at the expense of even worse over-runs at later stages. On the other hand, the need to sacrifice early milestones in favour of later success may not be accepted by the client and is often "culturally" seen within organization as a premature indication of failure; the earlier the slippage, the poorer the management and, hence, the worst the results. The client's reluctance to accept early delays is reinforced by the contractor's difficulties in providing convincing arguments that such decisions could be beneficial for the final project outcome.

Faced with a hostile client attitude, the contractor chooses to avoid reporting delays whenever these can be "hidden" hoping that staffs will soon catch-up with the work. As this communication process deteriorates the cooperation between client and contractor, reduces as conflicts become more and more counter-productive.

The continuous review of the system definition is also a major source of problems in communication. As the system is developed throughout the life-cycle, intermediate sub-products are assessed so that misrepresentations of the system requirements can be identified as early as possible. While this process aims to evolve towards a common and clear understanding, the result is often the opposite, a growing disagreement between client and contractor as the project progresses. Typically, the client tends to demand more or better system functionality than that which the contractor believes to have been agreed. Such demands might result from ambiguities in the contract or from compensations for delays in major milestones. The contractor's major concern might be to reduce costs for the sake of the project's profitability and, hence, there might be a tendency to accept low cost changes rejecting those, which appear to be more expensive. This is often a source of problems because the client's perceived value does not relate to the implementation cost but to the functional utility taken from the change. Furthermore, the client may not be even aware of the costs involved. Consequently, a low cost change readily accepted by the contractor could be perceived by the client as a valuable concession encouraging the demand for further changes. On the other hand, refusal to accept costly changes perceived as trivial by the client causes mutual trust to deteriorate.

The client behavior influence diagram (causal loop diagram) is provided in Appendix A, representing the feedback structure underlying this problem where the key "vicious circles" are identified. The control loop at the center shows how the introduction of changes is usually balanced by schedule adjustments negotiated with the client based on an estimate of how much extra effort is perceived needed (i.e. the cost of direct impacts). The dashed lines identify the secondary effects, usually complex and subjective, which in the long term are the cause for over-runs. The first major effect of changes in the system's requirements is work having to be done out of its normal sequence. Other major causes for work out of sequence are client delays in approving system design documents and staff directing their efforts to those system areas they believe to be more stable under schedule pressure. The immediate consequence of doing work out of sequence is a sharp increase in the number of errors being introduced in the system. As new errors start being detected in areas, which were thought to be stable, staff progressively lose trust in the current system's requirements. This poorer understanding about the system functionality slows down the development productivity and when associated with schedule pressure causes the effectiveness of quality activities to deteriorate, so they are skipped or compressed.

With a lower productivity and a high number of defects escaping to the later testing stages the inevitable result is the delay of major schedules. These slippages tend to cause the client's trust in the project team to deteriorate, the client becoming increasingly less tolerant in accepting further schedule adjustments and more demanding in progress reports which divert staff form the real development work.

Often, the only way of persuading the client to agree with the delays is to concede further requirements changes in the system at no extra cost. This continuous introduction of changes exacerbates the lack of trust in the requirements stability motivating staff to do work out of sequence even in those areas where the requirements are stable. The secondary ripple effects are identified in the influence diagram by reinforcing causal loops in which the client's actions play a core role.

The effect of client behavior diagram is found in Appendix A. Finding the appropriate balance is a difficult task and the client behavior can exacerbate the problem aggravating delays and imposing restrictions on schedule adjustments puts pressure on management to try increasing the work rate. This type of decision typically includes hiring more staff, putting pressure on staff to work quicker, using over-time, reducing quality and increasing activity concurrency. However, when over-applied, the several disruptive long-term effects become dominant reinforcing problems (as shown by the reinforcing loops in thin lines). Once more, these secondary effects are difficult to estimate and quantify. Thus, if not managed properly, the client behavior not only has the potential to disturb the normal work progress but also to encourages the implementation of inappropriate control decisions.

Frequently, the initial contractual agreements become violated and changes need to be agreed. Unfortunately, both parties often play counter-productive adversarial roles, ending in costly legal disputes. The client behavior thus has a strong impact on the project dynamics and if not handled properly may disrupt dramatically the project performance. Effective negotiation with the client when the project is on-going is therefore essential but can only be achieved through an improved understanding and accurate quantification of the full impacts of contractual changes. The current set of planning and controlling tools available within the traditional approach has proven not to match this need. Hence, SD is used as an appropriate alternative to approach this problem and an attempt is made to study the project dynamics evolving out of client behavior.

2.7.1.4 The Project Scope Structure

In general, Project Managers should pay a great deal of attention to managing scope. Allowing the project's scope to change mid-course usually means added costs, greater risks and longer duration. Many projects fail due to poor scope management. Very often, it is a large number of small scope changes that do the damage, rather than the big, obvious ones. The successful Project Manager has learned that rigorous scope control is essential to deliver projects on time and on budget.

Scope should be clearly defined as part of the Project Definition. Much of work at that time is directed at agreeing the optimum definition of the project; both in terms of its deliverables and in terms of how it will operate. This scope definition will form the baseline against which potential changes are assessed and against which the project's performance is measured.

In defining how the project will operate, the Project Manager should try to influence those factors that could lead to subsequent scope change. The importance of a sound Project Definition should be emphasized. Also, the Project Manager should make clear the dangers and potential costs of subsequent changes of direction, but, equally, encourage the leadership to allow change where that would be beneficial.

The final feedback loop, regarding the project scope, represents the adjustment of the project size and the changes to the overall definition of project from variety of sources, occurring during the project's life cycle. Where there is uncertainty in goals element of project complexity, the customer is likely to require changes to scope of work during the project. This can either take the form of substitution, changes to a design to give a product of an equivalent value, or addition, increasing the value of product. It can be couched in terms of contract change, in which case the client accepts responsibility and the contractor has to cost the change; or, it can be simply preferential engineering, where the client expresses preference despite being given a design fit for purpose, in which case the contractor has, as well as costing the effects of the change, also to submit a claim for the extra cost.

In any case, the cost of a mid-course change to the project definition or scope will nearly always be higher than if the change had been made before the project started. In some cases, the changes do not necessarily result from the client explicitly wishing to change the system functionality, but may result from the misrepresentation of the contract. Often, it is not until the work has moved towards the final testing stages that both client and contractor reach a stable consensus. It is important in all the cases to quantify and model the impacts of all these changes on the behavior of the project. When scope changes are introduced during the project's life, there is an immediate need to reassess, whether the final schedule should be readjusted.

The decision whether to accept or reject a change would be based on a number of rules. The fundamental logic should be:

- Is the change unavoidable?

Or

- Does the change increase the overall benefit to the organization (taking into account any impact on the costs, benefits, timescales and risks)?

And

- Is the Project Team able to make such a change?

And

- Is the change best done now, or would it be more beneficial to defer it until the current work is completed?

The causal loop diagram of a project feedback structure focused on scope changes is shown in Appendix A. It shows all the major dynamics that can generate project risks, related to scope changes imposed by any party (client/contractor) on the project. This understanding of risks is crucial for better identifying, assessing and controlling them.

2.8 SD Models of PM

The developments of SD in PM are summarized in Table 2-2, which includes a representative sample of studies drawn from a more exhaustive review (Rodrigues, 1994). The first description of the use of SD in understanding projects appeared in 1964, but it was not until the 1980s that the first project-specific applications began to be reported. Since 1990 there have been many more reported examples of the use of SD in PM.

Typically the application areas are those where budgets are high and the risks are greater, such as aerospace, software developments and the Channel Tunnel. The first models (Kelly, 1970 and Roberts, 1964) were developed to examine the dynamics of research and development projects. The concepts of perceived progress and real progress were introduced, addressing explicitly the fact that managerial decisions are based on perceptions of the project's state which may be quite different to the reality. Richardson and Pugh (1981) developed the model of the Research and Development (R&D) projects and various studies investigated the new concepts of rework, undiscovered rework, perceived progress, real progress, perceived productivity and real productivity. The "program management modeling system", developed by Pugh-Roberts Associates (1993), incorporates many of these features and has been used to support the management of several large projects. Other studies have examined specialized application areas, such as those of Abdel-Hamid (1988 and 1990) in the management of software development projects.

Table 2-2: Applications of SD to PM.

Author	Project Type	Summary
Roberts (1964)	R&D	Perceived vs. real progress
Kelly (1970)	R&D	Development of R&D dynamics, multi-project management
Richardson, Pugh (1981)	R&D	Productivity and rework generation staff hiring policy
Jessen (1988)	R&D, construction	Project team motivation and productivity, client and project team relationship
Keloharju, Wolstenholme (1989)	R&D	Time-cost trade-off
Abdel-Hamid (1988, 1990)	Software development	NASA Goddard Space Flight Center: project staffing policies, multi-project scheduling, quality assurance policies, cost and schedule estimates as targets, managerial turnover
Barlas, Bayraktutar (1992)	Software development	Simulation based game, staffing policies
Pugh-Roberts Associates (1993)	Various large projects	PMMS: a specialist SD project management tool, design and work-scope changes, dispute resolution
Smith et al. (1993)	Software development	Charles Stark Drapper Laboratory
Chichakly (1993)	Software development	High Performance Systems Inc, technology transition
Lin (1993)	Software development	NASA Jet Propulsion Laboratory: integrating engineering and management
Aranda et al. (1993)	Software development	Aragon Associates Inc, TQM and product life cycle
Cooper, Mullen (1993)	Software development	The rework cycle, project monitoring progress ramps
Williams et al. (1995)	Product development	Dispute resolution, impact of parallelism
Simmons (2002)	Software development	Needless restriction, simulation with Process Model
Lyneis, Ford (2007)	Software development	Improve project management and education
Lee et al. (2007)	Software development	Project duration, resource allocation

Three main problems were addressed by the model proposed by Richardson and Pugh (1981): monitoring and controlling, rework generation and staff hiring policies; the same basic problems have been investigated in most of the subsequent SD studies, as summarized in Table 2-2. The majority also refer to R&D or software development projects. The model developed by Williams et al. (1995) is more singular, using a SD model for a postmortem diagnosis in which the project behavior is described under a network perspective. It identifies important feedback processes responsible for the "vicious circles of parallelism". Parallel activities typically have implicit inter relationships which tend to increase the activities' durations, prompting a revision of the plan to incorporate yet more parallelism in an attempt to avoid an overrun. Whereas most projects experience problems in all three problem areas and the interactions between the three can be critical, each is considered separately for the sake of clarity.

Abdel-Hamid and Madnick (1989) developed a comprehensive model of the dynamics of software development that enhances our understanding and makes predictions about the process by which software development is managed. Also, they discussed the integrative dynamic model of software PM that has been developed.

Sterman (1992) described the use of SD modeling for management of large scale project, including large scale engineering and construction project. He presented the construction of projects that involve multiple feedback process. Also, mental models and traditional cost and scheduling tools such as CPM were discussed.

Ford (1995) has focused on a static view of PM. Also, he investigated the impacts of dynamic project structure on performance with a focus on the influence of the development process. A dynamic simulation model of a multiple phase project was built using the SD methodology. The model was applied to the investigation of coordination policies for improved project performance. Finally, he found that development processes significantly impact the dynamic behavior of projects through the feedback, delays and nonlinear relationships which are not used in traditional project models but are important descriptors of project complexity.

Simmons (2002) used Process Model simulation which allows the activity times of a project to be represented by a variety of distributions and further the resulting project time may also be represented by a variety of distributions. This is a significant improvement over the traditional methods of CPM and PERT. PERT takes the CPM network and adds distributions to represent the activity times of the project. CPM assumes the activity times to be constant, which is not likely in the real world. PERT assumes the activity times of the project to be distributed as Beta distributions and the resulting project time to be a Normal distribution. This is better than assuming them to be constant, but these assumptions are needlessly restrictive. He demonstrated how simulation with Process Model can remove these needless restrictions.

Ford, et al. (2002) identified the recognition modeling and capture of latent project value generated by dynamic uncertainty as an important but under-investigated aspect of construction PM. Also, they described the use of options in strategic project planning as a means of improving PM. Although they concluded that, the application of a real option approach to strategic construction PM can potentially improve construction management, additional research was required into several aspects of its implementation.

Lyneis and Ford (2007) reviewed the history of PM applications of the underlying structures that created adverse dynamics and their application to specific areas of PM. They surveyed the large body of SD work on projects and evaluated its progress. Many different types of models have been developed to improve PM. These models include some of the system features and characteristics addressed by SD. They summarized what has been accomplished in three categories: (1) theory development; (2) guidance in improving PM and education; and (3) applications.

Lee, et al. (2007) examined how to minimize project duration which is critical to success in many development projects. They focused on resource allocation policies during such projects which determine the fractions of resources that are to be assigned to constituent tasks. They obtained two major conclusions; first: the durations are minimized with resource adjustment times greater than their minimum values support a conclusion that projects have optimal managerial delays that may be positive. Second: the increasing uncertainty in project controls can decrease durations if delays are not optimal and the delay–duration relationship is convex by increasing the net amount of work performed near optimal conditions.

2.9 Summary of Literature Evaluation

The existing literature describes and documents recent fundamental changes in traditional construction PM techniques from a SD point view. The ideal of the traditional approach is based on a system methodology. It considers that PM is based on a dynamic control process that takes place within a project system and interacts with the external environment.

This Thesis seeks to show which parameter is significant to system behaviour using sensitivity analysis. This will be done by investigating the dynamic impact of PM and project coordination policies on construction project performance. Also, the potential impacts of the major feedback loop on project performance can be shown by explaining their structure in detail. The research work involves the use of dynamic computer simulation model to investigate the impact of major project parameters on project performance.

CHAPTER THREE

MODEL DESCRIPTION

Chapter Three Model Description

3.1 Model Purpose

From the SD perspective, a model is developed to address a specific set of questions. The fundamental purpose of a SD model is to improve understandings of the relationships between feedback structure and dynamic behavior of a system, so that policies for improving problematic behavior may be developed. Therefore, this research focuses on models and modeling projects whose major goal is policy design and improvement.

There are many advantages gained during the process of building the model. Few of the benefits gained by modeling complex projects are:

- First of all, and crucially, the model can show how inputs combine. For example, it can demonstrate the cumulative and compounding effect. In a complex project, how the individual influences combine is not obvious and a model enables us to understand this combination.
- Then, the model enables sensitivity analysis and "what-if" studies. By modeling a complex system, more can be learned about internal interactions than would ever be possible through manipulation of the real system.
- Having a project-wide dynamics model helps PM to visualize the whole project or to understand how the project as a whole entity behaves.
- Finally, the models help PM to prepare the project plan, allocate contingency and make the necessary pre-project planning.

Thus, the model here will be used to look at the effects of various events and effects on projects. This will be done by describing perceptions of a real system, simplified, and using a formal theoretical based language of concepts and causal relationships.

3.2 Model Structure

3.2.1 Introduction to Model Structure

Operationally, the model is a set of nonlinear ordinary differential equations. Also, it consists of a set of interrelated development phases and a set of PM features. Each phase is customized to reflect a specific stage of construction PM. A complete listing of the Model Equations is provided in Appendix B. Also, the definitions of the Model Variables used in the model equations are given in Appendix C.

3.2.2 Project Rework Structure

3.2.2.1 Description of Rework Structure

Figure 3-1, shows the project rework sub-system of the SD model that aims to capture all of the major feedback structure that influences the overall system behavior. These factors include the "hard" measurable factors like the total work for project, work rate and labor for project and the "soft" human factors like productivity. This rework cycle is the fundamental core of a model because it includes added rework, time to generate rework and time to correct amount of work. The main purpose of the rework model is to enable project members to manage effectively the complexity associated with rework in a project system.

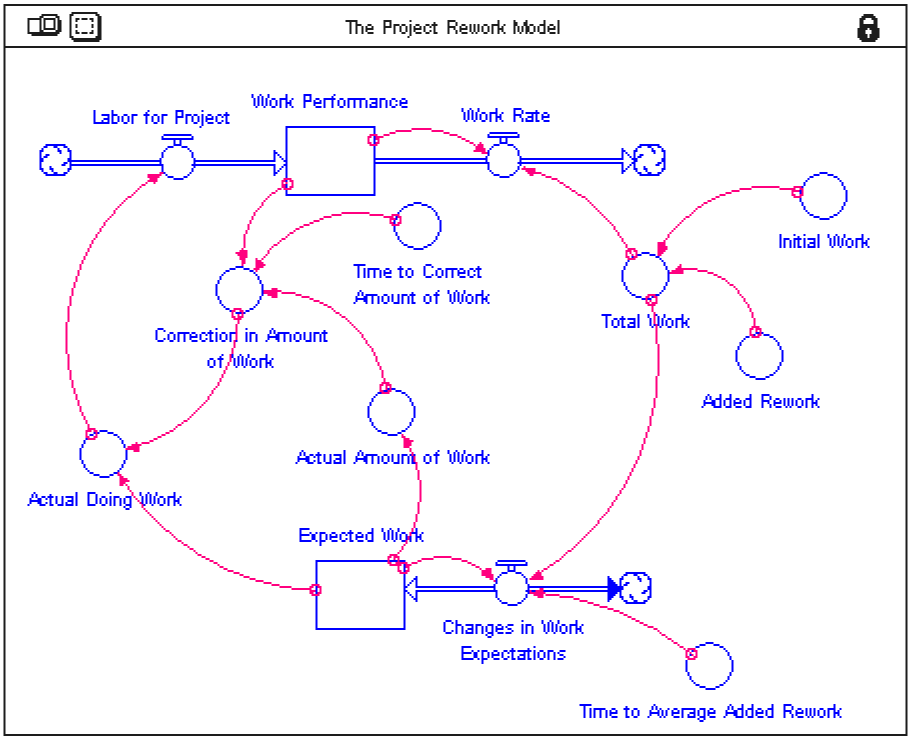

Figure 3-1: The Project Rework Model.

The model shown in Figure 3-1 consists of a set of Equations and Variables which are shown in Appendix B and Appendix C, respectively. Some of them are:

- Equations:

Expected_Work(t) = Expected_Work(t - dt) + (Changes_in_Work__Expectations) * dt .... (3.1)

INIT Expected_Work = Total_work .... (3.2)

Changes_in_Work__Expectations = (Total_work-Expected_Work)/ Time_to_Average_Added_Rework .... (3.3)

Work_Performance(t) = Work_Performance(t - dt) + (Labor_for_Project - Work_Rate) * dt .... (3.4)

- Variables:

Change in Work Expectations: The rate at which the workers' expectations about work changes.

Time to Average Added Work: The time it takes the workers to recognize a permanent change in work.

Correction in Amount of Work: The amount of work that the workers perform as a result of a different between the performed and the actual amount of work.

3.2.3 Project Human Resource Structure

3.2.3.1 Description of Human Resource Structure

The flow diagram of the added HR sub-system, shown in Figure 3-2, corresponds to the hiring structure of the workforce for project based on the workforce gap. The main purpose of the HR model is to enable project members to manage effectively the number of workers and the labor for the project to reach the desired amount of work.

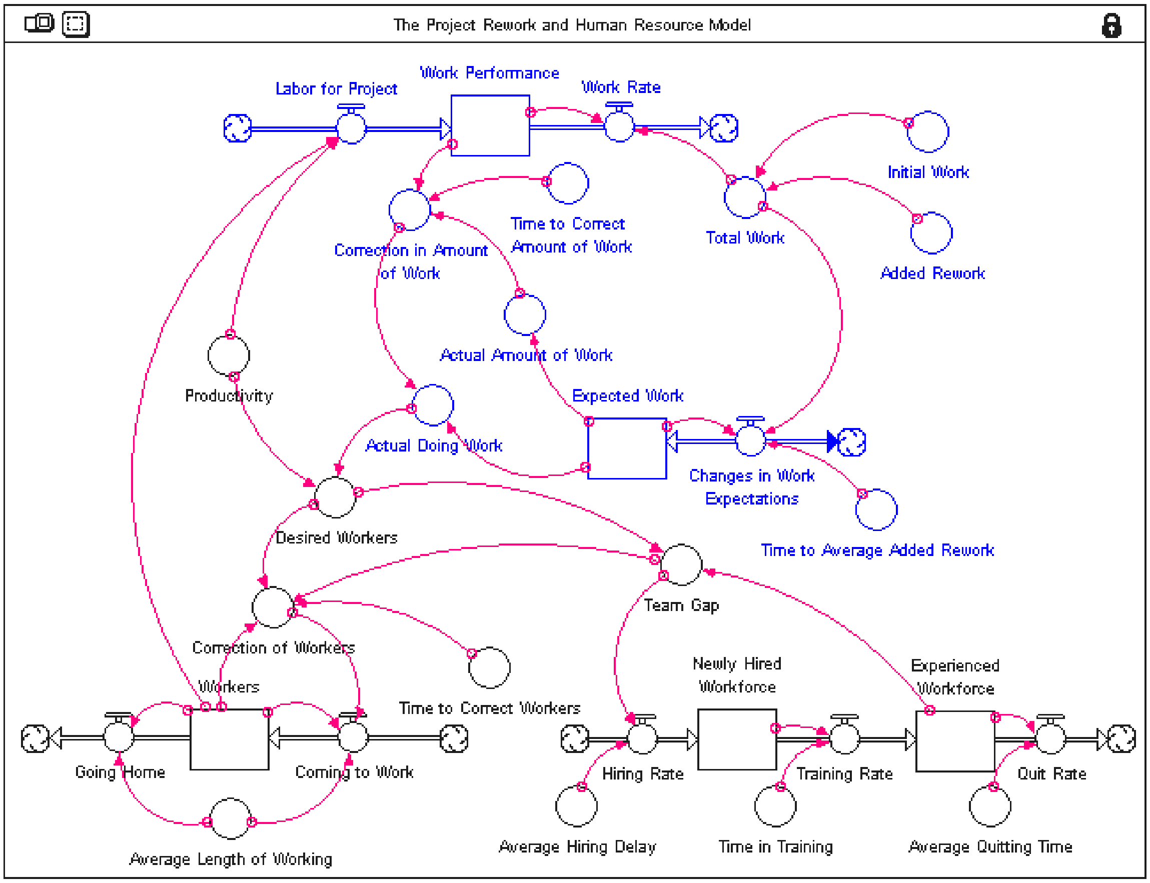

Figure 3-2: The Project HR Model.

The model shown in Figure 3-2 consists of a set of Equations and Variables which are shown in Appendix B and Appendix C, respectively. Some of them are:

- Equations:

Experienced_Workforce(t) = Experienced_Workforce(t - dt) + (Training_Rate - Quit_Rate) * dt .... (3.5)

Newly_Hired_Workforce(t) = Newly_Hired_Workforce(t - dt) + (Hiring_Rate - Training_Rate) * dt .... (3.6)

Hiring_Rate = Team_Gap/Average_Hiring_Delay .... (3.7)

Training_Rate = Newly_Hired_Workforce/Time_in_Training .... (3.8)

- Variables:

Experienced Workforce: The number of employees capable for working on their own.

Newly Hired Workforce: The most recently hired members of workforce and thereby have no experience.

Team Gap: The difference between the number of employees required and that already employed.

3.2.4 Client Behavior Structure

3.2.4.1 Description of Client Behavior Structure

When the PM team faces with crucial decisions related to project, they must consider the "soft" variables. Soft variables don't usually boil down to numbers. These variables often have a significant financial impact both in the short and long run of the project, yet, they are difficult to account.

In the engineering construction projects, it is important to know and estimate if there are some work changes or not during the project execution. The main purpose of the client behavior model, shown in Figure 3-3, is to enable project members to manage effectively the amount of changes in work and to estimate the time it takes the project to reach the desired amount of work.

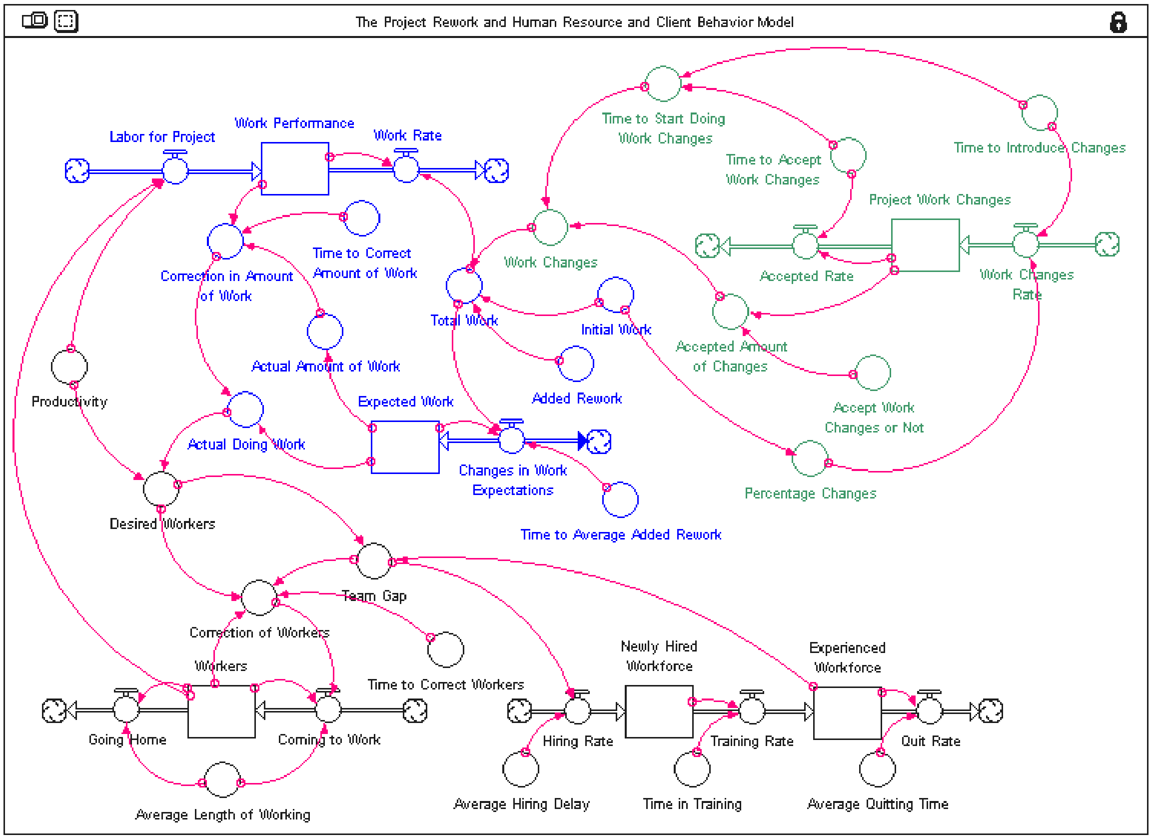

Figure 3-3: The Client Behavior Model.

