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Total Ownership Cost Modeling Of Technology Adoption Using System Dynamics: Implications For Erp Systems

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TOTAL OWNERSHIP COST MODELING OF TECHNOLOGY ADOPTION USING SYSTEM DYNAMICS: IMPLICATIONS FOR ERP SYSTEMS

by

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ABSTRACT

Investment in new technologies is considered by firms as a solution to improve their productivity, product and service quality and their competitive advantages in the global market. Unfortunately, not all technology adoption projects have met their intended objectives. The complexity of technology adoption along with little consideration of the long term cost of the technology, are among the factors that challenge companies while adopting a new technology.

Companies often make new technology adoption decision without enough attention to the total cost of the technology over its lifecycle. Sometimes poor decision making while adopting a new technology can result in substantial recurring loss impacts. Therefore, estimating the total cost of the technology is an important step in justifying the technology adoption. Total Ownership Cost (TOC) is a wildly-accepted financial metric which can be applied to study the costs associated with the new technology throughout its lifecycle. TOC helps companies analyze not only the acquisition and procurement cost of the technology, but also other cost components occurring over the technology usage and service stage.

The point is that, technology adoption cost estimation is a complex process involving consideration of various aspects such as the maintenance cost, technology upgrade cost and the cost related to the human-resource. Assessing the association between the technology characteristics (technology upgrades over its life cycle, compatibility with other systems, technology life span, etc) and the TOC encompasses a high degree of complexity. The complexity exists because there are many factors affecting the cost over time. Sometimes decisions made today can have long lasting impact on the system costs and there is a lag between the time the decision is taken and when outcomes occur.

An original contribution of this dissertation is development of a System Dynamics (SD) model to estimate the TOC associated with the new technology adoption. The SD model creates casual linkage and relationships among various aspects of the technology adoption process and allows decision makers to explore the impact of their decisions on the total cost that the technology brings into the company.

The SD model presented in this dissertation composes of seven sub-models including (1) technology implementation efforts, (2) workforce training, (3) technology-related workforce hiring process, (4) preventive and corrective maintenance process, (5) technology upgrade, (6) impact of technology on system performance and (7) total ownership cost sub model.

A case study of Enterprise Resource Planning (ERP) system adoption has been used to show the application of the SD model. The results of the model show that maintenance, upgrade and workforce hiring costs are among the major cost components in the ERP adoption case study presented in Chapter 4.

The simulation SD model developed in this dissertation supports trade-off analysis and provides a tool for technology scenarios evaluation. The SD model presented here can be extended to provide a basis for developing a decision support system for technology evaluation.

To:

My parents for their never ending support, belief and patience

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I want to confess that the secret of my success during PhD study was ‘positive thinking’ and following my heart while I was reminding myself these great sentences of one of our world leaders in technology and entrepreneurship. “You can’t connect the dots looking forward; you can only connect them looking backwards. So you have to trust that the dots will somehow connect in your future. You have to trust in something – your gut, destiny, life, karma, whatever. Because believing that the dots will connect down the road will give you the confidence to follow your heart even when it leads you off the well-worn path; and that will make all the difference.” Steve Jobs. I learned so many valuable leadership and management skills while I was working for my PhD degree with Dr. Waldemar Karwowski, the Professor and Chair of the IEMS Department. I consider myself very lucky to have the chance to work with him and I would like to express my sincere and profound appreciation for all his advice, patience and constant support during my doctorate study.

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CHAPTER 1
INTRODUCTION

1.1. Background

The rapid changing of business environments and the current global marketplace have resulted in increased interest among companies in investing in new technologies to increase their competitiveness in terms of quality, cost, and process flexibility as a way for survival and growth (Chuu, 2009). Unfortunately, not all technology implementations succeed. While some companies report significant profits as a result of technology implementation, others have not been successful (Small & Chen, 1997). The complexity of balancing technology implementation benefits against cost overruns continues to challenge managers as they try to bring improved new technologies in to their organizations.

When an organization is trying to buy or integrate a new technology, the cost estimation should not only be focused on reducing system acquisition and procurement costs, but considerable efficiencies may be gained by adopting a cost assessment approach that considers costs associated with the new technology throughout its lifecycle. Technology adoption decisions can significantly impact subsequent maintenance, personnel, training, system performance such as cycle time and throughput, and sustainment costs that often are not considered during the adoption decision process.