The model shown in Figure 3-3 consists of a set of Equations and Variables which are shown in Appendix B and Appendix C, respectively. Some of them are:

- Equations:

Project_Work_Changes(t) = Project_Work_Changes(t - dt) + (Work_Changes_Rate - Accepted_Rate) * dt .... (3.9)

Work_Changes_Rate = Percentage_Changes/Time_to_Introduce_Changes .... (3.10)

Accepted_Rate = Project_Work_Changes/Time_to_Accept_Work_Changes ...... (3.11)

Accepted_Amount__of_Changes = IF(Accept_Work__Changes_or_Not=1) THEN(Project_Work_Changes)ELSE(0) .... (3.12)

- Variables:

Time to Introduce Changes: The average time constant during which changes occur or introduced by the client.

Project Work Changes: The amount of work changes accepted by the manager which affect the time of the project.

Work Changes Rate: The rate at which changes occur or are introduced during the project.

3.2.5 Project Scope Structure

3.2.5.1 Description of Scope Structure

As discussed previously, the scope changes on construction projects are often inevitable and have significant time and cost impacts and range from those that may be easy to specify and calculate to those that are soft and ill defined. A practical tool, capable of providing quick qualitative and quantitative analysis to support negotiation of scope changes within the project parties while the project is on-going, is of major value to the PM team. Most of the times, scope changes can affect the project team in different ways like; rework, major design changes, loss in productivity, loss in team morale, defect generation and staff fatigue. All these effects occurring during project's life can result in excessive delays in schedule, increased cost and finally turn into legal disputes between the project parties. Figure 3-4, shows the SD model with the project scope sub-system that aims to capture and study the effects of all these major changes taking place during the project life.

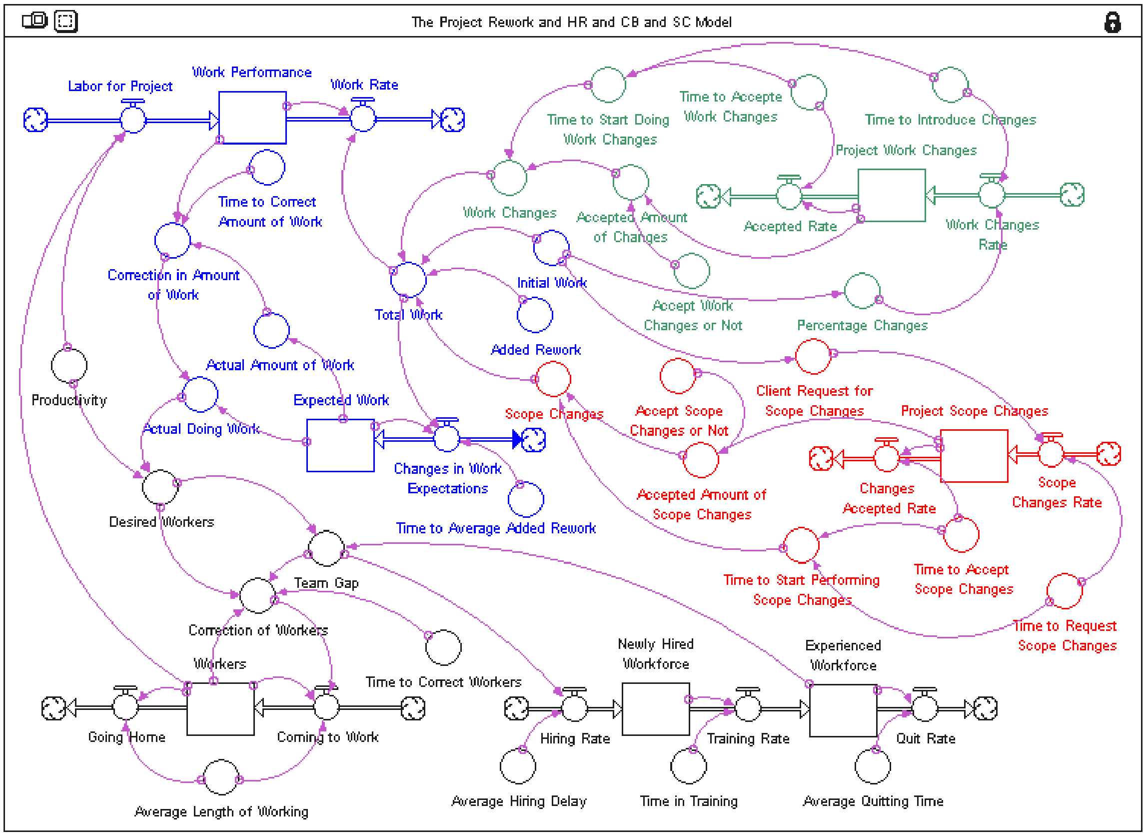

Figure 3-4: The Project Scope Model.

The model shown in Figure 3-4 consists of a set of Equations and Variables which are shown in Appendix B and Appendix C, respectively. Some of them are:

- Equations:

Project_Scope_Changes(t) = Project_Scope_Changes(t - dt) + (Scope__Changes_Rate - Changes__Accepted_Rate) * dt .... (3.13)

Scope__Changes_Rate = Client_Request_for__Scope_Changes/Time_to_Request__Scope_Changes .... (3.14)

Changes__Accepted_Rate = Project_Scope_Changes/Time_to_Accept__Scope_Changes .... (3.15)

Accepted_Amount_of__Scope_Changes = IF(Accept_Scope__Changes_or_Not=1) THEN(Project_Scope_Changes)ELSE(0) .... (3.16)

- Variables:

Project Scope Changes: The extra work which was not included in the original scope of work for the project.

Scope Changes Rate: The rate at which the additional work is introduced in project life cycle by client or contractor, which is not a part of the original scope of work.

Changes Accepted Rate: The rate at which the extra work is approved by the client or accepted by the contractor on the project.

3.3 Summary of Model Description

The four feedback structures that represent existing SD models were built using iThink 9.0.2 simulation software. The complexity of the combination of these feedback loops exceeds the bounded rationality of human to simulate or predict with any accuracy. This complexity helps to explain the difficulty in managing construction projects and investigating the impacts of management policies on performance. It also supports the need for computer-based simulation models for investigation. These four feedback structures will be applied to a realistic construction project to understand and control the impacts of the dynamic aspects on project performance. Also, the model enables scenario analysis to help project management to visualize the whole project and understand how the project as a whole entity behaves.

CHAPTER FOUR

SENSITIVITY ANALYSIS

Chapter Four Sensitivity Analysis

In this Chapter, a realistic construction project case will be applied to the SD simulation model. This will be done by describing each feedback structure of the simulation model using computer software, iThink 9.0.2, and defining each element in the interrelated subsystem. After setting the simulation parameter, alternative scenarios will be tested using one-way and multi-way sensitivity analysis. Finally, the SD and the traditional PM approach will be compared.

4.1 Introduction to Sensitivity Analysis

Sensitivity analysis is used to determine how "sensitive" a model is to changes in the value of the parameters of the model and to changes in the structure of the model. This research focuses on parameter sensitivity. Parameter sensitivity is usually performed as a series of tests in which the modeler sets different parameter values to see how a change in the parameter causes a change in the dynamic behavior of the system. By showing how the model behavior responds to changes in parameter values, sensitivity analysis is a useful tool in model building as well as in model evaluation. Sensitivity analysis helps to build confidence in the model by studying the uncertainties that are often associated with parameters in models.

To understand the sensitivity of the SD model, two different types of sensitivity analysis were used; one-way and multi-way sensitivity analysis.

4.1.1 One-Way Sensitivity Analysis

The simplest form of sensitivity analysis is to simply vary one value in the model by a given amount, and examine the impact that the change has on the model's behavior. For example, by decreasing the effectiveness of rework discovering time by 10%, the cost-effectiveness ratio falls by, say, 20%. This is known as one-way sensitivity analysis, since only one parameter is changed at one time. The analysis could, of course, be repeated on different parameters at different times. One-way sensitivity analysis can be undertaken using various different approaches, each of which is useful for different purposes. This research would like to test which parameters have the greatest influence on a model's behavior.

4.1.2 Multi-Way Sensitivity Analysis

While one-way sensitivity analysis is useful in demonstrating the impact of one parameter varying in the model, it may be necessary to examine the relationship of two or more different parameters changing simultaneously. This approach involves the changing of, say, two key parameters (for example, the rework discovering time and the workers productivity), showing the results for each potential combination of values within a given range. It should be noted, however, that the presentation and interpretation of multi-way sensitivity analysis becomes increasingly difficult and complex as the number of parameters involved increases. One method that is sometimes used to assess the confidence around all parameters is to undertake extreme sensitivity analysis, by varying all of the parameters in a model to their 'best' and 'worst' case. This analysis will be done using DOE.

4.1.2.1 DOE and Factorial Design

An experiment is a test or a series of tests. Experiments are performed in all engineering and scientific disciplines and are an important part of the way we learn about how systems and processes work. So, DOE is a systematic series of tests, in which purposeful changes are made to input factors, to identify causes for significant changes in the output response.

When several factors are of interest in an experiment and it is necessary to study the joint effect of the factors on the response, a factorial experiment should be used. It is a powerful technique for this type of problem. Each experiment has many factors with different levels, sometimes called treatments, and each treatment has number of observations or replicates. Therefore, by a factorial experiment it means that in each complete trial or replicate of the experiment all possible combinations of the levels of the factors are investigated. Finally, the Analysis of Variance (ANOVA) can be used to test hypotheses about the main factor effects of several factors and factors interactions.

4.2 Model Behavior

In this section, the SD model structure will be tested. Also, one-way and multi-way sensitivity analysis will be applied to the model to show which parameter is significant to the system behavior. The parameters used, the inputs for the SD model, is a realistic data which is described below. The output of the SD model which this research concerned about is the time it takes the system to return to normal. Therefore, the main objective of this research is to find out which parameter has the most influence on the output of the SD model.

The data used to test and analyze the model is:

- The initial (Planned) work is 60,000 man-hours.
- There is no planned (Expected) rework.
- The average time to added rework is 2 weeks.
- The average time to correct amount of work is 2 weeks.
- The average quitting time is 100 days.
- The average training time is 15 days.
- The average hiring delay is 8 days.
- The total number of available workers is 16 workers.
- The average time to correct workers is 3 days.
- The average length of working is 6 days/week.
- The average productivity is 75% man-hour/day/person.
- The average time to introduce work changes is 8 weeks.
- The average time to accept work changes is 2 weeks.
- The average percentage of work changes is 5% of the initial work.
- The average time to request scope changes is 8 weeks.
- The average time to accept scope changes is 2 weeks.
- The average percentage of scope changes is 2% of the initial work.

4.2.1 Project Rework Structure

4.2.1.1 Simulation Test and Discussion

The stock, called “Work Performance”, is increased by an inflow, called “Labor for Project”, and decreased by the outflow, “Work Rate”. “Work Rate” is a function of “Total Work”, an exogenous parameter (not present in a feedback loop of the system).

Based on his experience, the manager expects to perform a certain amount of work every two weeks. If the total work changed by generating more rework, it usually takes him approximately two weeks to recognize the shift in the total amount of work as opposed to just random fluctuations. This two weeks time constant is the “Time to Average Added Rework”.

The manager then compares the performed amount to the actual amount of “Work Performance”. He needs some time to compensate for this difference, called “Time to Correct Amount of Work”. The difference between the performed and the actual amount, divided by the “Time to Correct Amount of Work”, is the “Correction in Amount of Work”. He then adds the correction to the amount of work he expects to perform, and makes a corresponding amount of the total work. This number is the weekly inflow to the stock.

The behavior of the system when started is in equilibrium. It remains in equilibrium during the entire 52 weeks of the simulation. The value of “Work Performance” is 60,000 man-hours. Figure 4-1 shows the base run.

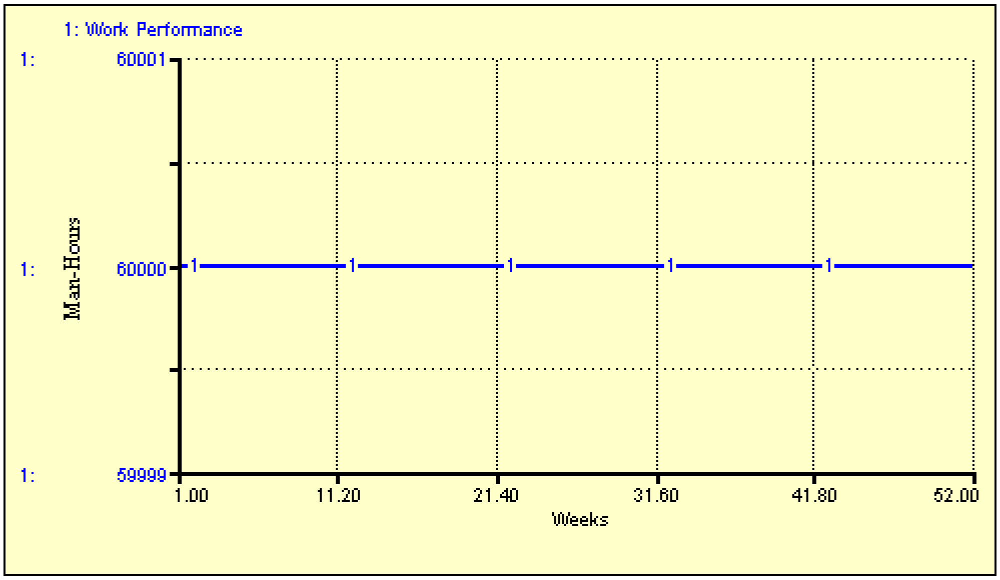

Figure 4-1: The Base Run of the Rework Model.

To test the model, the amount of rework will be changed. At week 7, a step increase of 3,000 man-hours in "Added Rework" is introduced. Figure 4-2, shows the resulting behavior of "Work Performance" and "Added Rework".

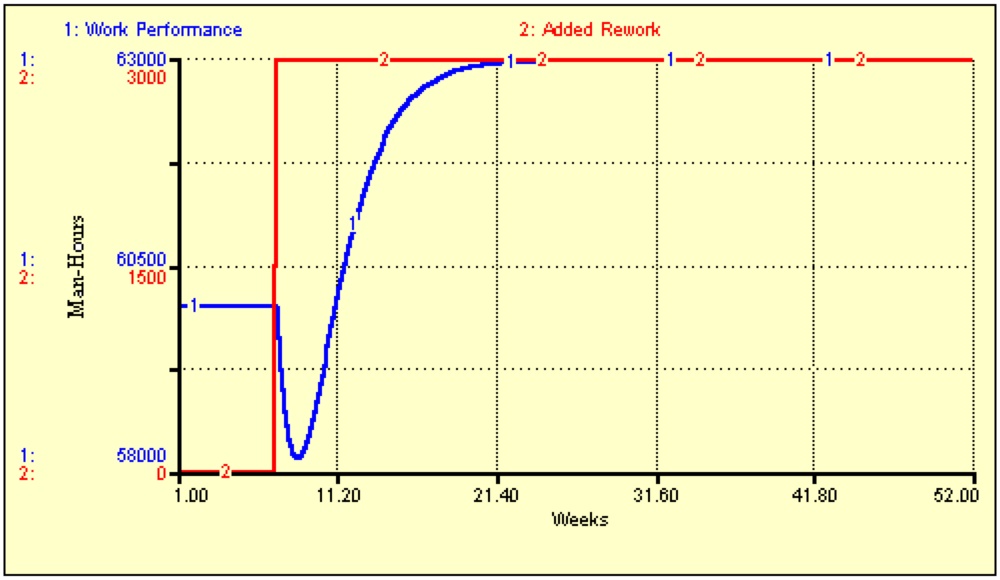

Figure 4-2: The Responding Behavior of the Rework Model.

In Figure 4-2, the system starts off in equilibrium, but only remains in equilibrium during the first seven weeks. Immediately after the change in the amount of rework, the “Work Performance” decreases slightly because “Work Rate” increases together with “Total Work”. In the meantime, it takes some time to perceive the change and then to adjust the expectations, so the system will not be able to react immediately by increasing the “Labor for Project”. It is the difference between the performed work and the “Actual Amount of Work” that prompts to increase the labor so that the stock can start increasing and approach its new equilibrium value.

4.2.2 Project Human Resource Structure

4.2.2.1 Simulation Test and Discussion

To manage effectively the number of workers, the HR sector is added to the SD model. The stock of “Workers” in the model measures only the number of workers currently work in the project. Each worker is able to do a certain amount of effort along the project life, determined by the parameter called “Productivity.” In the base run, “Experienced Workforce” is 16 workers. When divided the “Actual Doing Work” by “Productivity,” the “Desired Workers” is obtained.

Then, the “Desired Workers” is compared to the “Experienced Workforce” to find out the “Team Gap”. The difference between these two values, divided by a time constant called “Time to Correct Workers,” gives the “Correction for Workers”. The “Time to Correct Workers,” 3 days in the base run, is the time constant that needs to compensate for the difference between the desired and actual number of workers. Also, the gap in team size may need to hire more workers which are “Newly Hired Workforce” and the time constant to hire called “Average Hiring Delay”. After “Time in Training”, the new workers become experienced workers which change the team size and therefore the team gap.

Without any outside disturbance, the system starts out and remains in equilibrium at 60,000 man-hours during the 52 weeks of simulation. Figure 4-3 shows the base run of the model.

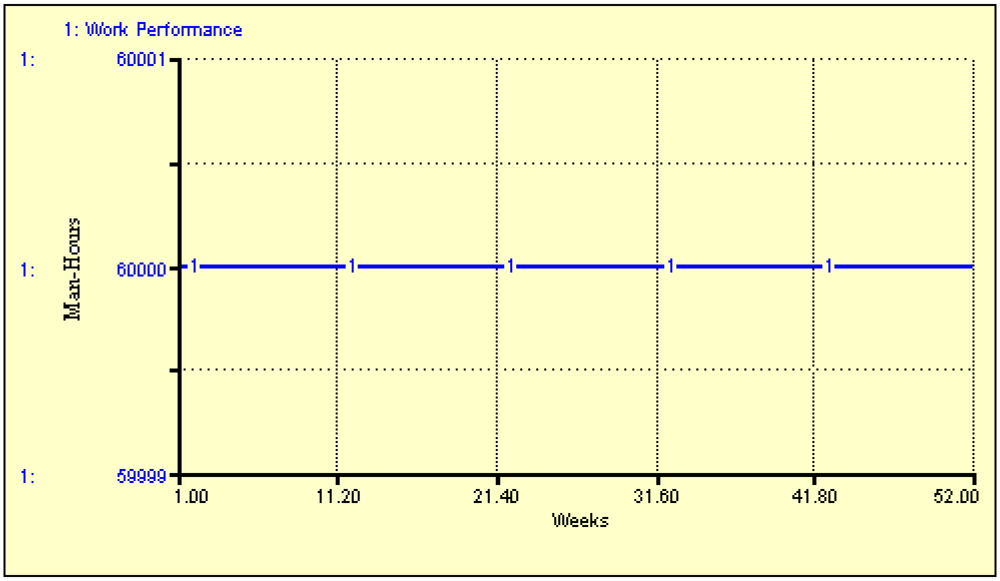

Figure 4-3: The Base Run of the HR Model.

To test the model, the amount of rework will be changed. At week 7, a step increase of 3,000 man-hours in “Added Rework” is introduced. Figure 4-4, shows the resulting behavior of “Work Performance” and “Added Rework”.

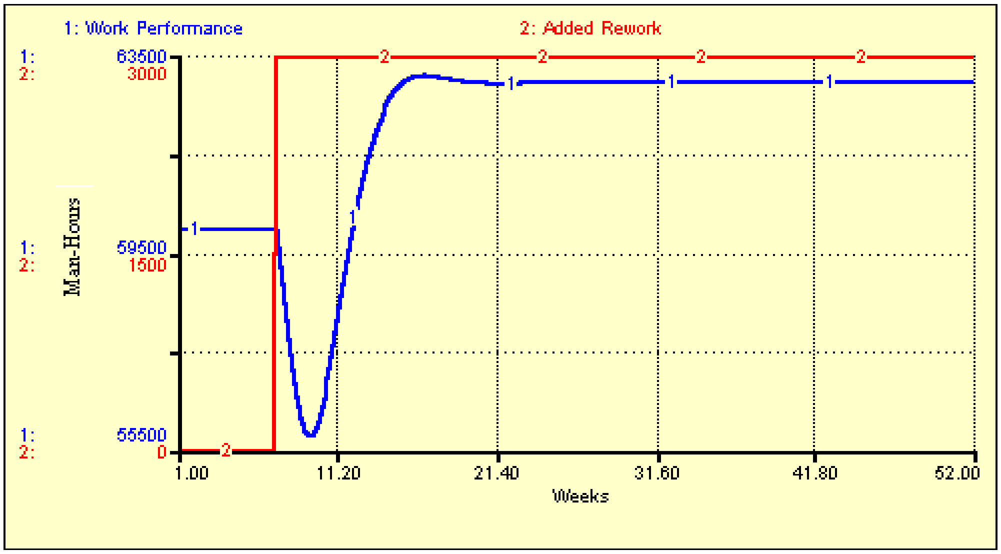

Figure 4-4: The Responding Behavior of the HR Model.

The additional structure added to the rework model significantly changes the behavior of the system; the stock of work performance is "damped oscillations." After the increase in rework, "Work Performance" decreases because "Work Rate" steps up together with total work. However, "Labor for Project" has not changed yet. It first takes a certain time to perceive the change in total work as opposed to random noise and to find out the new amount of work. Then, determines how many more workers should be working in the project. As they come to work, the stock of work performance starts increasing, reaches its new equilibrium value of 63,000 man-hours.

4.2.3 Client Behavior Structure

4.2.3.1 Simulation Test and Discussion

The Client Behavior sector is added to the SD model to manage effectively the work changes introduced by the client. The amount of work changes accepted by the manager is presented in stock called "Project Work Changes" which increased by inflow "Work

Changes Rate" and decreased by outflow "Accepted Rate". In the base run, the "Time to Introduce Changes" is 8 weeks and the "Time to Accept Work Changes" is 2 weeks with no any rework and without any changes.

The behavior of the system when started is in equilibrium. It remains in equilibrium during the entire 52 weeks of the simulation. The value of "Work Performance" is 60,000 man-hours. Figure 4-5 shows the base run.

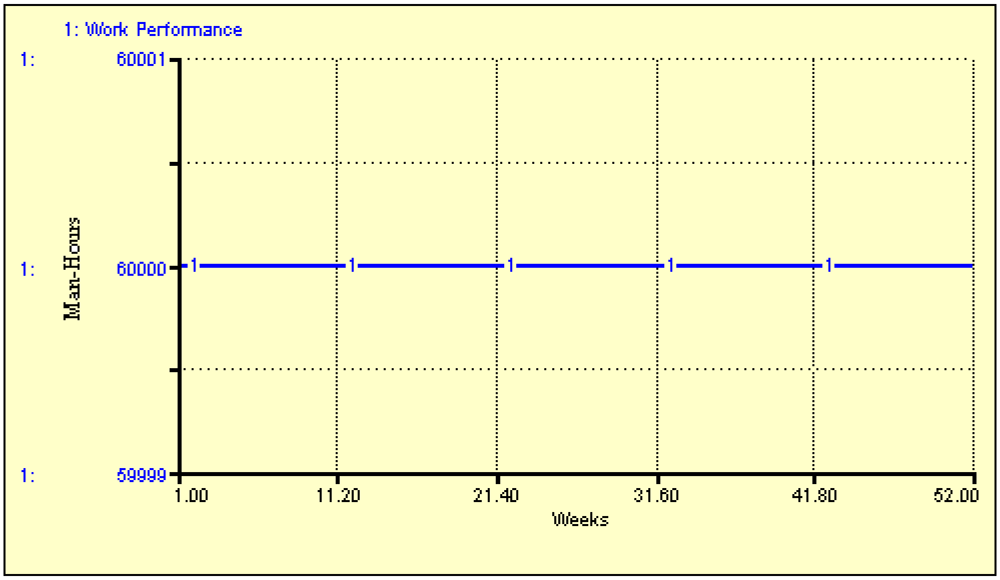

Figure 4-5: The Base Run of the Client Behavior Model.

To test the model, the amount of rework will be changed. At week 7, a step increase of 3,000 man-hours in "Added Rework" is introduced. Also, 5% changes of the total work are introduced at week 10. Figure 4-6, shows the resulting behavior of "Work Performance", "Added Rework" and "Work Changes".

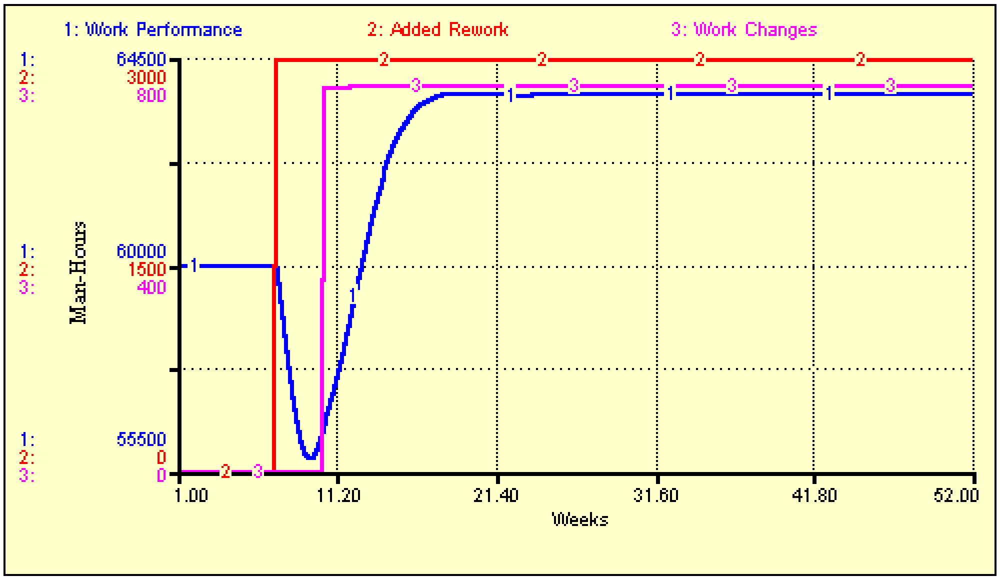

Figure 4-6: The Responding Behavior of the Client Behavior Model.

After the increase in rework and work changes, “Work Performance” decreases because “Work Rate” steps up together with total work. However, “Labor for Project” has not changed yet. It first takes a certain time to perceive the change in total work as opposed to random noise and to find out the new amount of work. Then, the stock of work performance starts increasing, reaches its new equilibrium value.

4.2.4 Project Scope Structure

4.2.4.1 Simulation Test and Discussion

The Scope Structure is added to the SD model to manage effectively the scope changes introduced by the client. The amount of scope changes accepted by the manager is presented in stock called “Project Scope Changes” which increased by inflow “Scope Changes Rate” and decreased by outflow “Changes Accepted Rate”. In the base run, the “Time to Request Scope Changes” is 8 weeks and the “Time to Accept Scope Changes” is 2 weeks with no any rework, no work changes and without any scope changes.

The behavior of the system when started is in equilibrium. It remains in equilibrium during the entire 52 weeks of the simulation. The value of "Work Performance" is 60,000 man-hours. Figure 4-7 shows the base run.

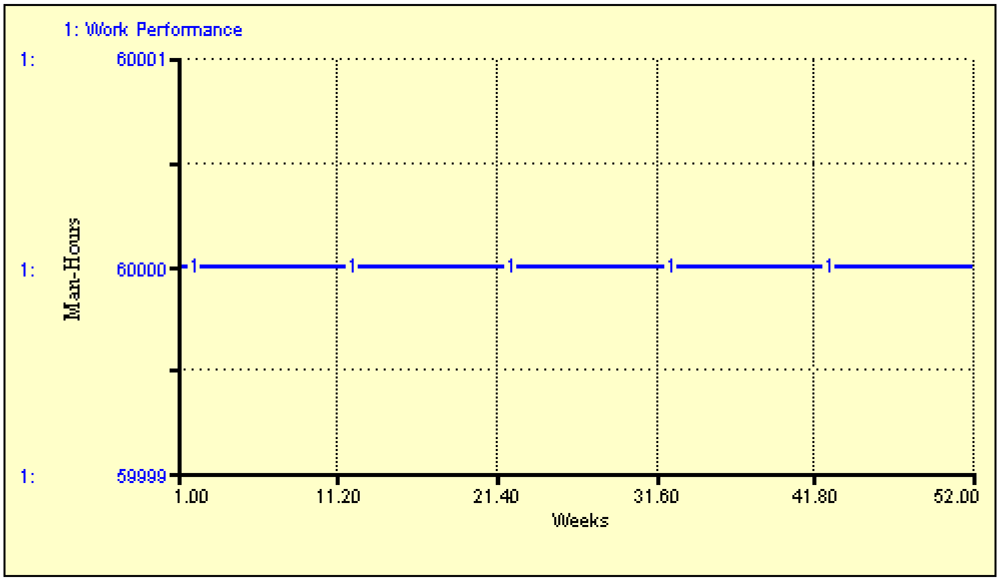

Figure 4-7: The Base Run of the Scope Structure Model.

To test the model, the amount of rework will be changed. At week 7, a step increase of 3,000 man-hours in "Added Rework" is introduced. Also, 5% changes of the total work and 2% changes of the work scope are introduced at week 10. Figure 4-8, shows the resulting behavior of "Work Performance", "Added Rework", "Work Changes" and "Scope Changes".

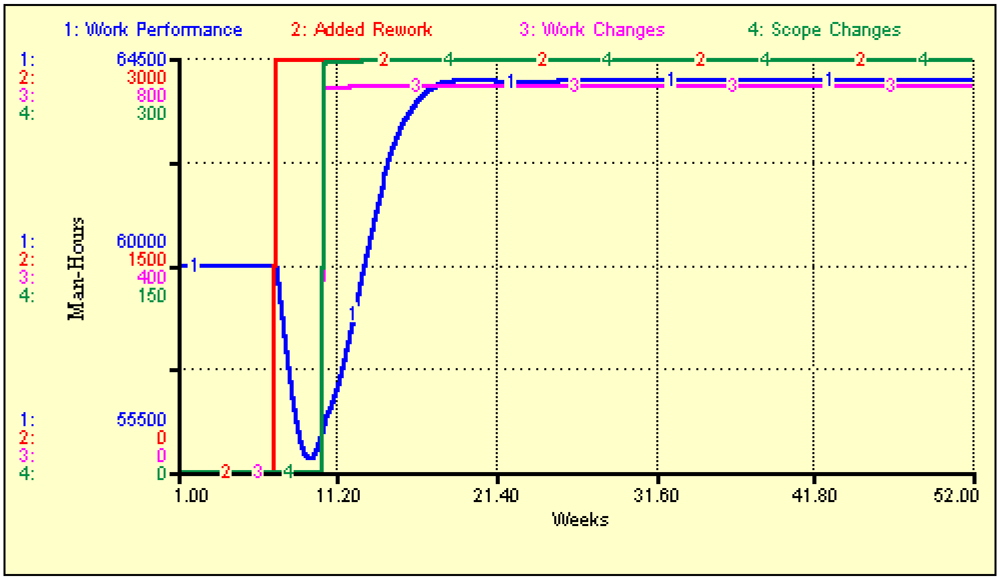

Figure 4-8: The Responding Behavior of the Scope Model.

After the increase in rework, work changes and work scope, “Work Performance” decreases because “Work Rate” steps up together with total work. However, “Labor for Project” has not changed yet. It first takes a certain time to perceive the change in total work as opposed to random noise and to find out the new amount of work. Then, the stock of work performance starts increasing to reach its new equilibrium value.

4.3 Model Sensitivity

4.3.1 Introduction to Model Sensitivity

An important part of understanding model behavior is the identification of parameters to which model behavior is sensitive. These parameters can be the focus of parameter estimation work for model calibration and policy and system design. Model sensitivity to parameters is addressed in this section. The model's sensitivity was tested using one-way and multi-way sensitivity analysis.

Sensitivity analysis of the model requires the investigation of variables which are described with a single numerical value at any time. The number of variables for testing in one-way sensitivity was reduced by eliminating those which do not describe the operation of the real system. Additional reduction was possible in the multi-way sensitivity by taking the parameters that affect the time to reach the equilibrium value and eliminating the parameters that affect the value of the equilibrium.

4.3.2 One-Way Sensitivity Test

After eliminating the variables which do not describe the operation of the real system, seventeen parameters remained in the one-way sensitivity test. Three sets of values were set for the seventeen selected parameters. Each set of values represents a consistent set of conditions. The first set of parameter values represents a pessimistic scenario. A likely scenario estimates the values of a typical project. The third set of values represents an optimistic scenario. The following values, shown in Table 4-1, were assigned for these parameters for the pessimistic, likely and optimistic scenarios to test a certain project behavior. Fifty sets of project input data were generated to test the sensitivity of the model behavior. Each set of project input data has three different scenarios value to test its behavior. A complete listing of the Project Generation is provided in Appendix D.

The focus of this test is to find out which parameter affect the time takes the project performance to return to normal and which parameter affect the amount of work. This Sensitivity Analysis for the project is found in Appendix E. Model sensitivity is the percent loss or improvement of project performance compared to the performance of the likely scenario due to changing a single parameter's value from the likely scenario value. The raw results of these tests are shown in Table 4-2.

Table 4-1: One-Way Sensitivity Test Parameter Values.

Parameter Name	Pessimistic Scenario Value	Likely Scenario Value	Optimistic Scenario Value
Rework Structure			
Initial Work	65,000	60,000	55,000
Added Rework	6%	5%	4%
Time to Average Added Rework	3	2	1
Time to Correct Amount of Work	3	2	1
HR Structure			
Average Quitting Time	90	100	110
Time in Training	20	15	10
Average Hiring Delay	10	8	6
Available Workers	15	16	17
Time to Correct Workers	4	3	2
The Length of Working	5	6	7
Productivity	70%	75%	80%
Client Behavior Structure			
Time to Introduce Changes	9	8	7
Time to Accept Work Changes	3	2	1
Percentage Changes	6%	5%	4%
Scope Structure			
Time to Request Scope Changes	9	8	7
Time to Accept Scope changes	3	2	1
Percentage Scope Changes	3%	2%	1%

Table 4-2: One-Way Sensitivity Test Results.

Parameter Name	Time to Return to Normal (weeks)		
	Pessimistic Scenario Value	Likely Scenario Value	Optimistic Scenario Value
Rework Structure			
Initial Work	____ *	____ *	____ *
Added Rework	____ *	____ *	____ *
Time to Average Added Rework	31.75	26	25
Time to Correct Amount of Work	30.5	26	20.75
HR Structure			
Average Quitting Time	25	24.5	23.25
Time in Training	28.75	26	21.75
Average Hiring Delay	31	26.25	21.5
Available Workers	27	26	22
Time to Correct Workers	28	25.5	21.25
The Length of Working	____ *	____ *	____ *
Productivity	21.5	20.75	20
Client Behavior Structure			
Time to Introduce Changes	____ *	____ *	____ *
Time to Accept Work Changes	____ *	____ *	____ *
Percentage Changes	____ *	____ *	____ *
Scope Structure			
Time to Request Scope Changes	____ *	____ *	____ *
Time to Accept Scope changes	____ *	____ *	____ *
Percentage Scope Changes	____ *	____ *	____ *

*. The change was affecting the amount of work not the time to return to normal.

After testing the fifty projects, eight parameters were found affecting the time to reach the equilibrium value but the others were affecting the amount of work. Five of these eight parameters were significant to study in multi-way sensitivity phase as explained in Appendix E. These five parameters are Time to Average Added Rework, Time to Correct Amount of Work, Available Workers, Time to Correct Workers and Productivity.

4.3.3 Multi-Way Sensitivity Test

A factorial design, specifically a two level (2^5) factorial design, was chosen for this research. There are five factors with two levels. Factorial designs investigate all possible combinations of the levels of factors in each complete trial. These factors are Time to Average Added Rework *(A)*, Time to Correct Amount of Work *(B)*, Available Workers *(C)*, Time to Correct Workers *(D)* and Productivity *(E)*.

The ANOVA can be used to test hypotheses about the main factor effects of the five factors and their interaction. The model and the hypotheses that will be tested are as follows:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \varepsilon \quad \text{(4.1)}$$

1. $H_0: \tau_1 = \tau_2 = 0$ (no main effect of factor *A*)
   H_1: at least one $\tau \neq 0$
2. $H_0: \beta_1 = \beta_2 = 0$ (no main effect of factor *B*)
   H_1: at least one $\beta \neq 0$
3. $H_0: \lambda_1 = \lambda_2 = 0$ (no main effect of factor *C*)
   H_1: at least one $\lambda \neq 0$
4. $H_0: \mu_1 = \mu_2 = 0$ (no main effect of factor *D*)
   H_1: at least one $\mu \neq 0$
5. $H_0: \gamma_1 = \gamma_2 = 0$ (no main effect of factor *E*)
   H_1: at least one $\gamma \neq 0$
6. H_0: *2-way interactions* $= 0$ (no interaction)
   H_1: at least one $\neq 0$
7. H_0: *3-way interactions* $= 0$ (no interaction)
   H_1: at least one $\neq 0$
8. H_0: *4-way interactions* $= 0$ (no interaction)
   H_1: at least one $\neq 0$
9. H_0: *effect of 5-way interactions* $= 0$ (no interaction)
   H_1: *effect of 5-way interactions* $\neq 0$

The multi-way sensitivity test was applied on the fifty generated projects shown in Appendix F. Minitab will analyze 2^5 factorial designs. The output from Minitab DOE module for the same data used in one-way sensitivity test is shown in Table 4-3. This test will use $\alpha = 0.05$.

Table 4-3: Minitab Analysis of Variance Output.

Estimated Effects and Coefficients for Y (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		22.6172	0.04555	496.49	0.000
A	2.6406	1.3203	0.04555	28.98	0.000
B	3.3906	1.6953	0.04555	37.22	0.000
C	0.8281	0.4141	0.04555	9.09	0.000
D	7.4531	3.7266	0.04555	81.80	0.000
E	2.5469	1.2734	0.04555	27.95	0.000
A*B	-0.8281	-0.4141	0.04555	-9.09	0.000
A*C	-0.0781	-0.0391	0.04555	-0.86	0.398
A*D	-1.2031	-0.6016	0.04555	-13.21	0.000
A*E	0.3281	0.1641	0.04555	3.60	0.001
B*C	0.1719	0.0859	0.04555	1.89	0.068
B*D	2.4844	1.2422	0.04555	27.27	0.000
B*E	0.7031	0.3516	0.04555	7.72	0.000
C*D	0.5469	0.2734	0.04555	6.00	0.000
C*E	0.8906	0.4453	0.04555	9.78	0.000
D*E	1.6406	0.8203	0.04555	18.01	0.000
A*B*C	-0.8594	-0.4297	0.04555	-9.43	0.000
A*B*D	-0.9219	-0.4609	0.04555	-10.12	0.000
A*C*D	0.0781	0.0391	0.04555	0.86	0.398
A*B*E	-0.2656	-0.1328	0.04555	-2.92	0.006
A*C*E	0.6094	0.3047	0.04555	6.69	0.000
A*D*E	1.7344	0.8672	0.04555	19.04	0.000
B*C*D	-0.2344	-0.1172	0.04555	-2.57	0.015
B*C*E	-1.7656	-0.8828	0.04555	-19.38	0.000
B*D*E	0.4219	0.2109	0.04555	4.63	0.000
C*D*E	0.9844	0.4922	0.04555	10.80	0.000
A*B*C*D	-0.4531	-0.2266	0.04555	-4.97	0.000
A*B*C*E	0.2031	0.1016	0.04555	2.23	0.033
A*B*D*E	-0.6094	-0.3047	0.04555	-6.69	0.000
A*C*D*E	0.5156	0.2578	0.04555	5.66	0.000
B*C*D*E	-1.2969	-0.6484	0.04555	-14.23	0.000
A*B*C*D*E	-0.1406	-0.0703	0.04555	-1.54	0.133

S = 0.364434   R-Sq = 99.75%   R-Sq(adj) = 99.51%

Analysis of Variance for Y (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	5	1299.05	1299.05	259.810	1956.22	0.000
2-Way Interactions	10	203.63	203.63	20.363	153.32	0.000
3-Way Interactions	10	149.82	149.82	14.982	112.81	0.000
4-Way Interactions	5	41.05	41.05	8.210	61.82	0.000
5-Way Interactions	1	0.32	0.32	0.316	2.38	0.133
Residual Error	32	4.25	4.25	0.133		
Pure Error	32	4.25	4.25	0.133		
Total	63	1698.12				

The upper portion of the table displays the effect estimates and regression coefficients for each factorial effect. The lower panel of the Minitab output is an ANOVA summary focusing on the types of terms in the model. The *P*-values for all the tests statistics are shown in the last column of Table 4-3. Since *P*-value is less than 0.05, the test has strong evidence to conclude that H_0 is not true.

Figure 4-9, shows Pareto chart that orders the bars from largest to smallest. It displays the absolute value of the effects and draws a reference line on the chart. Any effect that extends past this reference line is potentially important. Also, this chart helps to determine which of the effects comprise the "vital few" and the "trivial many". This helps to focus improvement efforts on areas where the largest gains can be made.

Figure 4-10, presents the important residual plots for the Minitab output. The normal probability plot has tails that do not fall exactly along a straight line passing through the center of the plot, indicating some potential problems with the normality assumption, but the deviation from normality does not appear severe.

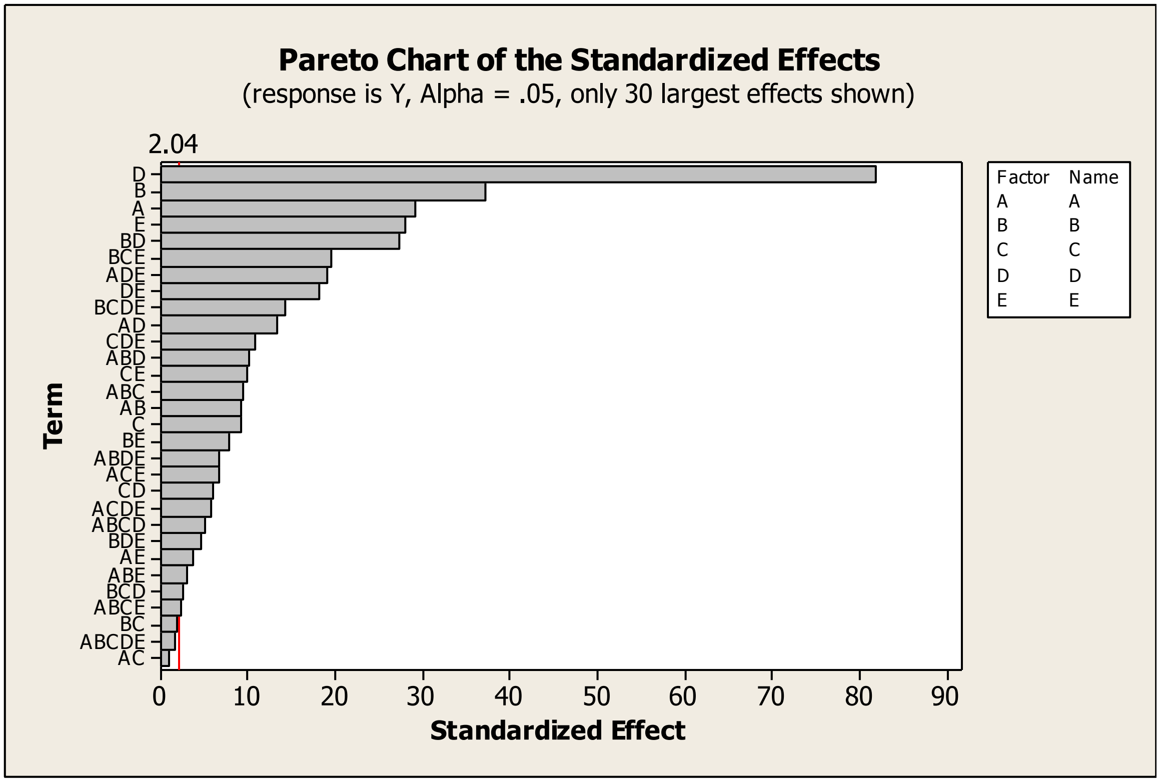

Figure 4-9: The Pareto Chart for the Minitab Output.

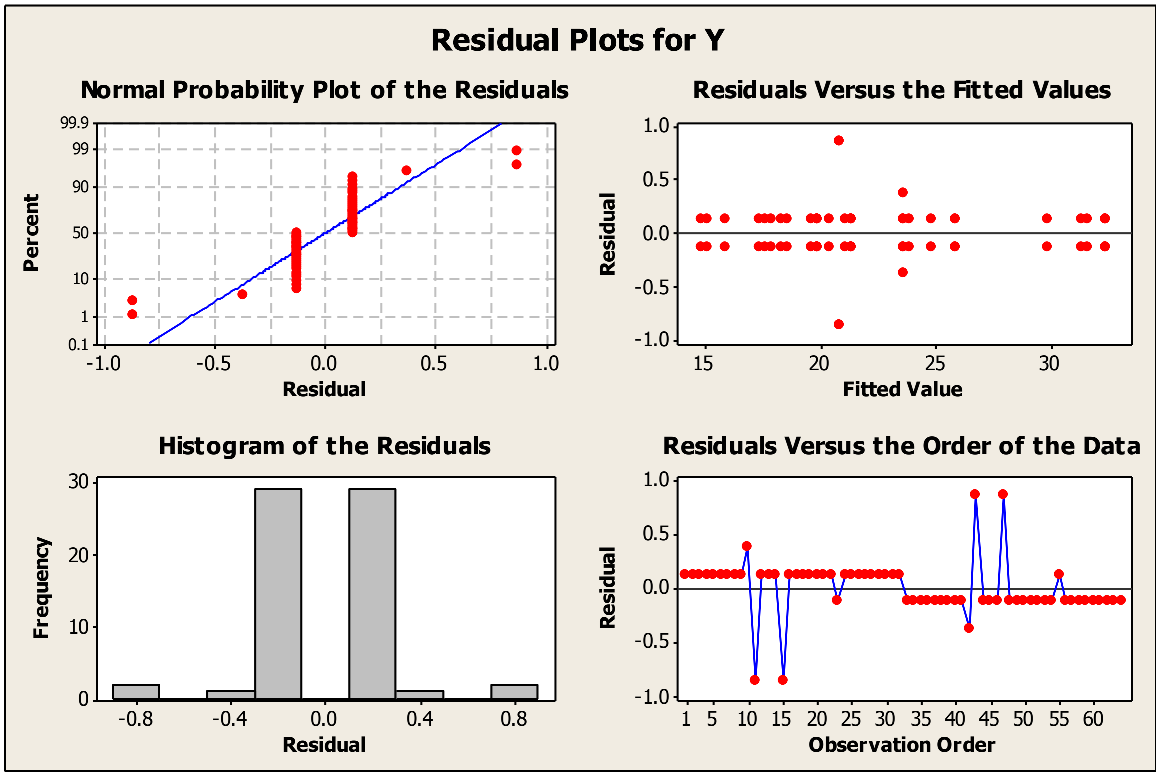

Figure 4-10: The Residual Plots for the Minitab Output.

After testing the multi-way sensitivity for the fifty projects to find out which factor is significant to the project time, it was found that 35 projects were significantly affected by changing in Time to Average Added Rework (Factor *A*). Moreover, 7 projects were affected by changing in Time to Correct Amount of Work (Factor *B*). Four projects and other three projects were affected by changing in Time to Correct Workers (Factor *D*) and Available Workers (Factor *C*), respectively. Finally, one project was affected by the interaction between Time to Correct Amount of Work and Available Workers (Factor *B* and *C*). These results are provided in Appendix F.

4.4 Comparing between SD and Traditional Approaches

4.4.1 The Project Estimations and the Project Work

One of the most relevant differences between traditional and SD approach is the way in which they model the project work. Although both assume that project implementation is based on the process of performing work through the employment of resources, they differ in the level of detail in which the work is considered and in the range of factors they explicitly address.

In the traditional approach tools like Gantt charts and PERT/CPM network, models provide the detailed development of a project schedule which is used for the estimation of the project cost and duration. These models view the project work as a set of work packages (activity) that have to be performed through the use or consumption of resources and according to their precedence relationships. The direct causes of the estimated project cost and duration are considered in detail.

In the SD approach, the project work is modeled under a high level view. It is generally represented by a flow of units of work that change from the initial state “to be done” to the final state “done”, as the staff allocated to the project perform the work. There is no specific considered of what work is done, when and by whom. The traditional WBS is not considered. However, a wide range factors like rework, changes in work-scope, quality, productivity, and motivation, are considered in the model. A SD model does not show in detail the direct causes of the estimated project cost and duration but it considers explicitly the indirect causes that result from the feedback processes, and are often responsible for over-runs.

The fact that both approaches provide estimations for project cost and duration raises a conflict. Traditional models focus on a detailed view of the project work and on evaluating possible alternatives they only assess the direct impacts on cost and time, while the full impact usually includes other higher order effects. This important argument suggests that the estimations provided by traditional models are not accurate and over-runs will occur. SD models focus on the feedback processes and assume a holistic view of the implementation process. On evaluating possible alternatives they consider a wide range of subjective and disruptive factors, but by ignoring the logic of the work structure they may overlook determinant operational issues. Particularly, they assume that the rate of work progress is imposed by the level of staff working in the project. In real projects, issues related to the management of material resources are often critical to the final project cost and duration.

The credibility of traditional models depends on the validity of the underlying assumptions. These are a mean of handling with subjective issues that are not possible to quantify. The weakness of this classic Operational Research approach is that the assumptions often mismatch reality. This is particularly true when the analysis targets a social system. Projects are long term planned actions which are complex, unique and undertaken within a social system. This fact reinforces the insufficiencies of empirical assumptions based on personal experience.

In a PM context, the validation of SD models is based on the accurate reproduction of past cases or other reference modes of behavior. However, a project is unique and is implemented under unique circumstances. This accurate reproduction may not be sufficient to assure accurate forecasting of the behavior of a new project.

4.4.2 The Managerial Needs Addressed

To understand the role of SD approach in PM, it is of major importance to identify the managerial needs it covers in comparison with the traditional approach. In fact, many of these needs are covered by both approaches and although a final judgment about their effectiveness in providing solutions is premature, a comparative analysis may provide important conclusions.

The application of SD models to PM is still at an early stage of development. Unlike in the traditional approach, there is not a well established consistent set of tools and techniques intended to support the project manager throughout the project life-cycle.

For a better understanding of both differences and similarities of the two approaches, the following issues were considered: the nature of the managerial needs, the factors explicitly considered, the basic managerial decision evaluated, the impacts of uncertain events addressed and the project estimations provided. Table 4-4, provides a brief summary of this analysis.

Table 4-4: The Nature of the Managerial Needs Addressed by Both Approaches.