Total Ownership Cost (TOC) is a common decision metric and financial estimate, which can be used to understand the economic impact of integrating a particular technology. Making smart decisions about how to acquire a new technology, when to trade, and how much budget to invest in adopting the new technology can reduce total costs. All of these decisions require an advanced understanding of TOC drivers including the costs of developing, implementing, owning and operating new technologies. However, investigating the technology-related TOC is not an easy task.

The technology adoption decision is a complex multiple attribute problem involving the consideration of long term impacts of technology on various aspects of the system from the impact on the production cycle time to the impact on the employees satisfaction and total cost. Therefore, many variables should be considered in justifying a particular technology selection. Moreover, assessing the relationships between the characteristics of technology (e.g. maturity of the technology, compatibility with other systems, technology life span, etc) and the TOC includes a high degree of complexity. The complexity exists because the advantages of adopting such technologies are not certain and there are many factors associated with the integration process that affect the final result. Moreover, the variables impacting decision results vary over time and often the outcomes are not known at the decision-making time. Sometimes decisions made today have a long term effect on system costs and there is a long lag between the time in which decisions are made and the time the outcomes are known.

System Dynamics (SD) modeling is a tool that can be applied to facilitate decision making in such a complex process. SD defines casual linkage and relationships between various attributes (variables) of the technology and allows decision makers to study the impacts of different decisions, analyze results, and learn about variables that affect the results. In addition, the SD model incorporates various complexities of the technology integration process, time lags, causal factors, and feedback effects into account.

This dissertation proposes a SD model to assess the cost and complexity of technology adoption in a company. The proposed model consists of four categories of variables: variables representing the characteristics of the proposed technology (e.g. required set up time, maturity, reliability, etc), variables describing the impacts of the technology on the performance of the system and, variables representing the impact of the technology on human resources and variables describing the implementation activities.

The resulting SD model provides an advanced and deeper understanding of TOC components from initial integration activities to the cost of operating and support activities. The proposed SD model allows companies managers to better understand causal factors impacting the technology adoption process and the resulting cost patterns. It also allows them to objectively evaluate technology alternative policies and conduct sensitivity analysis.

1.2. Statement of the Problem and Research Gap

Companies are trying to increase their competitive advantages and decrease their costs by investment in advanced technologies (Tan et al. 2006). In fact, in the current competitive market there is no choice between whether to adopt new technologies or not. The companies can only decide about the type and the extent of the technology investment (Da Costa & De Lima, 2009). Therefore, almost every organization faces the decision on the technology adoption. However, not all of the technology implementation will succeed. The development of appropriate justification methods are necessary to make sure that technology implementations are justified for all the expenditures related to their operation and acquisition (Small & Chen ,1997).

One point in economic validation of a technology implementation decision is the quantification of all the benefits and costs. While the technology acquisition costs are generally not hard to evaluate, the long term effects of the technology on the system such as the required maintenance activities, the personnel and skill sets needed to operate the system, and the improved system productivity, are difficult to evaluate.

One way to consider the overall cost of integrating a new technology is to apply the total ownership cost concept. TOC gives a cost basis for calculating the total economic value of an advanced technology investment. Gartner's definition of TOC describes it as “the costs incurred throughout the lifecycle of an asset, including acquisition, deployment, operation, support, and retirement”. TOC not only looks at the initial purchase price, but also it considers all the costs during the investment life span (Yam & Wei, 2003).

A review of the prior studies on technology adoption evaluation shows that the technology evaluation problem is a multi-attribute decision-making problem (Chuu, 2009). The arising uncertainty and complexity of decision situations make it difficult for managers to consider all relevant aspects of the problem (Chen & Ben-Arieh 2006). The point is that the organizations do not have the means to capture the rich and complex interactions among all aspects of technology integration processes and their impacts on TOC. Moreover, technology-related decisions usually occur temporarily or in a complex environment. Most of the current decision theories and tools evaluate the impact of technology decisions at one instant of time rather than considering the dynamic nature and impacts of the decisions over time. A systemic model is needed to help policy decision makers to fully analyze the impacts of their decisions and consider the complexity and the dynamic nature of technology management practices.

SD approach gives decision makers the ability to investigate different characteristics of the new technology and understand their effects on the TOC elements. Considering the life cycle impact that a decision may have is particularly important in companies where the impact of the decision made today may bring hundreds of millions expenses later over the life cycle (Scott, 2003). Therefore, justification of investment in new technologies should include studying the TOC including consideration of the operational and support costs as well as consideration of the acquisition costs and the human resource costs.

Similar to the concept of product life cycle, we assume that a new technology goes through phases during its entire life span from development, integration, operations and support to disposal stage. Several approaches have been developed for justifying investment in new technologies, however not much research has been done to study the dynamics perspective of technology integration processes. Small (2006) categorized the literature which covered the technology evaluation approaches in three groups: (1) the *economic approaches* including the typical financial evaluation methods such as Return on Investment (ROI), Payback Period (PP), and Net Present Value (NPV), (2) the *strategic approaches* including analysis of the competitive advantages and technical consequence and (3) the *analytic approaches* such as value and risk analysis (Chuu, 2009)(Lefley et al. 2004)(Raafat, 2002)(Naik & Chakravarty, 1992). The mentioned approaches usually favor short term perspective on the technology adoption projects evaluation and are based on crisp measurement and accurate evaluation without consideration of the technology characteristics (e.g. maturity, reliability and compatibility with other systems). Therefore a model is needed to study the dynamics the system behavior over time and the total impacts that the technology characteristics will have on the TOC. The SD model proposed in this dissertation advances understanding of TOC drivers and evaluates impacts of technology characteristics on total ownership cost. To the best of our knowledge, this study is among a few studies that use SD to evaluate the technology implementation. Moreover, different aspects of technology adoption have been covered in this research.

1.3. Research Objectives and Scope

The primary objective of this research is to develop a system dynamics model to determine the total ownership cost of adopting a new technology. In addition to analyzing the TOC, the developed model supports managers by providing a better understanding of different aspects of the system influenced by technology adoption (such as automation level, required maintenance activities, required skill sets, personnel training, system performance). Specifically, the objectives of the study can be summarized as follow:

- To develop a system dynamics model to estimate total ownership cost of adopting a new technology.
- To support decision makers with better understanding of different aspects of new technology adoption process including technology implementation stage, workforce hiring and training, technology upgrade, maintenance and support, and the impact of technology on system performance.

The scope of the model is illustrated in Figure 1.There are four main categories of variables in the model.

- *Technology features*: variables describing technology features (maturity, lifespan, reliability, compatibility, complexity, initial investment required, etc)
- *Process and System variables*: variables describing the elements of the system affected by technology implementation (system performance, upgrade, maintenance workload, etc)
- *Human resource-related variables*: variables representing the human resource aspect of the system affected by technology implementation (number of personnel, required skill set, required training, etc)
- *Variables associated with Implementation phase*: such as initial resource involvement, implementation time and budget allocated to technology.

The focus of the model is on three categories of costs: (1) implementation and investment costs (2) the costs associated with human resource, (3) the maintenance and support costs. The mentioned costs occur during the technology acquisition state and the sustainment stage. The SD model provides managers a better understanding of the technology insertion process. Moreover, identification of the TOC elements will facilitate the development of TOC theoretical models.