Nature of the Managerial Needs	Traditional Approach	System Dynamics Approach
Specification of the Work	Yes	No
Assignment of Responsibilities to the Work within the Organization	Yes	No
Work Scheduling	Yes	High Level
Resources Management / Scheduling	Yes	High Level
Cost Estimation / Budgeting	Yes	Yes
Project Control / Monitoring	Yes	Yes
Evaluate the Impacts of Decisions	Yes	Yes
Evaluate the Impacts of Uncertain Events	Yes	Yes
Post Mortem Diagnosis	No	Yes

Table 4-4, shows that many of the basic managerial needs are addressed in both approaches. However, it is important to note that the level of detail of the analysis is different; traditional models suggest decisions focused on operational issues, while SD models focus on the strategic issues providing more general directions. SD models ignore the logic of the project work structure but their applicability extends to the diagnosis of historical cases which is particularly useful in supporting dispute resolutions.

CHAPTER FIVE

CONCLUSION

Chapter Five Conclusion

5.1 Conclusions

The model was built to look at the effects of various events and effects on projects. This research used four feedback structures (Rework, Human Resource, Client Behavior and Scope) that represent existing SD models of construction projects. Also, the SD model structure was tested. One-way and multi-way sensitivity analysis was applied to the model to show which parameter was significant to the system behavior. The output of the SD model which this research concerned about was the time it takes the system to return to normal. Therefore, the main objective of this research was to find out which parameter has the most influence on the output of the SD model.

After eliminating the variables which did not describe the operation of the real system, seventeen parameters remained in the one-way sensitivity test. Three sets of values were set for the seventeen selected parameters. Each set of values represents a consistent set of conditions (Pessimistic, Likely and Optimistic scenarios).

Fifty sets of project input data were generated to test the sensitivity of the model behavior. The focus of this test was to find out which parameter affect the time takes the project performance to return to normal and which parameter affect the amount of work.

After testing the fifty projects, eight parameters were found affecting the time to reach the equilibrium value but the others were affecting the amount of work. Five of these eight parameters were significant to study in multi-way sensitivity phase.

These five parameters were Time to Average Added Rework, Time to Correct Amount of Work, Available Workers, Time to Correct Workers and Productivity.

A factorial design was chosen for this research. There were five factors with two levels. Factorial designs investigated all possible combinations of the levels of factors in each complete trial. After testing the multi-way sensitivity for the fifty projects to find out which factor is significant to the project time, it was found that 35 projects were significantly affected by changing in Time to Average Added Rework. Moreover, 7 projects were affected by changing in Time to Correct Amount of Work. Four projects and other three projects were affected by changing in Time to Correct Workers and Available Workers, respectively. Finally, one project was affected by the interaction between Time to Correct Amount of Work and Available Workers.

The weakness of traditional models is that they do not address properly the strategic issues of PM. On the other hand, the weakness of SD models is that they ignore the operational issues suggesting important insights and strategies but no means of how to translate them into operating actions.

It is clear from this brief comparison that SD models emerged in the PM field to provide a systematic analysis of the vital strategic issues of PM. In traditional project management approach, focus was given to the project work structure and as a consequence tools and techniques were developed to support operational decisions. Strategic decisions were left to be answered by rules of thumb and personal experience. This analytical gap is now being filled by SD models.

5.2 Recommendations

SD modeling is a very complete technique and tool that covers a wide range of PM needs. But there needs to be enough understanding and training within the PM team for developing the SD models and incorporating them in the project system. The two approaches will provide valuable complementary information; the traditional technique will supply the detailed output necessary for project control, whereas SD will offer useful general strategic lessons which should be considered when planning the project and producing the estimates for the traditional analyses.

This Thesis has considered the PM system in construction, as a dynamic system, which is subject to both attended and unattended dynamics. It is suggested that emphasis should also be placed on understanding how particular dynamics can hinder the performance of a PM system, so that appropriate actions and responses can be undertaken so as to maximize the effect of positive dynamics and minimize the effect of negative ones.

The research found that development processes significantly impact the dynamic behavior of projects through the feedback, delays and nonlinear relationships which are not used in traditional project models but are important descriptors of project complexity. SD models provide more strategic understanding about the effectiveness of different managerial policies. Also, it offers valuable strategic lessons for PM and should be seen as complementary to the detailed operational support supplied by the traditional techniques. For effective PM, both operational and strategic issues have to be handled properly.

5.3 Future Research

The model presented is a specific phase of Construction PM. It outlines the main features of the complex construction management system and can be used as a framework for policy experimentation since it provides insights and concepts into the feedback structure when working under different management problems and policies.

However, there are several areas for further detailed study in order to achieve better performance of the Construction PM models such as: (1) different categories of manpower requirement and training programs; (2) ways and means to integrate various professions and disciplines with a view to achieve better and more effective teamwork; (3) how equipment and working methods affect project cost, workforce management during construction and materials management; and (4) the management strategy related to workforce and equipment and their interactions.

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Appendix A Causal Loop Diagrams

1. Project Rework Structure:

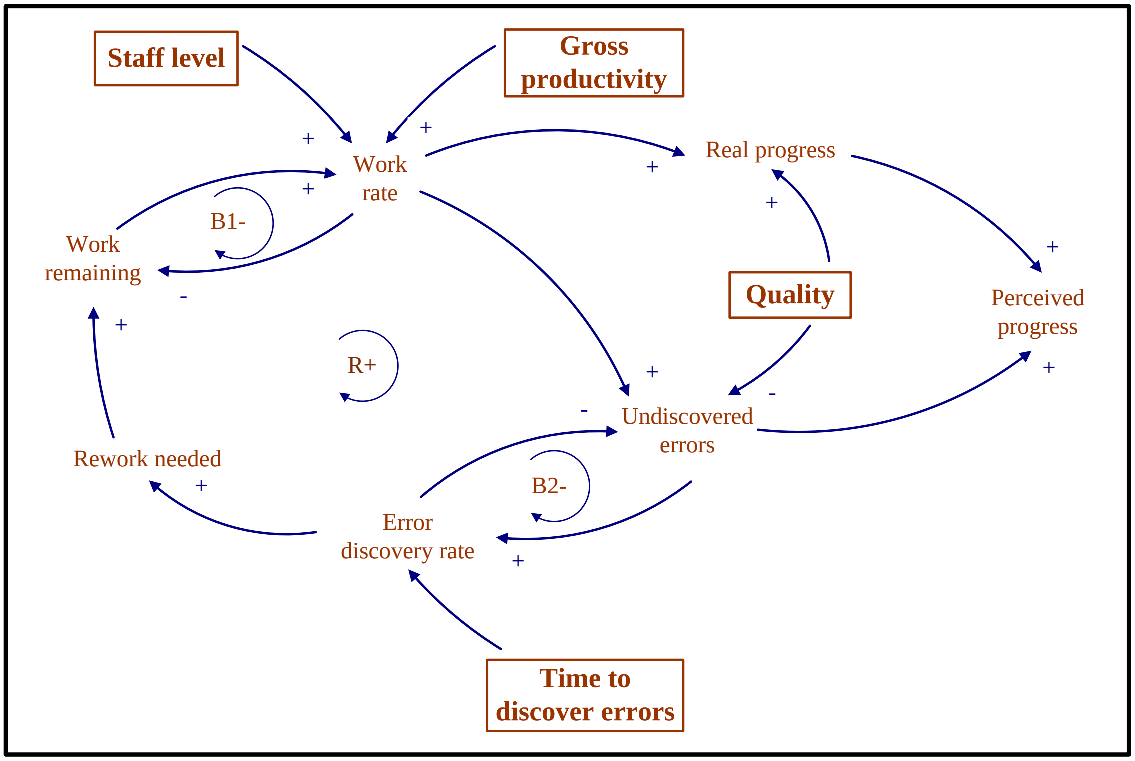

Figure A1: Causal Loop Diagram for the Rework Cycle (Rodrigues and Bowers, 1996).

2. Project Human Resource Structure:

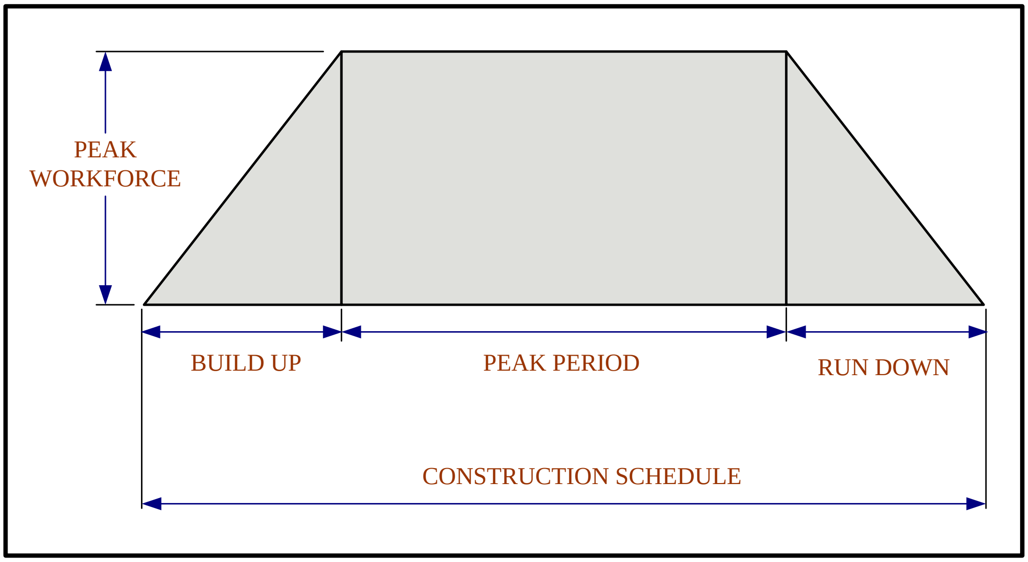

Figure A2: The Three Phases of Construction Duration (Sonawane, 2004).

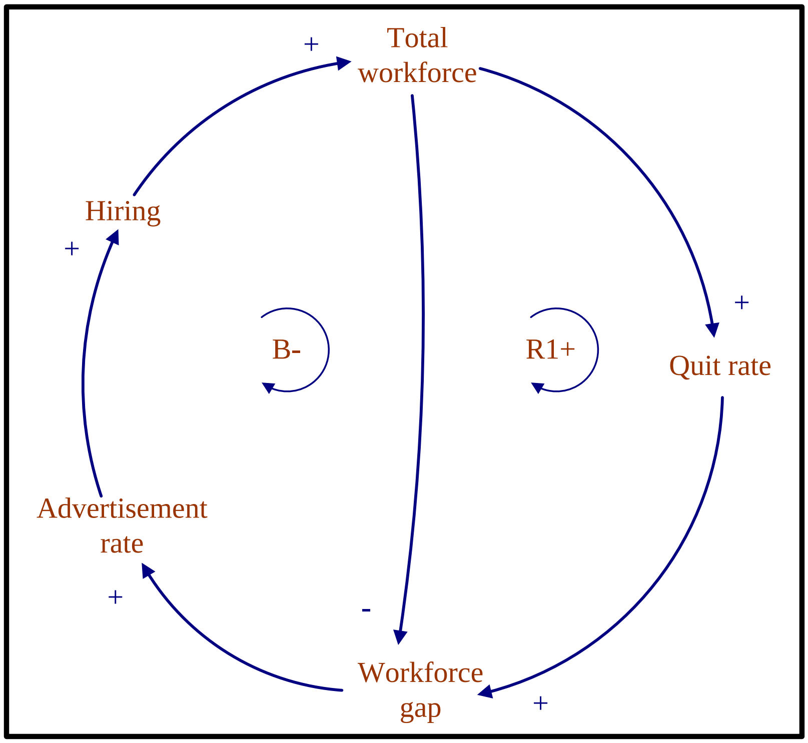

Figure A3: Causal Loop Diagram showing the Hiring Process (Sonawane, 2004).

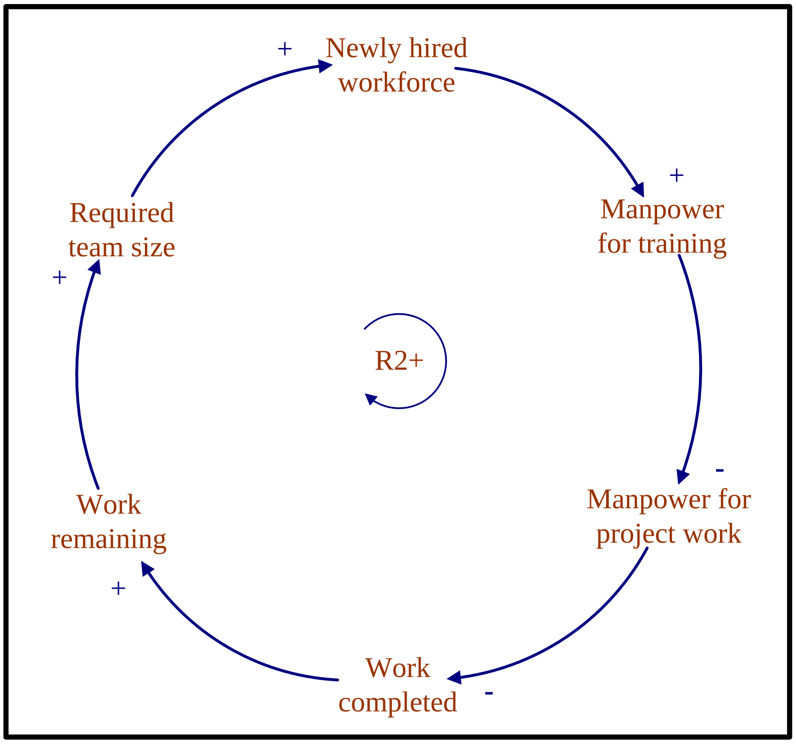

Figure A4: Causal Loop Diagram showing the Hiring Effect (Sonawane, 2004).

3. Client Behavior Structure:

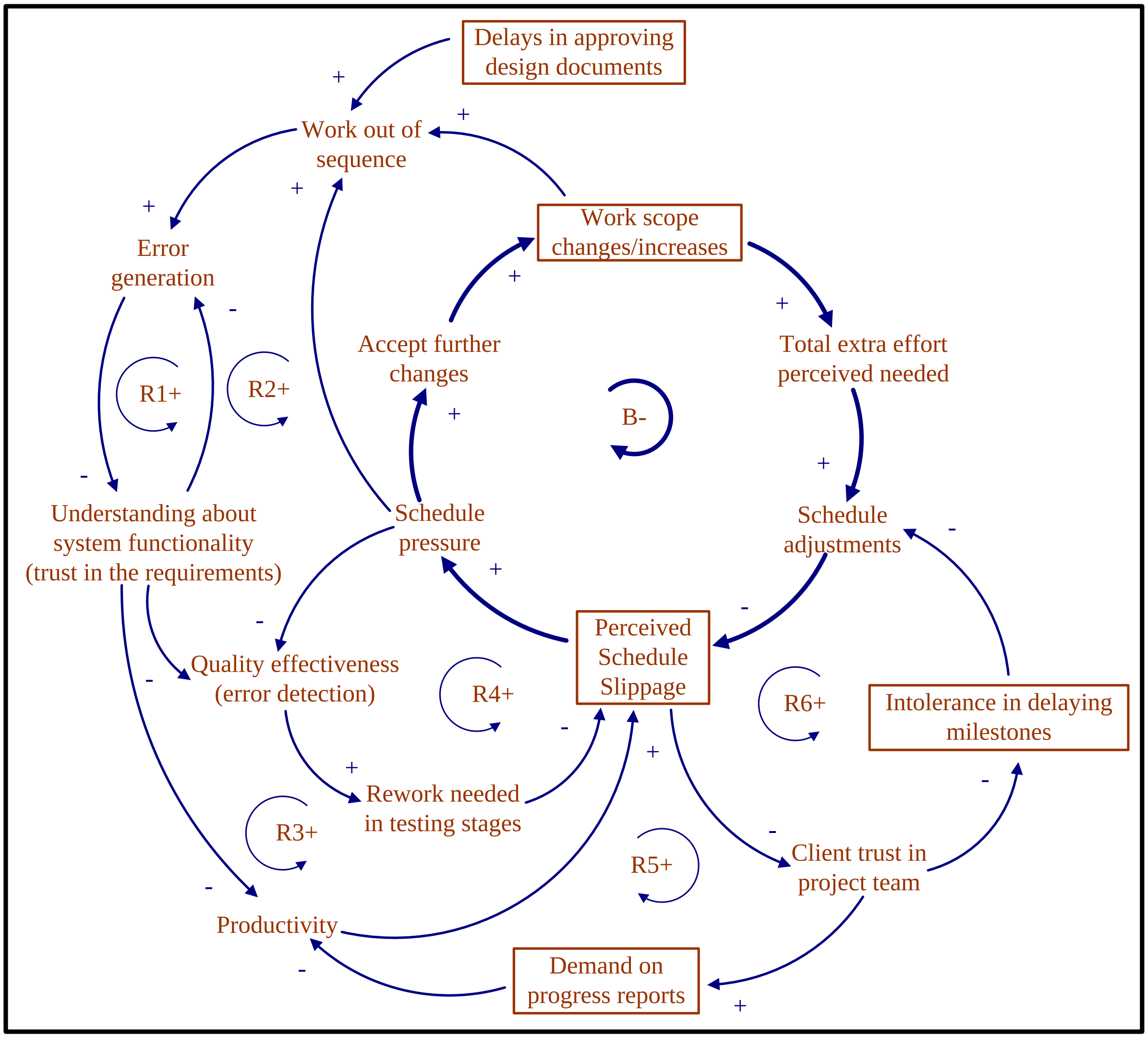

Figure A5: The Detrimental Effects of Client Behavior Exacerbate Schedule Over-runs. (Sonawane, 2004)

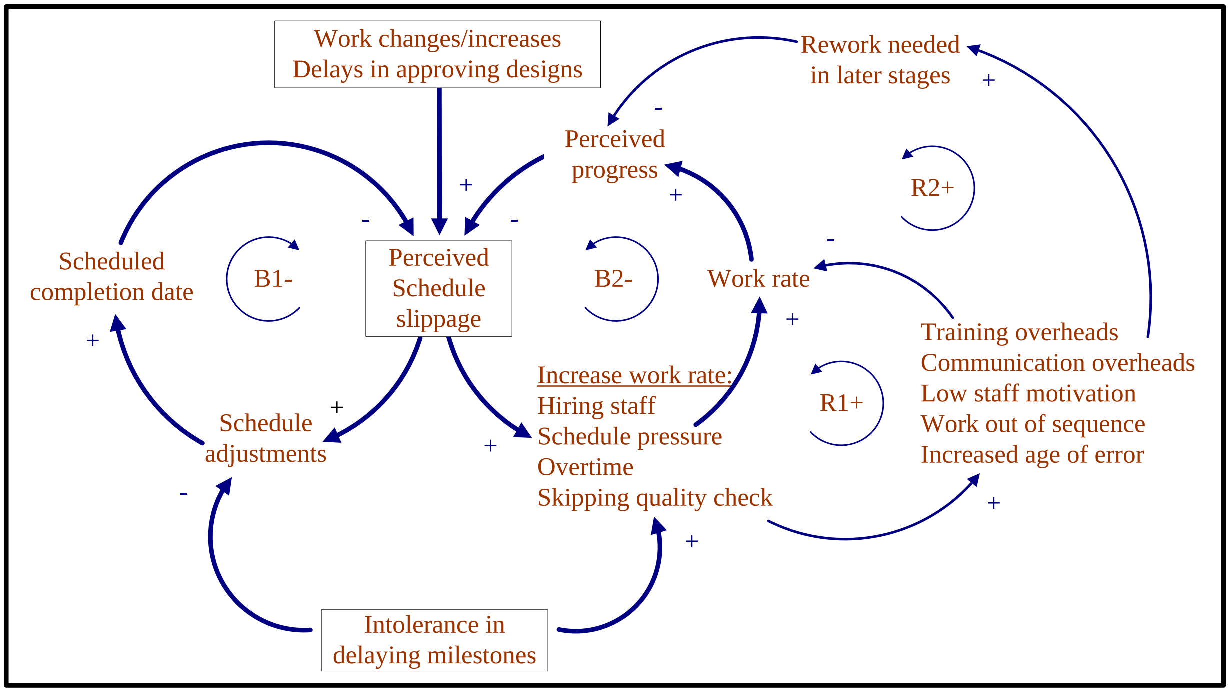

Figure A6: Client Behavior Restricts Control and Exacerbates "Vicious Circles". (Sonawane, 2004)

4. Project Scope Structure:

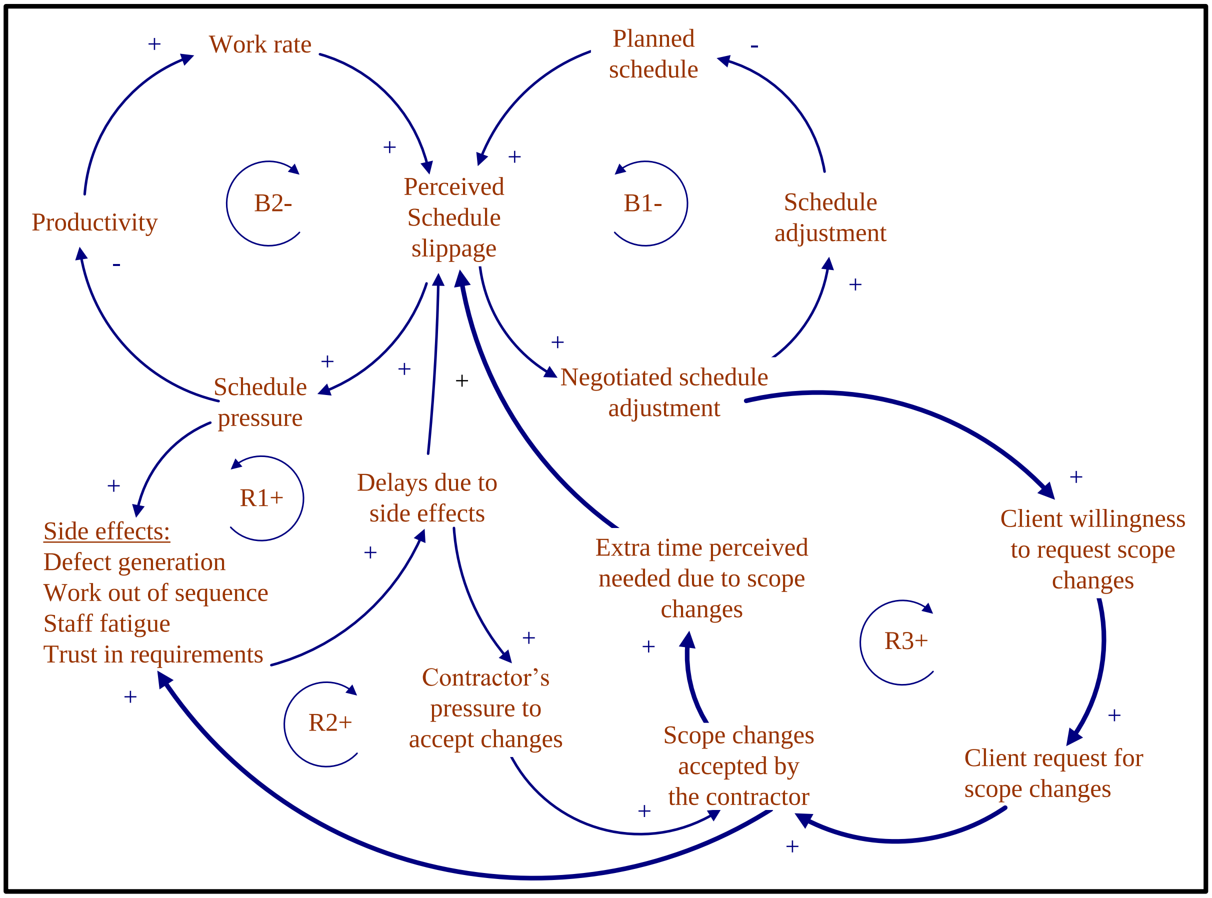

Figure A7: Causal Loop Diagram Focused on Scope Changes (Sonawane, 2004).