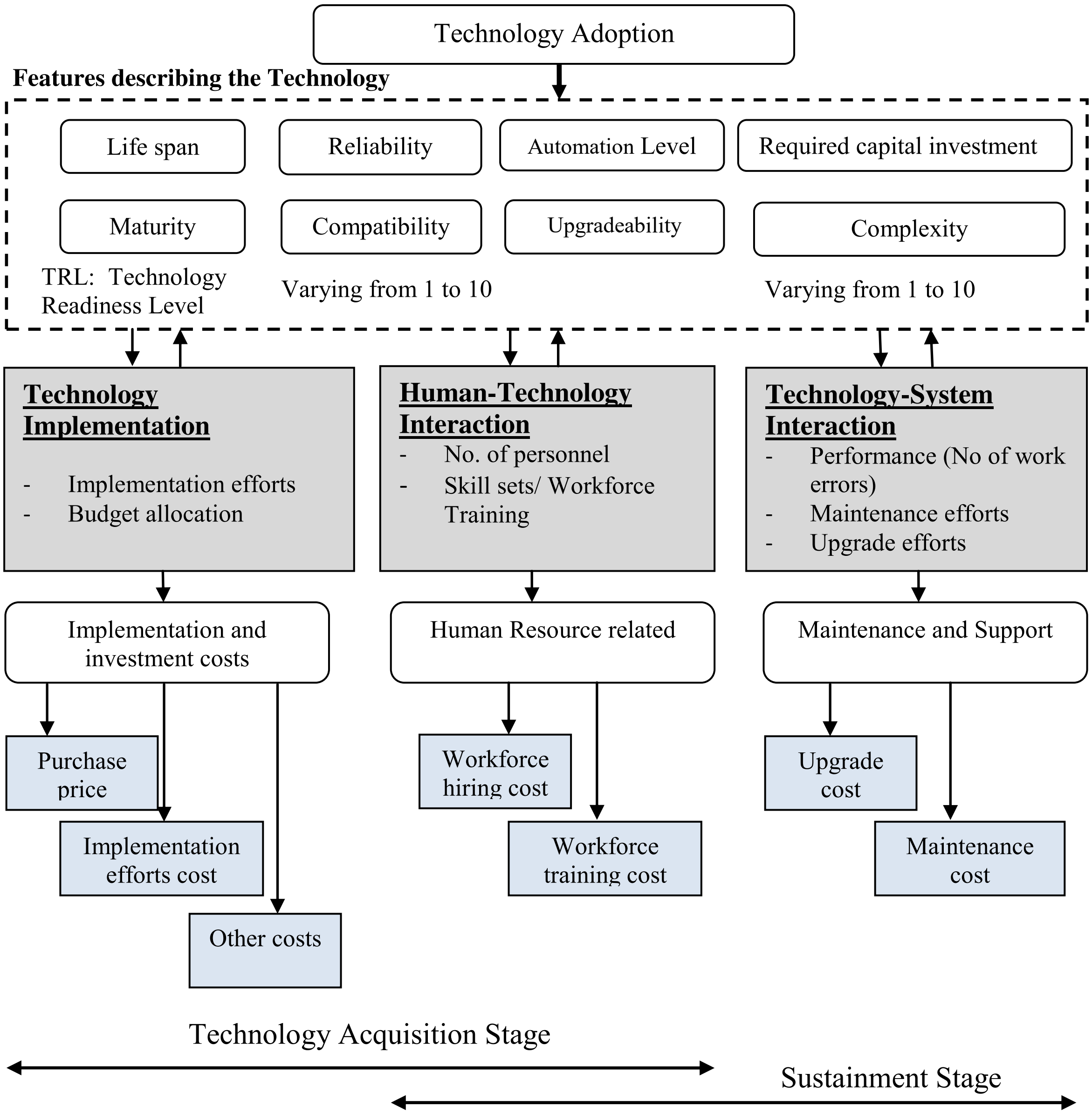


Figure 1. Framework of the model

1.4. Research Questions

The main objective of this dissertation is to develop a System Dynamics model that can help decision makers determine the total ownership cost of a new technology. Therefore, the main question addressed in this research is: what is the total ownership cost of adopting the new technology? This research question is divided into two sub-questions:

Question 1: What are the different aspects of technology adoption process?

New technology adoption is a complex problem with many variables to be considered (Yusuff, Yee, & Hashmi, 2001). These factors vary from the technology implementation stage to the challenge of supporting and upgrading the technology implemented. The first step in creating the SD model is to identify the complexity factors and determine the connection among them.

Question 2: What is the total ownership cost associated with adopting a new technology? (For example, in the case of adopting an ERP system, the question is: what is the total cost that the ERP system brings into the company over a long term horizon?)

After identifying the main elements and features that made up the complexity in the technology integration process, the next step is to identify the relation among different elements and determine how those factors affect the TOC components. An appropriate cost model provides decision makers with helpful information needed to make better decisions and evaluate different available technology alternatives. A case study of an ERP system adoption is used to show how the SD model developed in this dissertation helps decision makers answer the above questions.

1.5. Expected Benefits and Contributions of the Research

The research investigation potentially makes two significant contributions to the body of knowledge.

- First, the current study developed a dynamic model with feedback loops considering the complex and interconnected characteristics of the technology integration process. Technology integration process contains various interconnected activities, variables or factors. The interaction between these factors creates dynamic behavior within the technology adoption process. The SD approach used in this study provides a tool to model the structure present within the companies that leads to a dynamic behavior.
- Second, this research is the first study that uses the SD modeling to bring together various aspects of technology adoption process (implementation, human resource, maintenance and upgrade) to evaluate technology adoption through TOC modeling. While new technology adoptions provide a wide range of benefits, companies also deal with a set of impediments that stop them from adopting new technologies. One category of problems facing companies is the cost-related problems (Baldwin & Lin 2002). Cost-related problems include elements such as investment cost, cost of implementation activities, and increased maintenance and support expenses. The SD model provided in this research investigates how new technologies integration affects TOC. Specifically, the developed model captures and simulates three TOC elements: (1) the cost of technology implementation activities, (2) human resource-relate costs such as the training cost and the cost of planning and recruiting required skill sets and (3) the cost of the operational and support activities over the technology life cycle. The developed SD model supports tradeoff analysis and selection of technology implementation scenarios based on

TOC. The expected outcome of this study is a model that helps decision makers understand the dynamic behavior that characterizes the technology integration processes. The model can be used for evaluating available technology scenarios.

1.6. Approach and Research Method

The method used in this research is system dynamics developed by MIT Professor Jay W. Forrester in the mid-1950s. SD provides a model to analyze the dynamic behavior of complex systems from a whole system point of view. SD is a powerful tool in modeling complex social, economic, ecological or managerial systems, better say any dynamic systems featured by mutual interaction, circular and indirect causality and information feedback (Sterman, 2000).

What distinguishes SD from other typical engineering models is that it concentrates on system information feedback. The typical approach of modeling dependent/independent variables does not cope with complex systems (Scholl, 2001). As pointed out by Jay W. Forrester the cause and effect often are not directly related in complex systems. This is because the structure of complex systems are not just a simple feedback loop, but a multiplicity of feedback loops affecting each other. There are often some nonlinear interrelationships among variables that may alternate over time. "*In the complex system the cause of a difficulty may lie far back in time from the symptoms, or in a completely different and remote part of the system*" (J. W. Forrester, 1969). Therefore, we should look for the causes of the problem in the structure and policies of the system not just the prior events and variables.

SD provides us feedback based models and helps investigate systemic problems at an accumulated level during time. It should be noted that the purpose of SD is not point prediction but to provide insight about the overall behavior of the complex system. SD provides a method to analyze the characteristics of the nonlinear information-feedback complex system. The inter-relationship between any two components in a complex system is often nonlinear. Typical engineering models cannot help us describe non-linear interrelation between those factors. Even if some nonlinear functions are developed to describe such a system, it is not easy to solve those models. Therefore, the simulation results of the SD modeling can be applied to characterize the system behavior over time (Yuan, 2009).

There are several commercial software packages for creating SD models including: AnyLogic, Simulink, DYNAMO, TRUE, iThink/STELLA, VisSim, PowerSim and Vensim. The modeling software used in this research is Vensim PLE software (v5.11). Vensim is made by Ventana Systems, Inc and provides the opportunity to simulate dynamic complex processes and is capable of creating and evaluating extensive simulation loops for various alternative scenarios. The main difference between Vensim and other SD software like Stella, Powersim, etc, is the 'Reality Check' feature available in PLE version that gives the modeler a straightforward way to make statements s/he think must be true about a model for it to be useful (e.g. 'Without any budget there is no technology implementation', or 'without any workers we can't train them), and the software automatically tests the model for conformance with those statements. 'Reality Check' feature in Vensim adds significantly to our ability to validate and defend the models we create. Moreover, among available commercial software, Vensim is the only one to allow external and user-defined mathematical function calls. Other software packages provide only simple mathematical functions (e.g. abs, sin, min and max) and do not allow for more analytical descriptions (Ventana Systems Inc, 2012).

The modeling process consists of five phases: (1) The conceptualization phase (2) the formulation phase, (3) the model development phase, (4) the model evaluation and testing phase and (5) the analysis and policy design phase. The proposed methodology follows the general structure of the methodology indicated by John Sterman in his book, *Business Dynamics: Systems Thinking and Modeling for a Complex World* (2000). The reputation of the book as the handbook of system dynamics provides a support for the use of this methodology.

Phase (1): the conceptualization phase

The first step is to clearly define the problem and specify the scope of the work. The frame of the work defines what should be in the model and what should be excluded. For the purpose of this research, the developed model consists of three parts shown in Figure 1:

1) The new technologies integration processes and the corresponding cost components
2) The Technology-System Interaction
3) The Technology-Human Interaction

Phase 2. the formulation phase

After defining the problem and the scope of the work, the next step is to develop a 'mental model' of the real world. The 'mental model' is a verbal description of the feedback loops in the system (Luna-Reyes & Andersen, 2003). The feedback loops in the system are assumed to result into the reference modes. Reference modes are the behaviors of the system's key variables over time.