Appendix B Model Equations

The Project Rework, HR, Client Behavior and Scope Changes Model:

Expected_Work(t) = Expected_Work(t - dt) + (Changes_in_Work__Expectations) * dt

INIT Expected_Work = Total_work

INFLOWS:

Changes_in_Work__Expectations = (Total_work-Expected_Work)/Time_to_Average_Added_Rework

Experienced_Workforce(t) = Experienced_Workforce(t - dt) + (Training_Rate - Quit_Rate) * dt

INIT Experienced_Workforce = 15

INFLOWS:

Training_Rate = Newly_Hired_Workforce/Time_in_Training

OUTFLOWS:

Quit_Rate = Experienced_Workforce/Average_Quitting_Time

Newly_Hired_Workforce(t) = Newly_Hired_Workforce(t - dt) + (Hiring_Rate - Training_Rate) * dt

INIT Newly_Hired_Workforce = 0

INFLOWS:

Hiring_Rate = Team_Gap/Average_Hiring_Delay

OUTFLOWS:

Training_Rate = Newly_Hired_Workforce/Time_in_Training

Project_Scope_Changes(t) = Project_Scope_Changes(t - dt) + (Scope__Changes_Rate - Changes__Accepted_Rate) * dt

INIT Project_Scope_Changes = 0

INFLOWS:

Scope__Changes_Rate = Client_Request_for__Scope_Changes/Time_to_Request__Scope_Changes

OUTFLOWS:

Changes__Accepted_Rate = Project_Scope_Changes/Time_to_Accept__ Scope_Changes

Project_Work_Changes(t) = Project_Work_Changes(t - dt) + (Work_Changes_Rate - Accepted_Rate) * dt

INIT Project_Work_Changes = 0

INFLOWS:

Work_Changes_Rate = Percentage_Changes/Time_to_Introduce_Changes

OUTFLOWS:

Accepted_Rate = Project_Work_Changes/Time_to_Accepte_Work_Changes

Workers(t) = Workers(t - dt) + (Coming_to_Work - Going_Home) * dt

INIT Workers = Desired_Workers

INFLOWS:

Coming_to_Work = Correction_of_Workers+(Workers/Average_Length_of_Working)

OUTFLOWS:

Going_Home = (Workers/Average_Length_of_Working)

Work_Performance(t) = Work_Performance(t - dt) + (Labor_for_Project - Work_Rate) * dt

INIT Work_Performance = Initial_Work

INFLOWS:

Labor_for_Project = Workers*Productivity

OUTFLOWS:

Work_Rate = MIN(Total_work,Work_Performance/DT)

Accepted_Amount_of__Scope_Changes =

IF(Accept_Scope__Changes_or_Not=1)THEN(Project_Scope_Changes)ELSE(0)

Accepted_Amount__of_Changes =

IF(Accept_Work__Changes_or_Not=1)THEN(Project_Work_Changes)ELSE(0)

Accept_Scope__Changes_or_Not = 1

Accept_Work__Changes_or_Not = 1

Actual_Amount_of_Work = Expected_Work

Actual_Doing_Work = Expected_Work+Correction_in_Amount__of_Work

Added_Rework = STEP(500,5)

Average_Hiring_Delay = 5

Average_Length_of_Working = 8

Average_Quitting_Time = 100

Client_Request_for__Scope_Changes = (Initial_Work*2)/100

Correction_in_Amount__of_Work = (Actual_Amount_of_Work-

Work_Performance)/Time_to_Correct__Amount_of_Work

Correction_of_Workers = ((Desired_Workers-Workers)*Team_Gap)/Time_to_

Correct_Workers

Desired_Workers = Actual_Doing_Work/Productivity

Initial_Work = 33000

Percentage_Changes = (Initial_Work*5)/100

Productivity = 0.75*8*6*52

Scope_Changes = 0+STEP(Accepted_Amount_of__Scope_Changes,Time_

to_Start_Performing_Scope_Changes)

Team_Gap = Desired_Workers-Experienced_Workforce

Time_in_Training = 20

Time_to_Accepte_Work_Changes = 2

Time_to_Accept__Scope_Changes = 2

Time_to_Average_Added_Rework = 2

Time_to_Correct_Workers = 3

Time_to_Correct__Amount_of_Work = 1

Time_to_Introduce_Changes = 8

Time_to_Request__Scope_Changes = 8

Time_to_Start_Doing__Work_Changes =

Time_to_Introduce_Changes+Time_to_Accepte_Work_Changes

Time_to_Start_Performing_Scope_Changes =

Time_to_Request__Scope_Changes+Time_to_Accept__Scope_Changes

Total_work = Initial_Work+Added_Rework+Work_Changes+Scope_Changes

Work_Changes = 0+STEP(Accepted_Amount__of_Changes,Time_

to_Start_Doing__Work_Changes)

Appendix C Model Variables

1. The Project Rework Variables:

- **Work Performance:**

The number of performing work in the project.

- **Labor for Project:**

The amount of effort applied by the project workers.

- **Work Rate:**

The amount of work which is completed along the project life.

- **Expected Work:**

The project work that the workers expect.

- **Change in Work Expectations:**

The rate at which the workers' expectations about work changes.

- **Initial Work:**

The total planned work for the project.

- **Total Work:**

The total amount of work that needs to be completed.

- **Added Rework:**

The amount of rework for the project added to initial work.

- **Correction in Amount of Work:**

The amount of work that the workers perform as a result of a different between the performed and the actual amount of work.

- **Actual Amount of Work:**

The amount of work that has been corrected.

- **Actual Doing Work:**

The rate at which the correction in amount of work is added to the expected work.

- **Time to Average Added Work:**

The time it takes the workers to recognize a permanent change in work.

- **Time to Correct Amount of Work:**

The time in which the workers attempt to correct a difference between the performed and the actual amount of work.

2. The Project Human Resource Variables:

- **Workers:**

The number of workers currently working in the project.

- **Coming to Work:**

The rate at which workers comes to work.

- **Going Home:**

The rate at which the workers leave the project to go home.

- **Average Length of Working:**

The number of day(s) that a worker spends working in the week.

- **Correction of Workers:**

The number of workers who come to the project as a result of a difference between the desired and the actual number of workers.

- **Productivity:**

The average efficiency of the workers in the project life.

- **Desired Workers:**

The number of workers who must be working in the project.

- **Time to Correct Workers:**

The time it takes the manager to correct the number of workers.

- **Experienced Workforce:**

The number of employees capable for working by their own.

- **Newly Hired Workforce:**

The most recently hired members of workforce and thereby have no experience.

- **Team Gap:**

The difference between the number of employees required and that already employed.

- **Hiring Rate:**

The rate at which new employees are hired.

- **Average Hiring Delay:**

The average number of days it takes to interview and actually hired new employees.

- **Training Rate:**

The rate at which new employees graduate into experienced workforce.

- **Time in Training:**

The length of time it takes on the average to give new employed workers the necessary experience that required becoming part of the experienced workforce.

- **Quit Rate:**

The rate at which new employees are quitting, no one quits at first.

- **Average Quitting Time:**

The average time of employees quitting.

3. The Client Behavior Variables:

- **Project Work Changes:**

The amount of work changes accepted by the manager which affect the time of the project.

- **Work Changes Rate:**

The rate at which changes occur or are introduced during the project.

- **Accepted Rate:**

The rate at which work changes accepted during the project.

- **Time to Introduce Changes:**

The average time constant during which changes occur or introduced by the client.

- **Time to Accepted Work Changes:**

The average time required to accept work changes by the manger.

- **Time to Start Doing Work Changes:**

The average time required to start the extra work which equal to the time to introduced changes plus time to accept work changes.

- **Accept Work Changes or Not:**

The decision that the manager take to accept (1) or reject (0) the work changes.

- **Accepted Amount of Changes:**

The amount of work changes that is accepted and added to the total work.

- **Work Changes:**

The amount of work changes added to the total work in specific time of the project life.

4. The Project Scope Variables:

- **Project Scope Changes:**

The extra work which was not included in the original scope of work for the project.

- **Scope Changes Rate:**

The rate at which the additional work is introduced in project life cycle by client or contractor, which is not a part of the original scope of work.

- **Changes Accepted Rate:**

The rate at which the extra work is approved by the client or accepted by the contractor on the project.

- **Time to Request Scope Changes:**

The average time taken to introduce this additional work by any of the project parties.

- **Time to Accept Scope Changes:**

The average time required to accept the extra work to be completed for the project.

- **Time to Start Performing Scope Changes:**

The average time required to start the extra work which equal to the time to request scope changes plus time to accept scope changes.

- **Accept Scope Changes or Not:**

The decision that the manager take to accept (1) or reject (0) the scope changes.

- **Accepted Amount of Scope Changes:**

The amount of scope changes that is accepted and added to the total work.

- **Scope Changes:**

The amount of scope changes added to the total work in specific time of the project life.

Appendix D Random Generation of Projects

		Project Number									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Project Inputs	**Initial Work** (man-hours)	60000	55000	42300	11500	23456	30300	86500	14577	95000	10000
	Added Rework (%)	5.0	4.0	7.0	2.7	7.7	5.5	10.0	7.5	5.0	2.0
	Time to Average Added Rework (weeks)	2.0	3.0	3.0	1.5	3.6	2.9	2.2	3.3	3.0	1.0
	Time to Correct Amount of Work (weeks)	2.0	1.0	2.0	1.0	2.3	2.1	2.2	3.0	1.0	2.0
	Average Quitting Time (days)	100.0	120.0	110.0	95.0	88.0	150.0	120.0	122.0	120.0	100.0
	Time in Training (days)	15.0	30.0	10.0	14.0	13.0	20.0	15.0	20.0	14.0	17.0
	Average Hiring Delay (days)	8.0	10.0	9.0	9.0	7.0	10.0	12.0	12.0	10.0	15.0
	Available Workers (workers)	16.0	15.0	16.0	15.0	14.0	14.0	16.0	13.0	16.0	13.0
	Time to Correct Workers (days)	3.0	2.0	3.0	2.0	4.1	2.9	2.0	3.3	3.0	2.0
	Length of Working (days)	6.0	6.0	7.0	7.0	7.0	7.0	6.0	7.0	6.0	6.0
	Productivity (%)	75.0	75.0	80.0	88.0	89.0	78.0	75.0	79.0	88.0	75.0
	Time to Introduce Changes (weeks)	8.0	7.0	3.0	5.5	5.3	6.0	0.0	6.2	0.0	9.0
	Time to Accept Work Changes (weeks)	2.0	2.0	1.0	1.5	1.8	1.3	0.0	1.1	0.0	1.0
	Percentage Changes (%)	5.0	4.0	3.5	3.5	3.3	5.0	0.0	1.9	0.0	3.0
	Time to Request Scope Changes (weeks)	8.0	7.0	2.0	4.5	3.5	0.0	0.0	4.7	0.0	9.0
	Time to Accept Scope Changes (weeks)	2.0	2.0	1.0	2.0	1.5	0.0	0.0	2.9	0.0	1.0
	Percentage Scope Changes (%)	2.0	2.0	1.5	3.5	2.2	0.0	0.0	2.3	0.0	3.0

		Project Number									
		11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Project Inputs	**Initial Work** (man-hours)	20000	100000	80000	56789	13555	30300	72320	95000	66555	22334
	Added Rework (%)	3.0	4.0	4.5	8.0	5.4	5.5	5.0	5.0	6.5	10.0
	Time to Average Added Rework (weeks)	4.0	6.0	2.0	4.0	4.2	2.9	2.0	3.0	2.0	1.8
	Time to Correct Amount of Work (weeks)	1.0	2.0	1.0	2.0	1.9	2.1	3.0	1.0	1.0	2.3
	Average Quitting Time (days)	90.0	90.0	110.0	150.0	113.0	150.0	170.0	120.0	170.0	101.0
	Time in Training (days)	15.0	15.0	13.0	17.0	18.0	20.0	18.0	14.0	25.0	18.0
	Average Hiring Delay (days)	12.0	10.0	8.0	6.0	12.0	10.0	11.0	10.0	13.0	9.0
	Available Workers (workers)	14.0	17.0	17.0	17.0	14.0	14.0	17.0	16.0	17.0	11.0
	Time to Correct Workers (days)	2.0	3.0	2.0	4.0	2.7	2.9	2.0	3.0	3.0	2.7
	Length of Working (days)	6.0	6.0	7.0	6.0	7.0	7.0	6.0	6.0	6.0	7.0
	Productivity (%)	75.0	75.0	79.0	86.0	83.0	78.0	84.0	88.0	80.0	81.0
	Time to Introduce Changes (weeks)	6.0	8.0	0.0	7.0	4.8	0.0	6.0	5.0	0.0	4.3
	Time to Accept Work Changes (weeks)	2.0	2.0	0.0	1.5	2.2	0.0	1.0	1.0	0.0	1.8
	Percentage Changes (%)	2.0	3.0	0.0	3.5	4.4	0.0	4.0	4.0	0.0	3.9
	Time to Request Scope Changes (weeks)	6.0	8.0	0.0	2.5	3.9	0.0	0.0	5.0	0.0	2.2
	Time to Accept Scope Changes (weeks)	2.0	2.0	0.0	1.5	2.6	0.0	0.0	2.0	0.0	1.1
	Percentage Scope Changes (%)	2.0	2.0	0.0	1.5	2.6	0.0	0.0	3.0	0.0	2.0

Project Inputs	Project Number									
	21	22	23	24	25	26	27	28	29	30
Initial Work (man-hours)	10000	99990	70000	12000	30300	54320	86500	66555	100000	50000
Added Rework (%)	3.0	3.5	7.0	2.2	5.5	6.6	10.0	6.5	7.0	1.0
Time to Average Added Rework (weeks)	3.0	5.0	2.0	2.5	2.9	1.9	2.2	2.0	1.0	3.0
Time to Correct Amount of Work (weeks)	1.0	2.0	2.0	1.5	2.1	2.3	2.2	1.0	1.0	3.0
Average Quitting Time (days)	80.0	100.0	117.0	108.0	150.0	110.0	120.0	170.0	145.0	105.0
Time in Training (days)	13.0	14.0	17.0	19.0	20.0	18.0	15.0	25.0	23.0	15.0
Average Hiring Delay (days)	8.0	9.0	7.0	12.0	10.0	8.0	12.0	13.0	10.0	11.0
Available Workers (workers)	13.0	15.0	17.0	13.0	14.0	15.0	16.0	17.0	18.0	15.0
Time to Correct Workers (days)	2.0	2.5	2.0	2.5	2.9	3.2	2.0	3.0	2.0	4.0
Length of Working (days)	6.0	6.0	7.0	7.0	7.0	6.0	6.0	6.0	6.0	6.0
Productivity (%)	80.0	87.0	77.0	80.0	78.0	80.0	75.0	80.0	82.0	75.0
Time to Introduce Changes (weeks)	0.0	8.0	7.0	7.0	6.0	0.0	3.8	7.0	0.0	9.0
Time to Accept Work Changes (weeks)	0.0	1.0	1.0	1.9	1.3	0.0	1.5	2.0	0.0	1.0
Percentage Changes (%)	0.0	4.5	3.0	1.9	5.0	0.0	2.5	3.0	0.0	5.0
Time to Request Scope Changes (weeks)	0.0	6.0	6.0	5.8	4.4	0.0	0.0	6.0	0.0	9.0
Time to Accept Scope Changes (weeks)	0.0	2.0	2.0	2.1	2.1	0.0	0.0	1.0	0.0	1.0
Percentage Scope Changes (%)	0.0	2.5	2.5	2.8	1.7	0.0	0.0	2.0	0.0	1.0

Project Inputs	Project Number 31	32	33	34	35	36	37	38	39	40
Initial Work (man-hours)	100000	78910	86500	54320	10000	80000	72320	66555	10000	60000
Added Rework (%)	7.0	6.0	10.0	6.6	3.0	4.5	5.0	6.5	2.0	0.0
Time to Average Added Rework (weeks)	1.0	1.0	2.2	1.9	3.0	2.0	2.0	2.0	1.0	3.0
Time to Correct Amount of Work (weeks)	1.0	1.0	2.2	2.3	1.0	1.0	3.0	1.0	2.0	2.0
Average Quitting Time (days)	145.0	95.0	120.0	110.0	80.0	110.0	170.0	170.0	100.0	90.0
Time in Training (days)	23.0	12.0	15.0	18.0	13.0	13.0	18.0	25.0	17.0	18.0
Average Hiring Delay (days)	10.0	11.0	12.0	8.0	8.0	8.0	11.0	13.0	15.0	11.0
Available Workers (workers)	18.0	17.0	16.0	15.0	13.0	17.0	17.0	17.0	13.0	18.0
Time to Correct Workers (days)	2.0	2.0	2.0	3.2	2.0	2.0	2.0	3.0	2.0	4.0
Length of Working (days)	6.0	6.0	6.0	6.0	6.0	7.0	6.0	6.0	6.0	6.0
Productivity (%)	82.0	78.0	75.0	80.0	80.0	79.0	84.0	80.0	75.0	75.0
Time to Introduce Changes (weeks)	7.0	8.0	3.8	7.2	4.0	5.0	6.0	0.0	0.0	7.0
Time to Accept Work Changes (weeks)	2.0	1.0	1.5	2.3	2.0	1.0	1.0	0.0	0.0	1.0
Percentage Changes (%)	1.0	4.0	2.5	2.3	2.0	2.5	4.0	0.0	0.0	3.0
Time to Request Scope Changes (weeks)	9.0	9.0	4.0	0.0	3.0	0.0	6.0	6.0	0.0	0.0
Time to Accept Scope Changes (weeks)	2.0	2.0	2.0	0.0	2.0	0.0	1.0	1.0	0.0	0.0
Percentage Scope Changes (%)	1.0	2.0	2.0	0.0	2.0	0.0	4.0	2.0	0.0	0.0

Project Inputs	Project Number									
	41	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	**50**
Initial Work (man-hours)	10000	80000	54320	72320	60000	78910	100000	66555	72320	80000
Added Rework (%)	3.0	4.5	6.6	5.0	0.0	6.0	7.0	6.5	5.0	4.5
Time to Average Added Rework (weeks)	3.0	2.0	1.9	2.0	3.0	1.0	1.0	2.0	2.0	2.0
Time to Correct Amount of Work (weeks)	1.0	1.0	2.3	3.0	2.0	1.0	1.0	1.0	3.0	1.0
Average Quitting Time (days)	80.0	110.0	110.0	170.0	90.0	95.0	145.0	170.0	170.0	110.0
Time in Training (days)	13.0	13.0	18.0	18.0	18.0	12.0	23.0	25.0	18.0	13.0
Average Hiring Delay (days)	8.0	8.0	8.0	11.0	11.0	11.0	10.0	13.0	11.0	8.0
Available Workers (workers)	13.0	17.0	15.0	17.0	18.0	17.0	18.0	17.0	17.0	17.0
Time to Correct Workers (days)	2.0	2.0	3.2	2.0	4.0	2.0	2.0	3.0	2.0	2.0
Length of Working (days)	6.0	7.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	7.0
Productivity (%)	80.0	79.0	80.0	84.0	75.0	78.0	82.0	80.0	84.0	79.0
Time to Introduce Changes (weeks)	4.0	0.0	7.2	0.0	7.0	0.0	7.0	7.0	0.0	5.0
Time to Accept Work Changes (weeks)	2.0	0.0	2.3	0.0	1.0	0.0	2.0	2.0	0.0	1.0
Percentage Changes (%)	2.0	0.0	2.3	0.0	3.0	0.0	1.0	3.0	0.0	2.5
Time to Request Scope Changes (weeks)	0.0	5.0	7.2	0.0	9.0	0.0	0.0	0.0	6.0	5.0
Time to Accept Scope Changes (weeks)	0.0	1.0	2.3	0.0	2.0	0.0	0.0	0.0	1.0	1.0
Percentage Scope Changes (%)	0.0	2.5	2.3	0.0	2.0	0.0	0.0	0.0	4.0	2.5

Appendix E One-Way Sensitivity Test

Project Number		Project Parameters							
		Time to Average Added Rework	Time to Correct Amount of Work	Average Quitting Time	Time in Training	Average Hiring Delay	Available Workers	Time to Correct Workers	Productivity
1	Pessimistic	3.0	3.0	90.0	20.0	10.0	15.0	4.0	70.0
	Likely	2.0	2.0	100.0	15.0	8.0	16.0	3.0	75.0
	Optimistic	1.0	1.0	110.0	10.0	6.0	17.0	2.0	80.0
2	Pessimistic	4.0	1.5	110.0	35.0	12.0	14.0	3.0	70.0
	Likely	3.0	1.0	120.0	30.0	10.0	15.0	2.0	75.0
	Optimistic	2.0	0.5	130.0	25.0	8.0	16.0	1.0	80.0
3	Pessimistic	4.0	3.0	100.0	15.0	11.0	15.0	4.0	75.0
	Likely	3.0	2.0	110.0	10.0	9.0	16.0	3.0	80.0
	Optimistic	2.0	1.0	120.0	5.0	7.0	17.0	2.0	85.0
4	Pessimistic	2.0	1.5	90.0	18.0	11.0	14.0	3.0	86.0
	Likely	1.5	1.0	95.0	14.0	9.0	15.0	2.0	88.0
	Optimistic	1.0	0.5	100.0	10.0	7.0	16.0	1.0	90.0
5	Pessimistic	4.2	2.6	80.0	16.0	8.0	13.0	5.0	85.0
	Likely	3.6	2.3	88.0	13.0	7.0	14.0	4.1	89.0
	Optimistic	3.0	2.0	96.0	10.0	6.0	15.0	3.2	93.0
6	Pessimistic	3.9	3.1	140.0	25.0	12.0	13.0	3.9	76.0
	Likely	2.9	2.1	150.0	20.0	10.0	14.0	2.9	78.0
	Optimistic	1.9	4.1	160.0	15.0	8.0	15.0	1.9	80.0
7	Pessimistic	2.4	2.4	100.0	17.0	13.0	15.0	2.5	70.0
	Likely	2.2	2.2	120.0	15.0	12.0	16.0	2.0	75.0
	Optimistic	2.0	2.0	140.0	13.0	11.0	17.0	1.5	80.0
8	Pessimistic	3.6	4.0	112.0	21.0	13.0	12.0	3.6	78.0
	Likely	3.3	3.0	122.0	20.0	12.0	13.0	3.3	79.0
	Optimistic	3.0	2.0	132.0	19.0	11.0	14.0	3.0	80.0
9	Pessimistic	4.0	1.5	100.0	18.0	12.0	14.0	4.0	86.0
	Likely	3.0	1.0	120.0	14.0	10.0	16.0	3.0	88.0
	Optimistic	2.0	0.5	140.0	10.0	8.0	18.0	2.0	90.0
10	Pessimistic	1.2	3.0	90.0	20.0	20.0	11.0	3.0	70.0
	Likely	1.0	2.0	100.0	17.0	15.0	13.0	2.0	75.0
	Optimistic	0.8	1.0	110.0	14.0	10.0	15.0	1.0	80.0

Project Number			Project Parameters							
			Time to Average Added Rework	Time to Correct Amount of Work	Average Quitting Time	Time in Training	Average Hiring Delay	Available Workers	Time to Correct Workers	Productivity
	11	Pessimistic	4.2	1.3	80.0	17.0	14.0	12.0	2.2	74.0
		Likely	4.0	1.0	90.0	15.0	12.0	14.0	2.0	75.0
		Optimistic	3.8	0.7	100.0	13.0	10.0	16.0	1.8	76.0
	12	Pessimistic	7.0	3.0	85.0	17.0	12.0	16.0	4.0	70.0
		Likely	6.0	2.0	90.0	15.0	10.0	17.0	3.0	75.0
		Optimistic	5.0	1.0	95.0	13.0	8.0	18.0	2.0	80.0
	13	Pessimistic	3.0	1.5	100.0	15.0	9.0	16.0	3.0	73.0
		Likely	2.0	1.0	110.0	13.0	8.0	17.0	2.0	79.0
		Optimistic	1.0	0.5	120.0	14.0	7.0	18.0	1.0	85.0
	14	Pessimistic	4.3	3.0	140.0	18.0	7.0	16.0	4.2	85.0
		Likely	4.0	2.0	150.0	17.0	6.0	17.0	4.0	86.0
		Optimistic	3.7	1.0	160.0	16.0	5.0	18.0	3.8	87.0
	15	Pessimistic	4.4	2.8	100.0	20.0	13.0	12.0	3.4	80.0
		Likely	4.2	1.9	113.0	18.0	12.0	14.0	2.7	83.0
		Optimistic	4.0	1.0	126.0	16.0	11.0	16.0	2.0	86.0
	16	Pessimistic	3.9	3.1	140.0	22.0	11.0	13.0	3.9	76.0
		Likely	2.9	2.1	150.0	20.0	10.0	14.0	2.9	78.0
		Optimistic	1.9	1.1	160.0	18.0	9.0	15.0	1.9	80.0
	17	Pessimistic	3.0	4.0	150.0	21.0	12.0	16.0	3.0	83.0
		Likely	2.0	3.0	170.0	18.0	11.0	17.0	2.0	84.0
		Optimistic	1.0	2.0	190.0	15.0	10.0	18.0	1.0	85.0
	18	Pessimistic	2.0	1.5	100.0	16.0	11.0	15.0	4.0	87.0
		Likely	3.0	1.0	120.0	14.0	10.0	16.0	3.0	88.0
		Optimistic	1.0	0.5	140.0	12.0	9.0	17.0	2.0	89.0
	19	Pessimistic	3.0	1.6	150.0	30.0	14.0	16.0	4.0	75.0
		Likely	2.0	1.0	170.0	25.0	13.0	17.0	3.0	80.0
		Optimistic	1.0	0.4	190.0	20.0	12.0	18.0	2.0	85.0
	20	Pessimistic	2.0	2.6	90.0	17.0	10.0	10.0	3.0	75.0
		Likely	1.8	2.3	101.0	18.0	9.0	11.0	2.7	81.0
		Optimistic	1.6	2.0	122.0	19.0	8.0	12.0	2.4	87.0

Project Number		Project Parameters: Time to Average Added Rework	Time to Correct Amount of Work	Average Quitting Time	Time in Training	Average Hiring Delay	Available Workers	Time to Correct Workers	Productivity
21	**Pessimistic**	4.0	1.5	70.0	16.0	9.0	12.0	3.0	75.0
	Likely	3.0	1.0	80.0	13.0	8.0	13.0	2.0	80.0
	Optimistic	2.0	0.5	90.0	10.0	7.0	14.0	1.0	85.0
22	**Pessimistic**	5.1	3.0	90.0	15.0	10.0	14.0	3.0	84.0
	Likely	5.0	2.0	100.0	14.0	9.0	15.0	2.5	87.0
	Optimistic	4.9	1.0	110.0	13.0	8.0	16.0	2.0	90.0
23	**Pessimistic**	3.0	3.0	100.0	19.0	8.0	16.0	3.0	74.0
	Likely	2.0	2.0	117.0	17.0	7.0	17.0	2.0	77.0
	Optimistic	1.0	1.0	134.0	15.0	6.0	18.0	1.0	80.0
24	**Pessimistic**	3.0	2.0	100.0	20.0	13.0	12.0	3.0	75.0
	Likely	2.5	1.5	108.0	19.0	12.0	13.0	2.5	80.0
	Optimistic	2.0	1.0	116.0	18.0	11.0	14.0	2.0	85.0
25	**Pessimistic**	3.0	2.2	130.0	22.0	11.0	13.0	3.0	76.0
	Likely	2.9	2.1	150.0	20.0	10.0	14.0	2.9	78.0
	Optimistic	2.8	2.0	180.0	18.0	9.0	15.0	2.8	80.0
26	**Pessimistic**	2.9	3.3	80.0	22.0	10.0	13.0	3.4	79.0
	Likely	1.9	2.3	110.0	18.0	8.0	15.0	3.2	80.0
	Optimistic	0.9	1.3	140.0	14.0	6.0	17.0	3.0	81.0
27	**Pessimistic**	3.2	3.2	110.0	16.0	13.0	14.0	3.0	73.0
	Likely	2.2	2.2	120.0	15.0	12.0	16.0	2.0	75.0
	Optimistic	1.2	1.2	130.0	14.0	11.0	18.0	1.0	77.0
28	**Pessimistic**	3.0	1.5	160.0	26.0	14.0	16.0	4.0	78.0
	Likely	2.0	1.0	170.0	25.0	13.0	17.0	3.0	80.0
	Optimistic	1.0	0.5	180.0	24.0	12.0	18.0	2.0	82.0
29	**Pessimistic**	1.3	1.2	130.0	25.0	11.0	16.0	2.2	80.0
	Likely	1.0	1.0	145.0	23.0	10.0	18.0	2.0	82.0
	Optimistic	0.7	0.8	160.0	21.0	9.0	20.0	1.8	84.0
30	**Pessimistic**	4.0	4.0	90.0	16.0	12.0	12.0	5.0	70.0
	Likely	3.0	3.0	105.0	15.0	11.0	15.0	4.0	75.0
	Optimistic	2.0	2.0	120.0	14.0	10.0	18.0	3.0	80.0

Project Number		Scenario	Time to Average Added Rework	Time to Correct Amount of Work	Average Quitting Time	Time in Training	Average Hiring Delay	Available Workers	Time to Correct Workers	Productivity
			Project Parameters							
	31	Pessimistic	1.3	1.5	130.0	25.0	13.0	17.0	2.5	78.0
		Likely	1.0	1.0	145.0	23.0	10.0	18.0	2.0	82.0
		Optimistic	0.7	0.5	160.0	21.0	7.0	19.0	1.5	86.0
	32	Pessimistic	1.5	1.4	90.0	15.0	13.0	16.0	3.0	74.0
		Likely	1.0	1.0	95.0	12.0	11.0	17.0	2.0	78.0
		Optimistic	0.5	0.6	100.0	9.0	9.0	18.0	1.0	82.0
	33	Pessimistic	3.2	3.2	100.0	17.0	13.0	15.0	2.5	70.0
		Likely	2.2	2.2	120.0	15.0	12.0	16.0	2.0	75.0
		Optimistic	1.2	1.2	140.0	13.0	11.0	17.0	1.5	80.0
	34	Pessimistic	2.9	2.6	90.0	20.0	10.0	14.0	4.2	78.0
		Likely	1.9	2.3	110.0	18.0	8.0	15.0	3.2	80.0
		Optimistic	0.9	2.0	130.0	16.0	6.0	16.0	2.2	82.0
	35	Pessimistic	3.5	1.5	70.0	15.0	9.0	12.0	3.0	76.0
		Likely	3.0	1.0	80.0	13.0	8.0	13.0	2.0	80.0
		Optimistic	2.5	0.5	90.0	11.0	7.0	15.0	1.0	84.0
	36	Pessimistic	3.0	1.5	100.0	15.0	10.0	16.0	3.0	73.0
		Likely	2.0	1.0	110.0	13.0	8.0	17.0	2.0	79.0
		Optimistic	1.0	0.5	120.0	11.0	6.0	18.0	1.0	85.0
	37	Pessimistic	2.5	4.0	160.0	20.0	13.0	15.0	2.2	82.0
		Likely	2.0	3.0	170.0	18.0	11.0	17.0	2.0	84.0
		Optimistic	1.5	2.0	180.0	16.0	9.0	19.0	1.8	86.0
	38	Pessimistic	2.4	1.3	165.0	30.0	15.0	16.0	3.5	78.0
		Likely	2.0	1.0	170.0	25.0	13.0	17.0	3.0	80.0
		Optimistic	1.6	0.7	175.0	20.0	11.0	18.0	2.5	82.0
	39	Pessimistic	1.7	3.0	90.0	19.0	18.0	11.0	3.0	70.0
		Likely	1.0	2.0	100.0	17.0	15.0	13.0	2.0	75.0
		Optimistic	0.3	1.0	110.0	15.0	12.0	15.0	1.0	80.0
	40	Pessimistic	4.0	2.4	70.0	21.0	15.0	17.0	4.1	73.0
		Likely	3.0	2.0	90.0	18.0	11.0	18.0	4.0	75.0
		Optimistic	2.0	1.6	110.0	15.0	7.0	19.0	3.9	77.0

Project Number		Project Parameters: Time to Average Added Rework	Time to Correct Amount of Work	Average Quitting Time	Time in Training	Average Hiring Delay	Available Workers	Time to Correct Workers	Productivity
41	Pessimistic	4.0	1.5	75.0	15.0	10.0	12.0	3.0	75.0
	Likely	3.0	1.0	80.0	13.0	8.0	13.0	2.0	80.0
	Optimistic	2.0	0.5	85.0	11.0	6.0	14.0	1.0	85.0
42	Pessimistic	3.0	1.6	100.0	14.0	9.0	16.0	2.5	70.0
	Likely	2.0	1.0	110.0	13.0	8.0	17.0	2.0	79.0
	Optimistic	1.0	0.4	120.0	12.0	7.0	18.0	1.5	86.0
43	Pessimistic	2.9	3.3	80.0	26.0	11.0	13.0	3.4	79.0
	Likely	1.9	2.3	110.0	18.0	8.0	15.0	3.2	80.0
	Optimistic	0.9	1.3	140.0	10.0	5.0	17.0	3.0	81.0
44	Pessimistic	3.0	4.0	150.0	20.0	12.0	16.0	3.0	80.0
	Likely	2.0	3.0	170.0	18.0	11.0	17.0	2.0	84.0
	Optimistic	1.0	2.0	190.0	16.0	10.0	18.0	1.0	88.0
45	Pessimistic	4.0	3.0	80.0	19.0	13.0	16.0	5.0	70.0
	Likely	3.0	2.0	90.0	18.0	11.0	18.0	4.0	75.0
	Optimistic	2.0	1.0	100.0	17.0	9.0	20.0	3.0	80.0
46	Pessimistic	1.2	1.5	80.0	13.0	12.0	15.0	3.0	70.0
	Likely	1.0	1.0	95.0	12.0	11.0	17.0	2.0	78.0
	Optimistic	0.8	0.5	110.0	11.0	10.0	19.0	1.0	86.0
47	Pessimistic	1.5	1.7	140.0	26.0	12.0	16.0	2.5	80.0
	Likely	1.0	1.0	145.0	23.0	10.0	18.0	2.0	82.0
	Optimistic	0.5	0.3	150.0	20.0	8.0	20.0	1.5	84.0
48	Pessimistic	3.0	1.3	150.0	30.0	14.0	16.0	4.0	75.0
	Likely	2.0	1.0	170.0	25.0	13.0	17.0	3.0	80.0
	Optimistic	1.0	0.7	190.0	20.0	12.0	18.0	2.0	85.0
49	Pessimistic	2.5	4.0	160.0	26.0	15.0	16.0	3.0	82.0
	Likely	2.0	3.0	170.0	18.0	11.0	17.0	2.0	84.0
	Optimistic	1.5	2.0	180.0	10.0	7.0	18.0	1.0	86.0
50	Pessimistic	3.3	1.6	90.0	16.0	9.0	15.0	2.2	75.0
	Likely	2.0	1.0	110.0	13.0	8.0	17.0	2.0	79.0
	Optimistic	0.7	0.4	130	10.0	7.0	19.0	1.8	83.0

The Effect of Changing in Parameters Value According to the Three Scenarios:

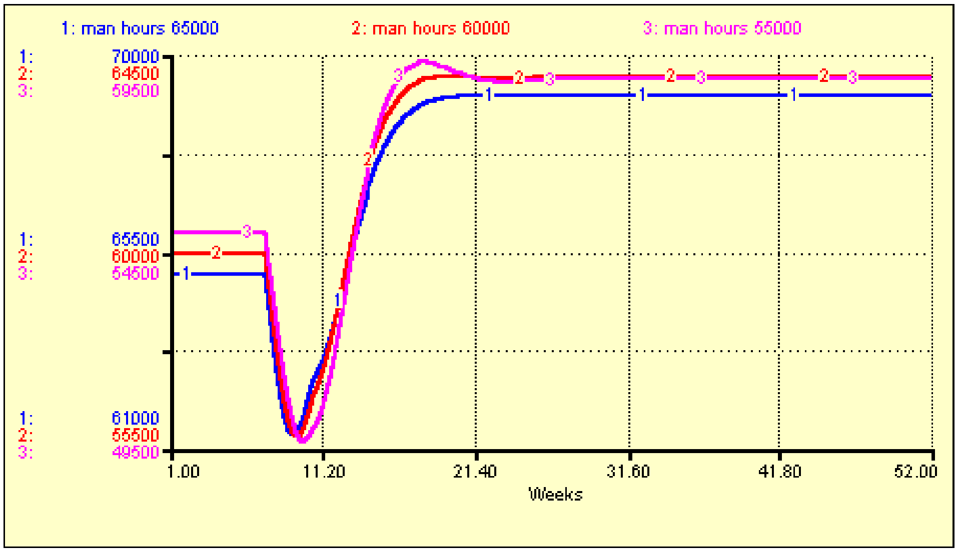

Figure E1: The effect of changes in the initial value of "Initial Work"

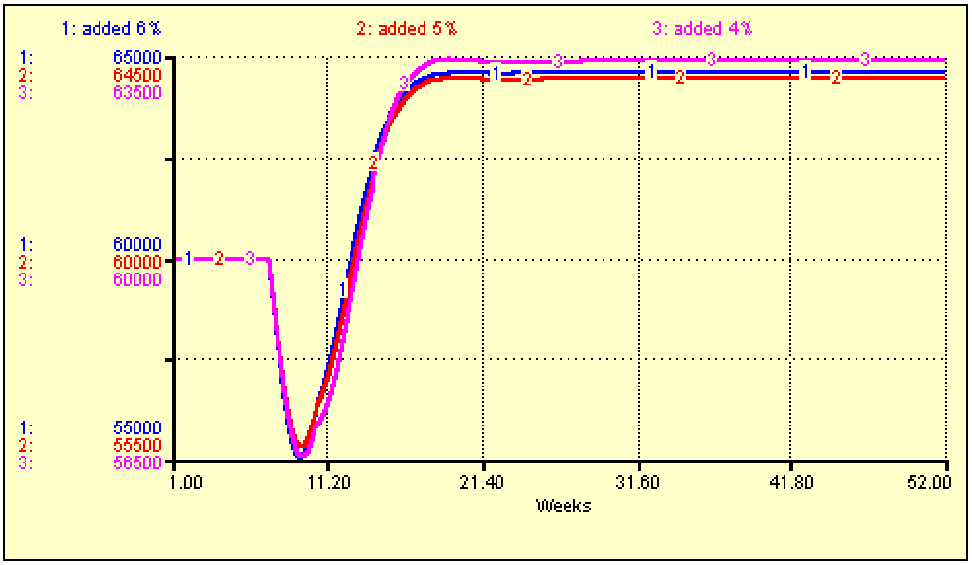

Figure E2: The effect of changes in "Added Rework"

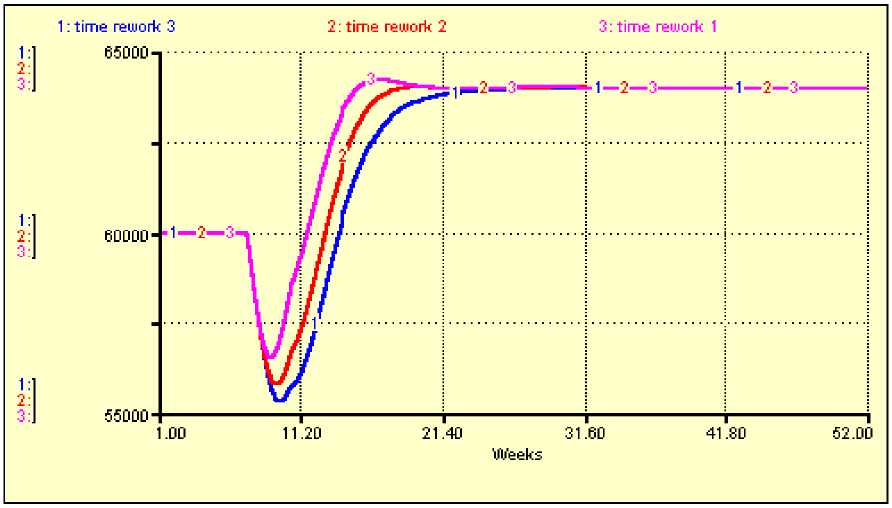

Figure E3: The effect of changes in "Time to Average Added Rework"

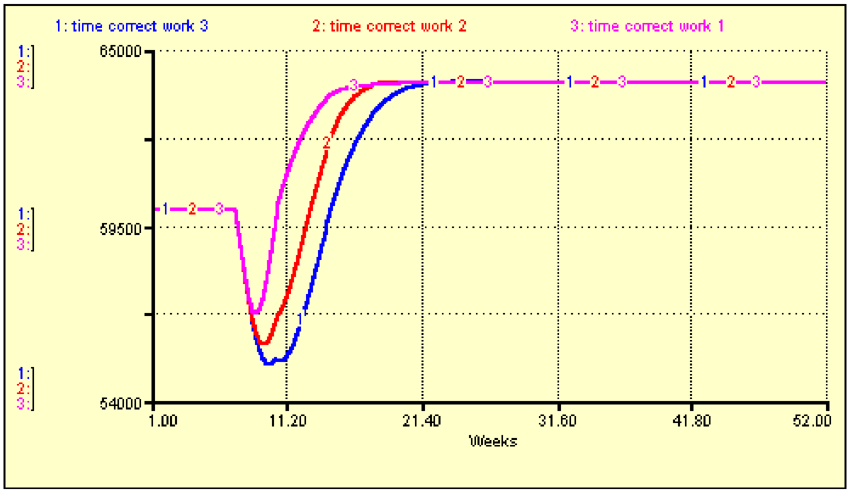

Figure E4: The effect of changes in "Time to Correct Amount of Work"

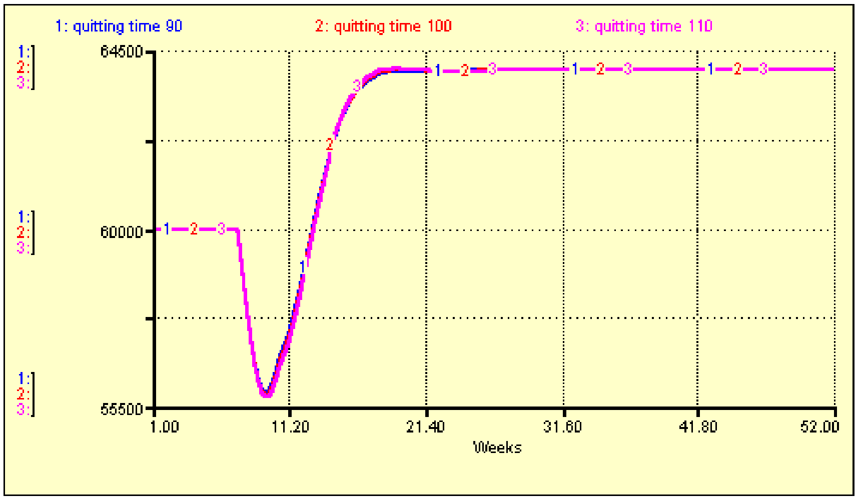

Figure E5: The effect of changes in "Average Quitting Time"

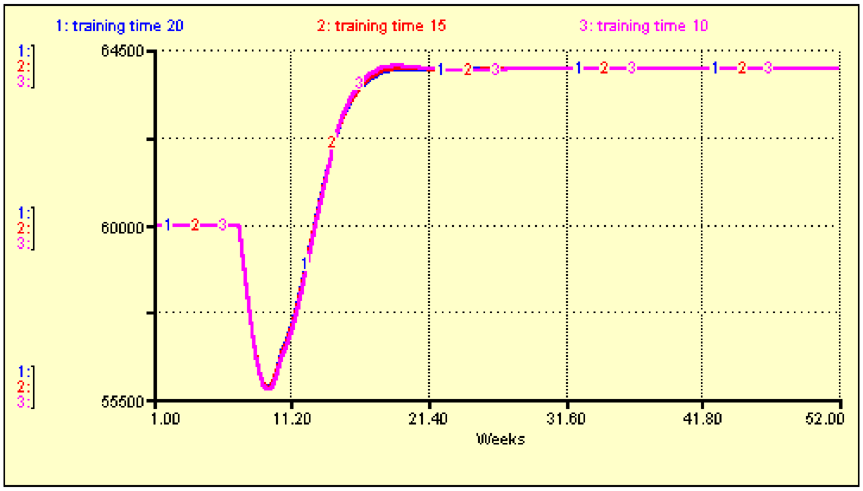

Figure E6: The effect of changes in "Time in Training"

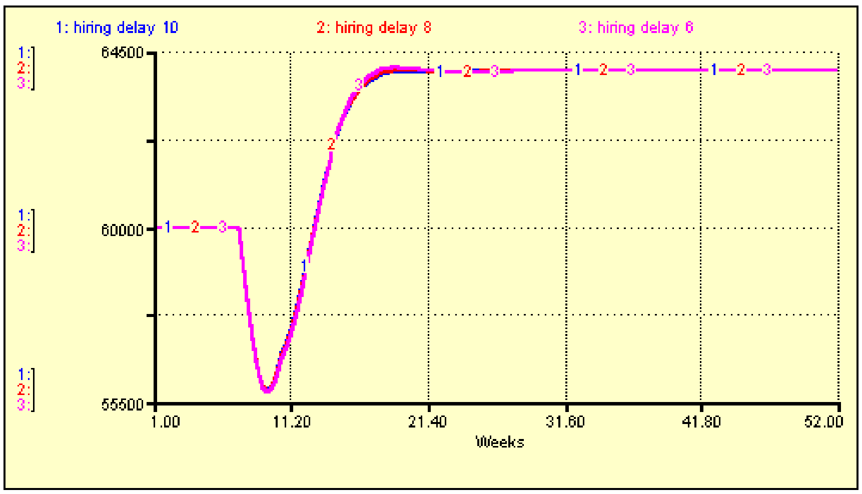

Figure E7: The effect of changes in "Average Hiring Delay"

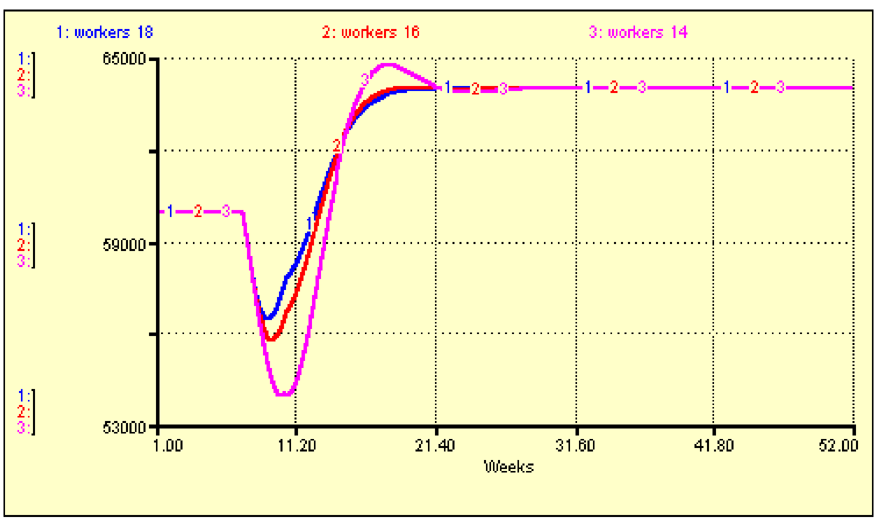

Figure E8: The effect of changes in the initial value of "Available Workers"

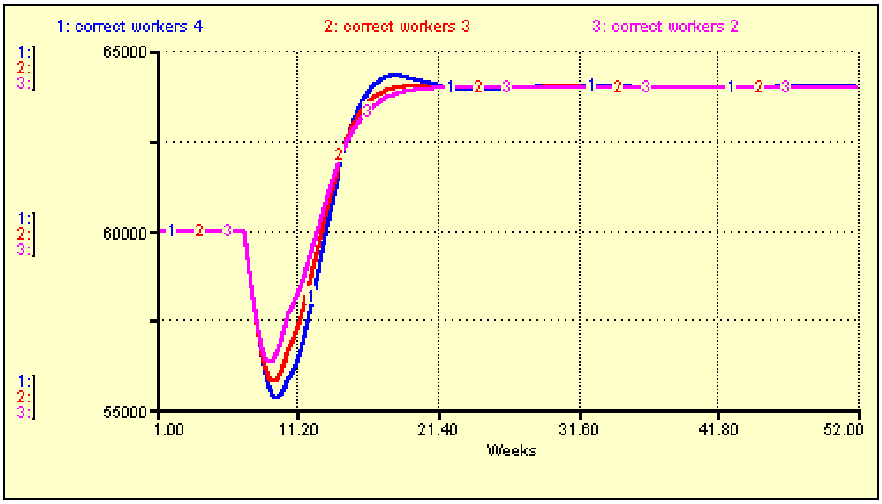

Figure E9: The effect of changes in "Time to Correct Workers"

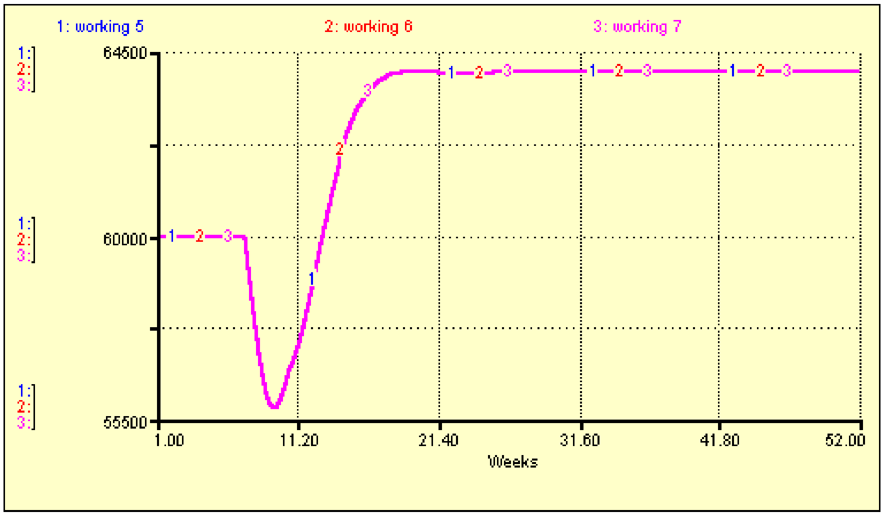

Figure E10: The effect of changes in "The Length of Working"

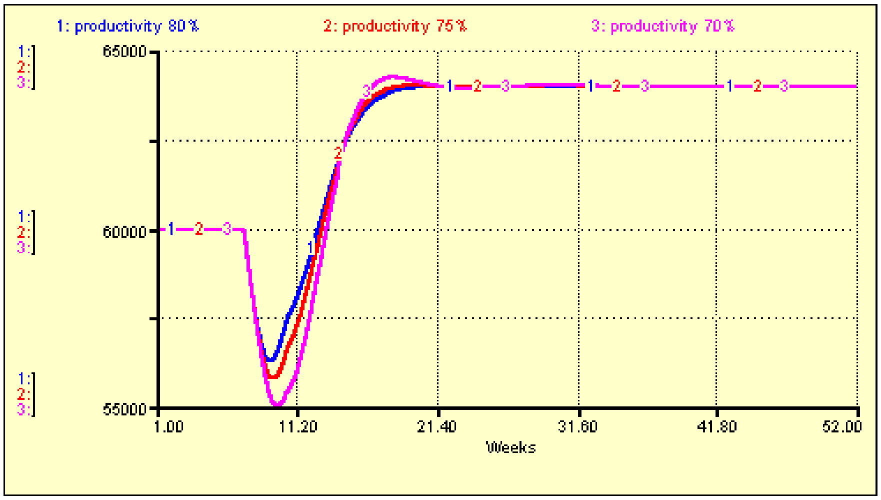

Figure E11: The effect of changes in "Productivity"

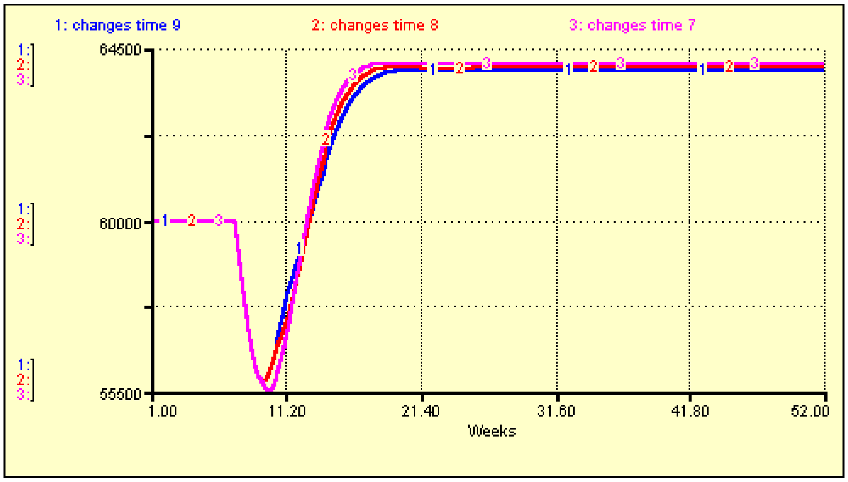

Figure E12: The effect of changes in "Time to Introduce Changes"

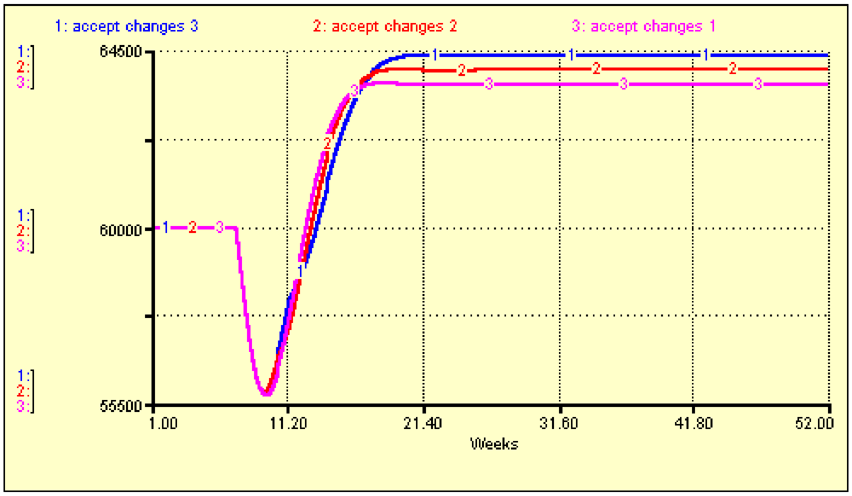

Figure E13: The effect of changes in "Time to Accept Work Changes"

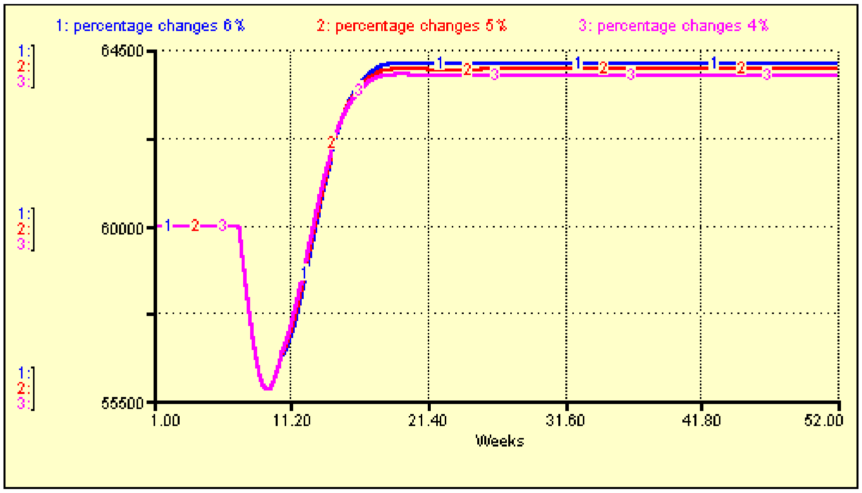

Figure E14: The effect of changes in the initial value of "Percentage Changes"

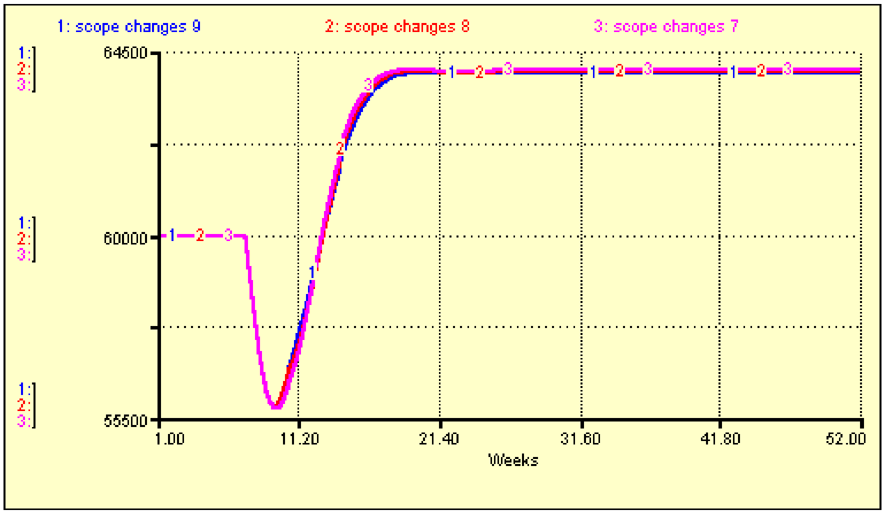

Figure E15: The effect of changes in "Time to Request Scope Changes"

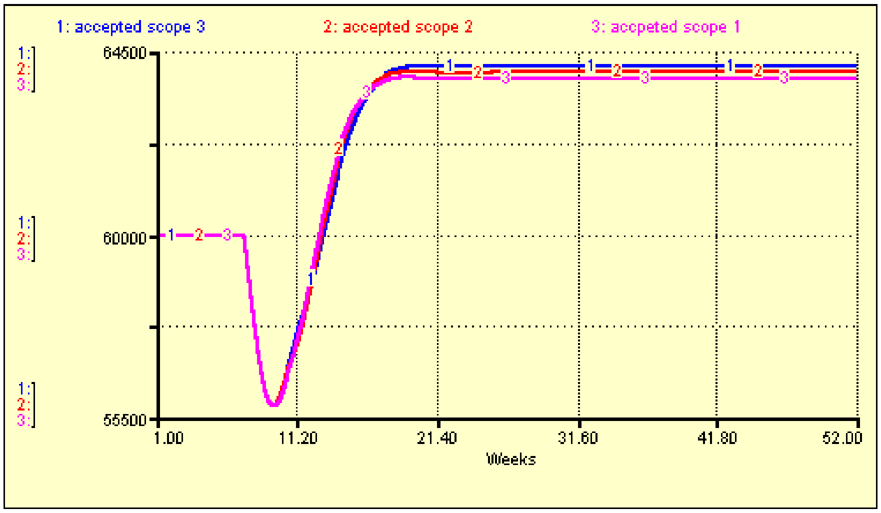

Figure E16: The effect of changes in "Time to Accept Scope Changes"

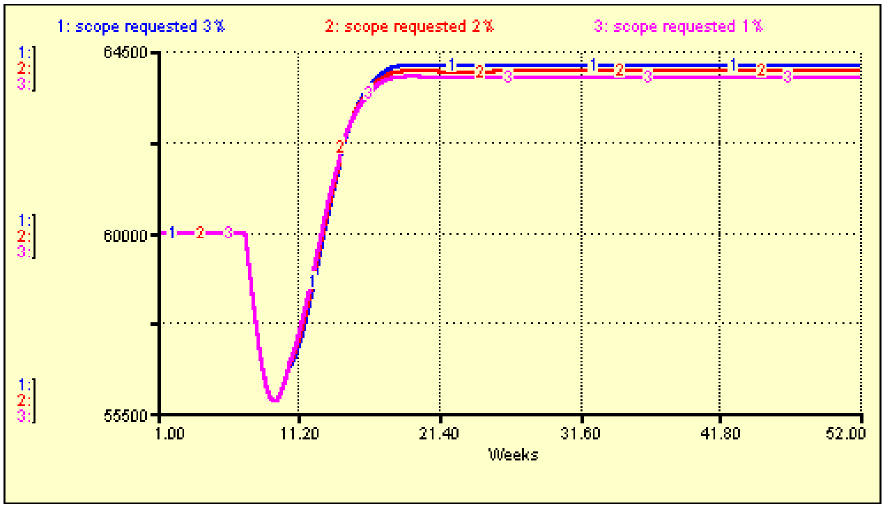

Figure E17: The effect of changes in the initial value of "Percentage Scope Changes"

Appendix F Multi-Way Sensitivity Test

The Levels for the Five Factors:

Project Number	Time to Average Added Rework (A)		Time to Correct Amount of Work (B)		Available Workers (C)		Time to Correct Workers (D)		Productivity (E)	
	Level (1)	*Level (2)*	*Level (1)*	*Level (2)*	*Level (1)*	*Level (2)*	*Level (1)*	*Level (2)*	*Level (1)*	*Level (2)*
1	2.0	1.0	2.0	1.0	16.0	17.0	3.0	2.0	0.75	0.80
2	3.0	2.0	1.0	0.5	15.0	16.0	2.0	1.0	0.75	0.80
3	3.0	2.0	2.0	1.0	16.0	17.0	3.0	2.0	0.80	0.85
4	1.5	1.0	1.0	0.5	15.0	16.0	2.0	1.0	0.88	0.90
5	3.6	3.0	2.3	2.0	14.0	15.0	4.1	3.2	0.89	0.93
6	2.9	1.9	2.1	4.1	14.0	15.0	2.9	1.9	0.78	0.80
7	2.2	2.0	2.2	2.0	16.0	17.0	2.0	1.5	0.75	0.80
8	3.3	3.0	3.0	2.0	13.0	14.0	3.3	3.0	0.79	0.80
9	3.0	2.0	1.0	0.5	16.0	18.0	3.0	2.0	0.88	0.90
10	1.0	0.8	2.0	1.0	13.0	15.0	2.0	1.0	0.75	0.80
11	4.0	3.8	1.0	0.7	14.0	16.0	2.0	1.8	0.75	0.76
12	6.0	5.0	2.0	1.0	17.0	18.0	3.0	2.0	0.75	0.80
13	2.0	1.0	1.0	0.5	17.0	18.0	2.0	1.0	0.79	0.85
14	4.0	3.7	2.0	1.0	17.0	18.0	4.0	3.8	0.86	0.87
15	4.2	4.0	1.9	1.0	14.0	16.0	2.7	2.0	0.83	0.86
16	2.9	1.9	2.1	1.1	14.0	15.0	2.9	1.9	0.78	0.80
17	2.0	1.0	3.0	2.0	17.0	18.0	2.0	1.0	0.84	0.85
18	3.0	1.0	1.0	0.5	16.0	17.0	3.0	2.0	0.88	0.89
19	2.0	1.0	1.0	0.4	17.0	18.0	3.0	2.0	0.80	0.85
20	1.8	1.6	2.3	2.0	11.0	12.0	2.7	2.4	0.81	0.87
21	3.0	2.0	1.0	0.5	13.0	14.0	2.0	1.0	0.80	0.85
22	5.0	4.9	2.0	1.0	15.0	16.0	2.5	2.0	0.87	0.90
23	2.0	1.0	2.0	1.0	17.0	18.0	2.0	1.0	0.77	0.80
24	2.5	2.0	1.5	1.0	13.0	14.0	2.5	2.0	0.80	0.85
25	2.9	2.8	2.1	2.0	14.0	15.0	2.9	2.8	0.78	0.80
26	1.9	0.9	2.3	1.3	15.0	17.0	3.2	3.0	0.80	0.81
27	2.2	1.2	2.2	1.2	16.0	18.0	2.0	1.0	0.75	0.77
28	2.0	1.0	1.0	0.5	17.0	18.0	3.0	2.0	0.80	0.82
29	1.0	0.7	1.0	0.8	18.0	20.0	2.0	1.8	0.82	0.84
30	3.0	2.0	3.0	2.0	15.0	18.0	4.0	3.0	0.75	0.80

Project Number	Time to Average Added Rework (A)		Time to Correct Amount of Work (B)		Available Workers (C)		Time to Correct Workers (D)		Productivity (E)	
	Level (1)	*Level (2)*	*Level (1)*	*Level (2)*	*Level (1)*	*Level (2)*	*Level (1)*	*Level (2)*	*Level (1)*	*Level (2)*
31	1.0	0.7	1.0	0.5	18.0	19.0	2.0	1.5	0.82	0.86
32	1.0	0.5	1.0	0.6	17.0	18.0	2.0	1.0	0.78	0.82
33	2.2	1.2	2.2	1.2	16.0	17.0	2.0	1.5	0.75	0.80
34	1.9	0.9	2.3	2.0	15.0	16.0	3.2	2.2	0.80	0.82
35	3.0	2.5	1.0	0.5	13.0	15.0	2.0	1.0	0.80	0.84
36	2.0	1.0	1.0	0.5	17.0	18.0	2.0	1.0	0.79	0.85
37	2.0	1.5	3.0	2.0	17.0	19.0	2.0	1.8	0.84	0.86
38	2.0	1.6	1.0	0.7	17.0	18.0	3.0	2.5	0.80	0.82
39	1.0	0.3	2.0	1.0	18.0	19.0	4.0	3.9	0.75	0.77
40	3.0	2.0	2.0	1.6	18.0	19.0	3.0	3.9	0.75	0.77
41	3.0	2.0	1.0	0.5	13.0	14.0	2.0	1.0	0.80	0.85
42	2.0	1.0	1.0	0.4	17.0	18.0	2.0	1.5	0.79	0.86
43	1.9	0.9	2.3	1.3	15.0	17.0	3.2	3.0	0.80	0.81
44	2.0	1.0	3.0	2.0	17.0	18.0	2.0	1.0	0.84	0.88
45	3.0	2.0	2.0	1.0	18.0	20.0	4.0	3.0	0.75	0.80
46	1.0	0.8	1.0	0.5	17.0	19.0	2.0	1.0	0.78	0.86
47	1.0	0.5	1.0	0.3	18.0	20.0	2.0	1.5	0.82	0.84
48	2.0	1.0	1.0	0.7	17.0	18.0	3.0	2.0	0.80	0.85
49	2.0	1.5	3.0	2.0	17.0	18.0	2.0	1.0	0.84	0.86
50	2.0	0.7	1.0	0.4	17.0	19.0	2.0	1.8	0.79	0.83

The Time It Takes to Return to Normal in Each Combination:

(The Output of the SD Model)

Combination Number	***Response Time*** *(Y)*									
	Project 1	**Project 2**	**Project 3**	**Project 4**	**Project 5**	**Project 6**	**Project 7**	**Project 8**	**Project 9**	**Project 10**
1	26.00	30.25	25.50	20.25	31.00	33.00	31.75	37.25	33.25	20.00
2	32.50	30.00	25.25	20.00	30.75	32.75	31.50	37.00	33.25	21.25
3	21.25	30.75	24.50	20.25	32.75	34.00	31.75	38.25	33.50	21.75
4	21.5	30.75	24.25	20.25	34.00	34.00	31.75	37.75	34.00	20.00
5	26.00	30.50	25.25	20.00	30.75	33.00	31.50	37.75	33.50	26.50
6	32.50	29.00	25.00	20.00	30.25	33.25	31.25	37.25	33.50	24.75
7	21.50	31.00	25.25	20.25	34.00	34.00	32.00	37.75	33.75	21.50
8	21.50	30.00	25.00	20.25	33.00	34.00	31.75	37.50	33.75	19.25
9	23.75	29.50	23.50	18.00	29.25	35.25	30.75	35.50	32.50	18.25
10	24.00	28.50	23.25	18.50	28.25	35.25	30.50	35.50	32.75	18.75
11	20.00	28.25	23.50	19.25	34.00	37.75	31.00	36.00	32.75	17.25
12	19.75	28.00	23.25	19.25	33.25	38.25	31.00	35.75	32.75	17.00
13	20.50	29.00	23.25	18.50	28.50	35.25	30.50	35.75	32.75	24.00
14	32.50	28.00	23.00	19.00	27.75	35.25	30.50	35.50	32.75	25.00
15	20.00	29.00	23.00	19.50	38.25	38.25	31.00	35.75	32.75	17.50
16	20.00	28.00	23.00	19.25	37.75	38.75	30.75	35.75	32.75	19.00
17	25.00	21.00	19.00	17.75	30.25	25.25	30.50	35.25	24.50	18.50
18	31.50	20.50	18.25	17.50	30.00	25.00	30.00	35.00	24.25	18.50
19	15.25	21.00	20.25	18.00	30.50	26.50	30.50	35.75	24.50	22.00
20	18.50	20.50	20.50	17.75	30.25	26.50	30.50	35.50	24.50	21.50
21	30.00	21.00	18.75	15.75	29.50	25.50	30.00	35.25	24.25	20.25
22	31.75	20.25	18.50	15.50	29.50	24.75	30.25	35.25	24.25	20.00
23	17.25	21.25	20.50	17.75	30.25	26.25	30.50	36.00	24.50	21.00
24	18.75	20.50	20.25	17.50	30.00	26.25	30.50	35.50	24.50	17.75
25	23.75	20.25	19.25	15.00	27.00	34.50	29.00	33.50	23.50	18.00
26	20.00	19.75	19.25	17.50	26.75	34.25	29.00	33.25	23.50	18.50
27	16.00	20.50	19.50	17.00	30.00	36.75	29.75	33.50	23.75	15.75
28	17.75	20.00	19.50	16.75	28.75	36.50	29.50	33.50	23.50	14.75
29	20.00	19.75	19.25	18.25	26.50	34.00	29.00	33.50	23.25	21.25
30	24.00	19.50	19.25	17.00	26.75	34.25	28.75	33.25	23.25	22.50
31	15.00	20.50	19.75	17.00	29.25	37.25	29.25	33.25	23.50	17.25
32	18.00	20.00	19.75	17.00	27.25	37.50	29.25	33.50	23.50	19.25

Combination Number	Response Time (Y)									
	Project 11	**Project 12**	**Project 13**	**Project 14**	**Project 15**	**Project 16**	**Project 17**	**Project 18**	**Project 19**	**Project 20**
1	37.00	70.75	25.50	29.00	40.75	33.25	31.00	34.25	25.50	25.00
2	36.00	70.50	25.50	29.00	41.25	33.25	31.00	34.25	25.50	24.75
3	36.00	71.25	26.00	28.75	41.00	34.00	33.75	34.75	25.50	25.50
4	36.00	70.75	26.00	28.75	41.25	34.00	33.50	34.75	26.00	25.00
5	36.00	70.50	25.50	30.00	41.00	33.50	30.75	34.50	25.50	25.00
6	35.75	71.00	25.50	30.75	41.00	33.50	30.75	34.50	25.50	24.50
7	36.25	71.00	26.00	29.50	41.25	34.50	33.50	35.00	25.50	25.50
8	36.50	70.75	26.00	30.25	41.25	34.25	33.75	35.00	25.50	25.00
9	35.50	67.25	24.75	29.25	39.00	32.25	25.75	34.00	24.25	23.75
10	35.50	67.25	24.50	29.75	38.75	32.00	25.75	34.00	24.00	23.50
11	35.25	67.25	25.00	28.50	39.00	32.75	27.00	34.25	24.75	24.00
12	35.25	67.50	25.00	29.00	39.00	32.75	27.00	34.25	24.00	23.75
13	35.50	67.50	24.75	26.25	38.75	32.25	25.75	34.00	24.25	23.75
14	35.50	67.25	24.50	28.50	38.75	32.25	25.75	34.50	24.00	23.50
15	35.00	67.50	25.00	28.00	39.25	32.75	27.00	34.25	24.25	24.00
16	33.50	67.25	25.00	28.25	39.25	32.50	27.00	34.50	24.00	23.75
17	34.50	60.50	16.25	28.75	39.25	25.25	28.75	19.00	16.00	24.25
18	34.50	60.25	16.00	28.75	39.25	25.25	28.75	18.75	16.00	24.00
19	33.75	60.25	17.00	28.50	39.75	26.50	31.00	19.25	15.75	24.75
20	32.50	60.50	16.75	28.50	39.50	26.50	31.00	19.00	16.25	24.50
21	35.00	60.25	16.25	30.000	39.50	25.00	28.75	19.25	16.00	24.25
22	34.50	60.00	15.75	30.75	39.50	25.00	28.25	18.75	16.00	23.75
23	36.00	60.50	16.75	29.50	39.75	26.50	30.75	18.50	16.25	24.50
24	35.75	60.75	16.75	30.00	39.75	26.50	30.75	18.75	16.25	24.25
25	34.00	57.50	15.50	29.25	37.25	23.50	20.50	17.75	14.50	22.50
26	33.75	57.25	15.00	29.75	37.25	23.50	20.75	17.75	14.75	22.25
27	34.25	57.25	15.75	28.25	37.25	24.00	22.50	18.25	14.75	23.00
28	33.75	57.25	16.00	28.75	37.25	23.75	22.25	18.00	14.75	22.75
29	33.75	57.75	14.25	26.50	37.50	23.50	20.00	18.00	14.75	22.75
30	34.50	57.50	14.00	28.25	37.25	23.75	20.00	18.00	14.00	22.00
31	34.00	57.25	15.75	27.50	37.25	23.75	22.25	18.50	15.00	23.25
32	34.00	57.25	15.75	27.75	37.25	23.75	22.25	18.25	14.75	22.75

Combination Number	*Response Time (Y)*									
	Project 21	**Project 22**	**Project 23**	**Project 24**	**Project 25**	**Project 26**	**Project 27**	**Project 28**	**Project 29**	**Project 30**
1	24.00	39.75	26.50	32.50	33.50	23.00	34.25	25.75	14.50	34.00
2	25.75	41.25	26.25	32.50	33.25	22.75	34.50	25.75	15.00	34.00
3	26.50	40.50	28.50	32.75	34.00	23.00	32.25	26.00	14.50	34.75
4	26.50	42.50	28.25	32.75	33.75	23.00	31.50	26.00	14.50	34.50
5	26.00	44.75	26.75	32.75	34.00	22.25	34.50	25.75	14.25	34.00
6	26.25	44.75	26.50	32.25	34.00	22.00	34.25	25.75	14.25	34.00
7	26.50	44.00	28.75	32.75	33.75	22.75	31.50	25.75	14.50	35.00
8	26.50	48.50	28.50	33.00	34.00	22.50	30.75	25.75	14.50	35.00
9	25.00	43.00	25.75	31.50	33.75	21.25	31.50	24.50	13.75	32.25
10	25.00	42.50	25.75	31.50	33.75	21.25	31.25	24.25	13.75	32.00
11	25.00	41.75	26.50	31.50	33.75	21.25	31.75	25.00	14.00	32.50
12	25.00	43.50	26.25	31.50	33.50	21.25	31.50	24.25	14.00	32.50
13	25.00	44.75	26.00	32.00	34.00	21.00	31.50	24.50	14.00	32.25
14	25.00	46.00	25.75	31.50	34.00	21.00	31.25	24.25	14.00	32.75
15	25.00	45.75	26.50	31.50	33.75	21.00	32.0	24.50	14.00	32.75
16	25.00	46.00	26.50	33.25	34.00	21.00	32.25	24.25	14.00	32.75
17	19.25	39.00	21.25	28.00	33.00	19.25	29.25	18.00	12.50	30.00
18	19.25	40.00	20.75	28.00	32.75	19.00	29.25	18.00	12.25	30.00
19	19.50	39.75	24.00	28.25	33.25	19.75	34.25	17.75	12.50	31.25
20	19.75	41.00	24.25	28.25	33.00	19.75	33.25	18.25	12.50	31.00
21	19.25	41.50	21.00	28.25	33.00	18.00	29.25	18.00	12.25	30.50
22	19.00	43.75	20.00	28.25	33.25	17.50	29.00	18.00	12.25	30.50
23	19.50	43.25	24.00	28.25	33.00	18.50	32.25	18.25	12.00	31.25
24	19.50	45.50	23.75	28.50	33.25	18.25	32.00	18.25	12.00	31.00
25	18.25	40.75	17.50	27.00	32.75	11.00	20.50	16.50	11.00	26.00
26	19.00	42.00	17.00	27.00	32.75	10.50	20.50	16.75	11.00	26.00
27	18.25	41.25	17.75	27.00	32.75	11.75	26.50	16.75	11.00	26.50
28	18.25	42.75	17.50	27.25	32.75	11.50	26.50	16.75	11.00	26.75
29	17.75	43.50	17.00	27.25	33.00	13.25	20.25	16.75	10.75	26.75
30	17.25	44.75	16.50	27.25	33.00	13.75	20.50	16.00	10.75	25.75
31	18.25	44.25	17.75	27.00	33.50	13.75	25.50	17.00	10.75	26.50
32	18.50	44.75	17.75	27.50	33.50	13.50	25.25	16.75	10.75	26.50

Combination Number	Response Time (Y)									
	Project 31	Project 32	Project 33	Project 34	Project 35	Project 36	Project 37	Project 38	Project 39	Project 40
1	19.25	18.75	34.50	24.50	27.25	25.50	31.25	26.50	18.00	30.50
2	19.00	18.75	34.25	24.25	26.00	25.50	31.25	26.50	19.25	30.50
3	19.25	23.50	32.75	25.00	27.00	26.00	31.75	26.50	19.75	30.75
4	19.25	22.25	31.00	25.00	26.75	26.00	31.75	26.50	18.00	30.75
5	19.00	18.75	34.50	23.75	25.50	25.50	30.50	26.25	24.50	30.50
6	19.00	18.75	34.25	23.50	25.25	25.50	30.50	26.25	22.75	30.50
7	19.25	23.50	35.00	24.75	25.00	26.00	31.50	26.25	19.50	30.75
8	19.25	22.50	35.00	24.50	25.00	26.00	31.50	26.25	17.25	30.75
9	18.50	17.25	31.75	24.50	24.75	24.75	26.50	25.50	16.25	28.50
10	18.50	17.75	31.50	24.25	24.50	24.50	26.50	25.50	16.75	28.50
11	18.00	22.75	32.00	24.50	24.00	25.00	25.25	25.50	15.25	28.75
12	18.00	21.00	31.75	24.25	24.00	25.00	25.25	25.50	15.00	28.75
13	18.25	18.00	31.75	24.50	25.50	24.75	26.75	25.25	22.00	28.50
14	18.00	17.75	31.50	24.50	25.50	24.50	26.75	25.25	23.00	28.50
15	18.25	22.00	32.25	24.50	25.50	25.00	25.25	25.25	15.50	28.25
16	18.25	20.75	32.50	24.50	25.50	25.00	25.25	25.25	17.00	28.25
17	17.75	16.75	29.50	21.50	23.50	16.25	29.25	22.25	16.50	24.00
18	17.50	17.25	29.50	21.25	23.25	16.00	29.25	22.25	16.50	24.00
19	17.75	24.25	30.25	22.00	23.50	17.00	31.25	22.00	20.00	24.25
20	17.75	23.25	30.00	22.00	23.25	16.75	31.25	22.00	19.50	24.25
21	17.50	16.75	29.25	21.00	24.00	16.25	29.25	21.75	18.25	24.00
22	17.50	16.50	29.25	20.75	24.00	15.75	29.25	21.75	20.00	24.00
23	17.00	23.00	29.00	21.75	24.50	16.75	31.00	21.75	19.00	24.00
24	17.00	22.50	29.00	21.50	24.25	16.75	31.00	21.75	15.75	24.00
25	16.25	15.00	22.50	19.75	23.25	15.50	21.25	21.50	16.00	23.25
26	16.25	14.50	22.50	19.25	23.00	15.00	21.50	21.50	16.50	23.25
27	16.25	20.50	28.50	20.00	23.25	15.75	22.75	21.50	13.75	23.25
28	16.25	18.00	28.50	19.75	23.00	16.00	22.50	21.50	12.75	23.25
29	16.00	14.75	22.25	19.25	22.50	14.25	20.75	21.00	19.25	23.25
30	16.00	14.75	22.50	19.50	22.25	14.00	20.75	21.00	20.50	23.25
31	16.00	19.25	27.50	19.50	22.50	15.75	22.50	21.00	15.25	23.25
32	16.00	16.25	27.25	19.25	22.00	15.75	22.50	21.00	17.25	23.00

Combination Number	Response Time (Y)									
	Project 41	Project 42	Project 43	Project 44	Project 45	Project 46	Project 47	Project 48	Project 49	Project 50
1	28.25	26.50	25.50	30.00	31.25	15.00	16.50	27.50	31.00	27.50
2	29.50	26.50	25.25	30.00	31.25	15.00	17.00	27.50	31.00	27.50
3	30.50	27.00	26.00	32.75	31.50	20.00	16.50	27.50	33.75	28.00
4	30.50	27.00	26.00	32.50	31.50	19.25	16.50	27.50	33.25	28.00
5	30.00	26.50	24.75	29.75	31.25	15.25	16.25	27.25	30.50	27.50
6	30.25	26.50	24.50	29.75	31.25	15.25	16.25	27.25	30.50	27.25
7	30.50	27.00	25.75	32.50	31.50	20.00	16.50	27.25	33.25	28.25
8	30.50	27.00	25.50	32.75	31.50	19.50	16.50	27.25	33.50	28.00
9	29.00	25.75	25.50	24.75	29.75	14.25	15.75	26.50	25.50	26.75
10	29.00	25.50	25.25	24.75	29.75	14.75	15.75	26.50	25.50	26.50
11	29.00	26.00	25.50	26.00	30.00	19.75	16.00	26.50	27.00	27.00
12	29.00	26.00	25.25	26.00	30.00	18.00	16.00	26.50	27.00	26.75
13	29.00	25.75	25.50	24.75	29.75	15.00	16.00	26.25	25.50	26.75
14	29.00	25.50	25.50	24.75	29.75	14.75	16.00	26.25	25.50	26.50
15	29.00	26.00	25.50	26.00	29.50	19.00	16.00	26.25	27.25	27.00
16	29.00	26.00	25.50	26.00	29.50	18.00	16.00	26.25	27.25	27.00
17	23.25	17.25	22.50	27.75	25.00	14.75	13.50	23.25	28.50	18.00
18	23.25	17.00	22.25	27.75	25.00	14.25	13.25	23.25	28.75	17.75
19	23.50	16.00	23.00	30.00	25.25	21.00	13.50	23.00	30.00	19.00
20	23.75	17.75	23.00	30.00	25.00	20.25	13.50	23.00	30.00	18.50
21	23.25	17.25	22.00	27.75	25.00	15.00	12.25	22.75	28.75	18.25
22	23.00	16.75	21.75	27.25	24.75	15.00	12.25	22.75	28.25	17.50
23	23.50	17.75	22.75	29.75	25.00	20.00	13.00	22.75	30.50	18.50
24	23.50	17.75	21.50	29.75	24.75	19.50	13.00	22.75	30.50	18.50
25	22.25	16.50	20.75	19.50	24.25	15.00	12.00	22.50	20.50	17.50
26	23.00	16.00	20.25	19.75	24.25	15.00	12.00	22.50	20.75	17.00
27	22.25	16.75	21.00	21.50	24.25	20.50	12.00	22.50	22.50	17.25
28	22.25	17.00	20.75	21.25	24.25	18.00	12.00	22.50	22.25	18.00
29	20.75	15.25	20.25	19.00	24.00	14.75	11.25	22.00	20.00	16.25
30	20.75	15.00	20.25	19.00	24.00	14.50	11.25	22.00	20.00	16.00
31	22.25	16.75	20.50	21.25	24.00	14.25	11.25	22.00	22.25	17.75
32	22.50	16.75	20.25	21.25	24.00	14.00	11.25	22.00	22.25	17.50

The *P*-Value for Each Factor using α = 0.05:

(The Minitab Output)

Source of Variation	*P-Value*									
	Project 1	**Project 2**	**Project 3**	**Project 4**	**Project 5**	**Project 6**	**Project 7**	**Project 8**	**Project 9**	**Project 10**
A	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
B	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C	0.000	0.000	0.726	0.437	0.348	0.034	0.281	0.790	0.689	0.000
D	0.000	0.156	0.000	0.000	0.000	0.000	0.000	0.006	0.179	0.000
E	0.000	0.351	0.000	0.198	0.000	0.662	0.077	0.032	0.689	0.247
A*B	0.000	0.001	0.000	0.000	0.000	0.000	0.077	0.427	0.936	0.010
A*C	0.398	0.000	0.297	0.198	0.000	0.384	0.588	0.254	0.810	0.000
A*D	0.000	0.124	0.000	0.198	0.000	0.662	0.368	0.536	0.689	0.000
A*E	0.001	0.098	0.297	0.795	0.850	0.194	0.588	0.536	0.472	0.867
B*C	0.068	0.059	0.019	0.000	0.000	0.034	0.154	0.536	0.936	0.000
B*D	0.000	0.124	0.000	0.004	0.000	0.000	0.154	0.189	0.472	0.000
B*E	0.000	0.156	0.087	0.013	0.000	0.034	0.717	0.333	0.689	0.000
C*D	0.000	0.851	0.003	0.437	0.000	0.034	0.588	0.254	0.689	0.000
C*E	0.000	0.124	0.726	0.000	0.451	1.000	0.368	0.658	0.689	0.617
D*E	0.000	0.492	0.087	0.024	0.451	0.034	0.856	0.333	0.689	0.038
A*B*C	0.000	0.662	0.000	0.000	0.000	0.087	0.856	0.536	0.689	0.002
A*B*D	0.000	0.492	0.000	0.000	0.000	0.194	0.856	0.536	0.472	0.000
A*C*D	0.398	0.492	0.087	0.437	0.000	0.087	1.000	0.099	0.472	0.000
A*B*E	0.006	0.026	0.297	0.603	1.000	0.662	0.588	0.790	0.689	0.617
A*C*E	0.000	0.950	0.726	0.000	0.137	0.662	0.471	0.333	0.472	0.206
A*D*E	0.000	0.950	0.297	0.795	0.000	0.662	0.281	0.658	0.689	0.867
B*C*D	0.015	0.239	0.019	0.000	0.000	0.004	0.368	0.929	0.689	0.001
B*C*E	0.000	0.351	0.726	0.000	0.019	1.000	0.588	0.658	0.689	0.000
B*D*E	0.000	0.754	0.297	0.013	0.007	0.662	0.856	0.427	0.472	0.028
C*D*E	0.000	0.851	0.297	0.000	0.001	0.662	0.471	0.536	0.689	0.046
A*B*C*D	0.000	0.194	0.000	0.000	0.000	1.000	0.281	0.427	0.689	0.406
A*B*C*E	0.033	0.950	0.726	0.000	0.044	0.034	0.471	0.658	0.689	0.781
A*B*D*E	0.000	0.291	0.087	1.000	0.096	0.194	0.717	0.427	0.689	0.541
A*C*D*E	0.000	0.851	0.087	0.000	0.096	0.087	0.210	0.138	0.689	0.091
B*C*D*E	0.000	0.851	0.087	0.000	0.261	0.662	0.471	0.536	0.472	0.017
A*B*C*D*E	0.133	0.950	0.297	0.000	0.012	0.384	0.368	0.536	0.689	0.010
R-Sq (%)	99.75	99.41	99.74	98.60	99.36	99.80	93.08	97.31	99.65	97.52
Most Significant Factor	D	A	A	A	D	B	A	A	A	C

Source of Variation	P-Value									
	Project 11	Project 12	Project 13	Project 14	Project 15	Project 16	Project 17	Project 18	Project 19	Project 20
A	0.000	0.000	0.000	0.021	0.000	0.000	0.000	0.000	0.000	0.001
B	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C	0.026	0.487	0.005	0.071	0.540	0.926	0.027	0.112	0.921	0.742
D	0.102	0.372	0.000	0.021	0.007	0.000	0.000	0.003	0.145	0.133
E	0.005	0.372	0.265	0.004	1.000	0.519	0.870	0.315	0.921	0.106
A*B	0.442	0.011	0.265	0.248	0.683	0.000	0.000	0.004	0.045	0.570
A*C	0.000	0.765	0.005	0.538	0.838	0.313	0.513	0.163	0.100	0.976
A*D	0.164	0.372	0.708	0.632	0.047	0.408	0.743	0.545	0.921	0.881
A*E	0.898	0.619	0.455	0.452	0.683	0.926	0.870	0.112	0.921	0.834
B*C	0.001	0.921	0.265	0.000	0.310	0.519	0.195	0.163	0.921	0.697
B*D	0.700	0.141	0.455	0.307	0.683	0.000	0.001	0.840	0.491	0.834
B*E	0.521	0.765	0.265	0.307	0.225	0.644	0.870	0.230	0.018	0.976
C*D	0.019	0.619	0.265	0.029	0.838	0.644	0.623	0.163	0.622	0.976
C*E	0.521	0.619	0.708	0.053	0.838	0.644	1.000	0.686	0.068	0.697
D*E	0.204	0.372	0.265	0.307	1.000	0.519	1.000	0.420	0.491	0.834
A*B*C	0.026	0.619	0.265	0.156	0.540	0.781	0.743	0.003	0.491	0.928
A*B*D	0.102	0.921	0.265	0.053	0.109	0.408	0.108	0.007	0.145	0.881
A*C*D	0.005	0.372	0.265	0.837	0.540	0.781	0.255	0.007	0.045	0.834
A*B*E	0.164	0.487	0.140	0.945	0.225	0.781	0.870	0.545	0.921	0.697
A*C*E	0.164	0.619	0.708	0.452	0.838	0.519	0.743	0.840	0.282	0.928
A*D*E	0.442	0.043	0.455	0.945	1.000	0.644	1.000	0.315	0.921	0.928
B*C*D	0.000	0.921	0.265	0.021	0.310	0.313	0.870	0.686	0.622	0.976
B*C*E	0.898	0.277	0.708	0.945	0.310	0.519	1.000	0.840	0.622	0.834
B*D*E	0.130	0.141	0.455	0.156	0.225	0.644	0.743	0.163	0.100	0.492
C*D*E	0.307	0.487	0.708	0.307	0.838	0.926	0.623	0.840	0.282	0.928
A*B*C*D	0.521	0.277	0.265	0.632	0.310	0.644	0.078	0.163	0.767	0.881
A*B*C*E	0.010	0.277	0.708	0.945	0.158	0.644	0.743	0.686	0.282	0.928
A*B*D*E	0.130	0.065	0.708	0.425	0.415	0.519	0.743	0.230	0.921	0.976
A*C*D*E	0.130	0.487	0.708	0.945	0.838	0.519	0.870	0.686	0.767	0.787
B*C*D*E	0.130	0.619	0.140	0.156	0.310	0.781	0.870	0.686	0.205	0.976
A*B*C*D*E	0.608	0.619	0.140	0.452	0.310	0.644	0.870	0.840	0.767	0.834
R-Sq (%)	88.92	99.83	99.76	91.24	97.66	99.70	99.60	99.93	99.79	61.76
Most Significant Factor	A	A	A	B*C	B	A	B	A	A	B

Source of Variation	P-Value									
	Project 21	Project 22	Project 23	Project 24	Project 25	Project 26	Project 27	Project 28	Project 29	Project 30
A	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
B	0.000	0.000	0.000	0.000	0.544	0.000	0.000	0.000	0.000	0.000
C	0.331	0.000	0.060	0.062	0.229	0.478	0.000	0.540	0.014	0.698
D	0.019	0.000	0.000	0.081	0.364	0.001	0.000	0.385	0.391	0.006
E	0.080	0.000	0.015	0.843	0.364	0.039	0.008	0.458	0.391	0.295
A*B	0.040	0.331	0.000	0.081	0.449	0.000	0.000	0.583	0.000	0.000
A*C	0.000	0.010	0.003	0.644	0.879	0.000	0.000	0.498	0.033	0.407
A*D	0.870	0.515	0.001	0.533	0.648	0.091	0.000	0.674	0.296	0.618
A*E	0.417	0.386	0.192	0.469	0.879	0.478	0.517	0.722	0.632	0.542
B*C	0.000	0.003	0.363	0.644	0.761	0.000	0.001	0.923	0.503	0.698
B*D	0.004	0.002	0.000	0.843	0.364	0.267	0.000	0.923	0.014	0.074
B*E	0.870	0.022	0.760	0.105	0.761	0.363	0.022	0.385	0.391	0.472
C*D	0.744	0.057	0.134	0.393	0.761	0.478	0.000	0.974	0.503	0.542
C*E	0.198	1.000	0.760	0.265	0.229	0.611	0.517	0.871	0.391	0.781
D*E	0.417	0.071	0.015	0.081	0.761	0.192	0.022	0.974	0.924	0.295
A*B*C	1.000	0.386	0.192	0.553	0.879	0.000	0.058	0.923	0.051	0.295
A*B*D	0.002	0.109	0.000	0.843	0.449	0.478	0.000	0.923	0.391	0.698
A*C*D	0.057	0.236	0.134	0.325	0.648	0.611	0.000	0.190	0.774	0.036
A*B*E	0.258	0.236	0.919	0.214	0.291	0.611	0.829	0.628	0.296	0.618
A*C*E	0.331	0.331	0.760	0.644	0.449	0.919	0.517	0.771	0.296	0.542
A*D*E	0.625	0.004	0.015	0.393	0.648	0.760	0.829	0.871	0.774	0.407
B*C*D	0.000	0.236	0.760	0.644	0.229	0.192	0.001	0.583	0.296	0.618
B*C*E	0.516	0.448	0.192	0.644	0.761	0.267	0.829	0.974	0.391	0.868
B*D*E	0.417	0.057	0.267	0.553	0.364	0.363	0.022	0.923	0.110	0.171
C*D*E	0.057	0.664	0.611	0.105	1.000	0.363	0.283	0.674	0.110	0.698
A*B*C*D	0.110	1.000	0.760	0.947	0.449	0.134	0.058	0.583	0.110	0.698
A*B*C*E	0.744	0.386	0.192	0.741	0.291	0.091	0.283	0.871	0.632	0.618
A*B*D*E	0.080	0.331	0.267	0.843	0.291	0.919	0.283	0.974	0.774	0.348
A*C*D*E	0.331	0.236	0.363	0.325	0.449	0.919	0.829	0.583	0.774	0.295
B*C*D*E	0.744	0.010	0.760	0.644	0.761	0.478	0.283	0.771	0.924	0.781
A*B*C*D*E	0.013	0.001	0.919	0.741	0.648	0.091	0.283	0.674	0.774	0.248
R-Sq (%)	99.41	96.54	99.73	97.65	56.63	99.72	99.78	97.05	97.48	98.31
Most Significant Factor	A	C	A	A	A	A	A	A	A	A

Source of Variation	P-Value									
	Project 31	**Project 32**	**Project 33**	**Project 34**	**Project 35**	**Project 36**	**Project 37**	**Project 38**	**Project 39**	**Project 40**
A	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
B	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C	0.336	0.010	0.834	0.028	0.118	0.624	0.804	0.000	0.000	0.482
D	0.705	0.000	0.000	0.012	0.330	0.000	0.000	0.838	0.000	0.615
E	0.833	0.000	0.000	0.005	0.011	0.003	0.026	1.000	0.225	0.920
A*B	0.426	0.000	0.000	0.000	0.011	0.894	0.000	0.011	0.019	0.000
A*C	0.585	0.038	0.000	0.823	0.541	0.505	0.679	0.030	0.000	0.920
A*D	0.768	0.000	0.000	0.964	0.806	0.352	0.000	0.838	0.000	0.763
A*E	0.833	0.945	0.530	0.754	0.806	0.234	0.740	1.000	0.310	0.920
B*C	0.833	0.835	0.006	0.199	0.073	0.964	0.219	0.158	0.000	0.763
B*D	0.966	0.000	0.000	0.104	0.226	0.563	0.012	0.838	0.000	0.482
B*E	0.768	0.015	0.675	0.687	0.625	0.563	0.740	1.000	0.000	0.920
C*D	0.705	0.004	0.349	0.502	0.902	0.824	0.250	0.838	0.000	0.482
C*E	0.833	0.534	1.000	0.622	0.274	0.894	0.740	1.000	0.158	0.920
D*E	0.899	0.000	0.916	0.687	0.625	0.148	0.679	1.000	0.000	0.920
A*B*C	0.768	0.534	0.042	0.267	0.000	0.624	0.122	0.158	0.000	0.615
A*B*D	0.297	0.000	0.000	0.349	0.806	0.689	0.409	0.838	0.000	0.920
A*C*D	0.585	0.090	0.000	0.349	0.541	0.505	0.323	0.838	0.000	0.920
A*B*E	0.705	0.007	1.000	0.754	0.806	0.964	0.740	1.000	0.073	0.920
A*C*E	0.768	0.303	0.530	0.687	0.274	0.964	0.740	1.000	0.002	0.920
A*D*E	0.899	0.118	0.601	0.754	0.464	0.563	0.679	1.000	0.001	0.920
B*C*D	0.585	0.152	0.021	0.754	0.902	0.755	0.740	0.838	0.000	0.763
B*C*E	0.644	0.534	0.404	0.502	0.541	0.689	0.740	1.000	0.000	0.920
B*D*E	0.966	0.068	0.465	0.823	0.330	0.202	0.679	1.000	0.000	0.920
C*D*E	0.966	0.729	0.753	0.893	0.118	0.505	0.804	1.000	0.540	0.920
A*B*C*D	0.966	0.835	0.013	0.964	0.118	0.894	0.868	0.838	0.000	0.615
A*B*C*E	0.966	0.194	1.000	0.687	0.025	0.624	0.740	1.000	0.225	0.920
A*B*D*E	0.966	0.729	0.349	0.754	0.330	0.964	0.679	1.000	0.030	0.920
A*C*D*E	0.899	0.303	0.753	0.823	0.541	0.234	0.804	1.000	0.000	0.920
B*C*D*E	0.705	0.628	0.465	0.754	0.902	0.624	0.804	1.000	0.000	0.920
A*B*C*D*E	0.899	0.118	0.916	0.823	0.902	0.505	0.804	1.000	0.000	0.920
R-Sq (%)	82.15	98.82	98.66	94.85	92.43	98.82	98.08	99.04	99.38	99.46
Most Significant Factor	A	D	A	A	A	A	B	A	C	A

Source of Variation	P-Value									
	Project 41	Project 42	Project 43	Project 44	Project 45	Project 46	Project 47	Project 48	Project 49	Project 50
A	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
B	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C	0.109	0.140	0.000	0.027	0.007	0.000	0.009	0.000	0.154	0.030
D	0.000	0.000	0.000	0.000	0.173	0.000	0.527	0.838	0.000	0.000
E	0.042	0.708	0.012	0.870	0.247	0.000	0.833	1.000	0.836	0.019
A*B	0.000	0.708	0.000	0.000	0.000	0.000	0.000	0.011	0.000	1.000
A*C	0.000	0.140	0.191	0.513	0.750	0.000	0.002	0.030	0.410	0.002
A*D	1.000	0.265	0.571	0.743	0.247	0.000	1.000	0.838	0.070	0.415
A*E	0.815	0.455	0.096	0.870	0.247	1.000	0.673	1.000	1.000	0.540
B*C	0.000	0.013	0.000	0.195	0.596	0.000	0.007	0.158	0.536	0.310
B*D	0.167	0.030	0.002	0.001	0.750	0.000	0.916	0.838	0.045	0.540
B*E	0.815	0.708	0.451	0.870	0.247	0.099	0.916	1.000	0.836	0.109
C*D	0.109	0.013	0.191	0.623	0.173	0.000	0.598	0.838	0.029	0.158
C*E	0.068	0.068	0.571	1.000	0.342	0.061	0.461	1.000	1.000	1.000
D*E	0.109	0.013	0.571	1.000	0.915	0.000	0.751	1.000	0.836	0.225
A*B*C	0.247	0.013	0.348	0.743	0.050	0.000	0.751	0.158	0.018	0.047
A*B*D	0.000	0.013	0.044	0.108	0.596	0.000	0.250	0.838	0.004	0.225
A*C*D	0.000	0.013	0.066	0.255	0.247	0.000	0.751	0.838	0.679	1.000
A*B*E	0.042	1.000	0.571	0.870	0.247	0.631	0.751	1.000	1.000	0.011
A*C*E	1.000	0.068	0.451	0.743	0.342	0.012	0.751	1.000	0.536	0.540
A*D*E	0.485	0.030	0.451	1.000	0.915	1.000	0.461	1.000	1.000	0.073
B*C*D	0.000	0.708	0.850	0.870	0.247	0.000	1.000	0.838	0.305	0.030
B*C*E	0.641	0.265	0.044	1.000	0.342	0.339	0.527	1.000	1.000	0.683
B*D*E	0.815	0.455	0.850	0.743	0.915	0.234	0.833	1.000	0.836	1.000
C*D*E	0.068	0.265	0.705	0.623	0.915	0.002	0.833	1.000	0.410	0.683
A*B*C*D	0.109	0.708	0.451	0.078	0.173	0.000	0.527	0.838	0.410	0.109
A*B*C*E	0.167	0.265	0.137	0.743	0.342	0.036	0.673	1.000	0.536	0.073
A*B*D*E	0.042	0.265	1.000	0.743	0.915	0.631	0.400	1.000	0.679	0.540
A*C*D*E	1.000	0.265	0.850	0.870	0.915	0.472	1.000	1.000	0.836	0.540
B*C*D*E	1.000	1.000	0.451	0.870	0.915	0.002	0.751	1.000	0.679	0.225
A*B*C*D*E	0.068	1.000	0.571	0.870	0.915	0.234	0.916	1.000	0.836	0.030
R-Sq (%)	99.72	99.77	98.84	99.60	99.54	99.45	95.61	99.04	99.74	99.80
Most Significant Factor	A	A	A	B	A	D	A	A	B	A

محاكاة إدارة المشاريع الإنشائية بإستخدام الأنظمة الديناميكية

إعداد
أحمد عوني أبو السباع

المشرف
الأستاذ الدكتور غالب يوسف عباسي

ملخص

على الرغم من أن الوسائل التقليدية لإدارة المشاريع تزودنا بالدعم المفيد، إلا أنها في أغلب الأحيان تبدو وكأنها على علاقة ضعيفة بالمشاريع الواقعية، وتشير التجربة إلى أن العلاقة بين مختلف مكونات المشروع تكون أكثر تعقيدا مما تقترحه الطريقة التقليدية لهيكل تقسيم العمل في شبكة المشروع. وتقدم الأنظمة الديناميكية وجهة نظر بديلة للمشروع وهي التركيز على المشروع بأكمله.

في هذه الدراسة ، تم استخدام نموذج للنظر في الآثار المترتبة على الأحداث المختلفة وآثارها على المشاريع باستخدام برامج المحاكاة بالحاسوب . في هذا البحث، تم استخدام أربعة هياكل للتغذية الراجعة (العمل المراد إعادته، الموارد البشرية، سلوك العميل ومجال المشروع) التي تمثل نماذج الأنظمة الديناميكية القائمة على المشاريع الإنشائية. وتم تطبيق تحليل الحساسية بطريقة واحدة وبعدة طرق على النموذج لإيجاد العامل المتغير الذي كان له دوراً كبيرا في التأثير على سلوك النظام . لذلك، فإن الهدف الرئيسي من هذا البحث هو معرفة العامل المتغير الذي له التأثير الأكبر على نتائج نموذج الأنظمة الديناميكية.

تم إنشاء خمسون مجموعة من البيانات المدخلة للمشروع لاختبار حساسية سلوك النموذج ، وتم التوصل إلى ثمانية عوامل تؤثر على وقت الوصول إلى قيمة الإتزان وهي (زمن إضافة العمل المراد إعادته وزمن تعديل كمية العمل وزمن الإستقالة وزمن التدريب وزمن التوظيف وعدد العمال المتوفرين وزمن تعديل عدد العمال والإنتاجية). وتبين أن هناك خمسة من هذه العوامل الثمانية كانت في غاية الأهمية للدراسة في مرحلة تحليل الحساسية بعدة طرق وهي (زمن إضافة العمل المراد إعادته وزمن تعديل كمية العمل وعدد العمال المتوفرين وزمن تعديل عدد العمال والإنتاجية). تم اختيار طريقة تصميم المضروب لهذا البحث مع وجود مستويين للعوامل الخمسة. وقد وجد أن 35 مشروعاً قد تأثرت بشكل كبير في تغيير معدل الزمن اللازم لإضافة واكتشاف العمل المراد إعادته.

وبينت نتائج الدراسة أن عمليات التطوير كان لها تأثيراً كبيراً على السلوك الديناميكي للمشاريع من خلال التغذية الراجعة والتأخير الزمني والعلاقات غير الخطية التي لا تستخدم في نماذج المشروع التقليدية، ولكنها تعتبر وصف هام لتعقيدات المشروع . لذلك، ولفعالية إدارة المشروع ، فإن كلا الجانبين التشغيلي و الإستراتيجي يجب أن يعالجا بشكل سليم