The behaviors of system's variables usually are shown in graphs. There are three basic modes of observed behavior in a dynamic system including exponential growth, goal seeking, and oscillation. These modes are shown in Figure 2 and discussed in detail in Sterman's book (2000). The behavior of a variable in the model could be one of the fundamental modes or an interaction of two or more of the dynamic behaviors mentioned above

Figure 2. Fundamental modes of behavior (Sterman, 2000)

Using the current knowledge and experience of our research team supplemented by reviewing relevant literature and available data, the initial characterization of the problem is developed. Various opinions arise during this phase and the idea is to capture as much of them as possible. Finally, the related variables are selected and the variables that do not add too much to the model are excluded. The Causal Loop Diagrams (CLD) are used in this phase to model the feedbacks structure of the system. CLDs are discussed in more detail in Chapter 2.

Phase 3. the model development phase

This phase starts formulating the simulation model. The purpose is to connect the different explanations of the feedback loops into one single model that simulates the different behaviors defined in Phase 2. The system description provided in Phase 2 is translated into the level and rate equations of a system dynamics model. The detailed model created in this phase contains a formal structure complete with equations, parameters and initial conditions that represent the system. At the end of this phase, all variables and equations are defined and the units of measurement are consistent throughout the model.

Phase 4. the model evaluation and testing phase

This phase concentrates on testing the model to assure it shows the behavior of the real world system. A case study of implementing an Enterprise Resource Planning (ERP) system in an educational institute is represented in Chapter 4 to show the application of the model. The results of the SD model have been compared with the real data. In addition, some sensitivity analyses are conducted to show the model robustness when changing the parameters of the model.

Phase 5. the analysis and policy design phase

The analysis phase is a process of deriving insights and describing the results of the model. It requires discussion more than examination of parameter values and equation formulation. This phase consists of two main parts:

- To analyze the behavior of all system variables over time
- To analyze the validity and sensitivity of the mode to changes in: (1) structure, (2) policies and (3) delays, uncertainties.

New policies and scenarios can be developed and their impact on the final goal of the system can be evaluated. The analysis phase involves the identification of policies that can be changed or modified to improve the behavior of the system toward its goal. Figure 3 provides a graphical representation of the five phases mentioned above.

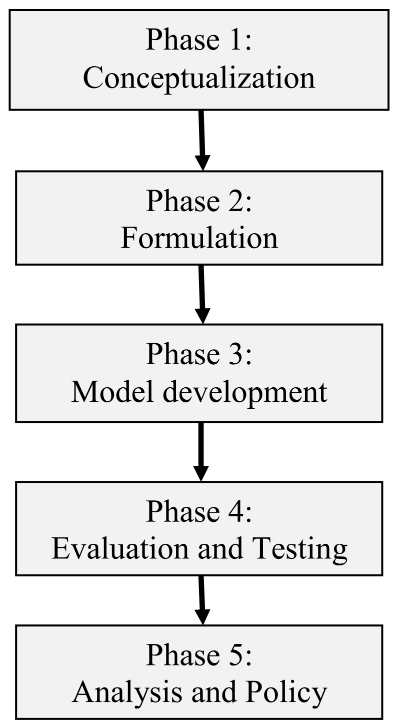


Figure 3. Research method flowchart

1.7. Organization of the Dissertation

The remainder of this document is organized as follows. Chapter 2 reviews the previous literature including technology definition, technology complexity and maturity, technology selection methods, system dynamics modeling tools, SD in technology integration and implementation activities, human-system integration, cost estimation techniques and total ownership cost. Chapter 3 provides an overview of the SD model created in this dissertation.

Chapter 4 uses a case study of an ERP system to show the application of the model in estimating the total cost of adopting a new technology. Finally, Chapter 5 concludes the document and discusses the future work.

CHAPTER 2
LITERATURE REVIEW

2.1. Introduction

Advanced technologies are expected to be critical and strategic for the survival and growth of any company. New technologies improve the company's performance in several ways such as improving the productivity, lowering the cost of rework, decreasing the cost of direct manpower, reducing the cycle time and increasing the production capacity (Harvey et al. 1992). The decision on whether to adopt a new technology or not depends on the advantages the technology implementation creates and the overall cost of its implementation (Baldwin & Lin 2002).

Technologies implementation projects that go over time and budget provide considerable financial and strategic organizational results. Some believe that insufficient planning, team capabilities and learning, and misunderstanding of specification and requirements, are the reasons behind cost and schedule overruns (Plaza et al. 2010). Some argue that these technology integration projects are often mismanaged because corporations apply the wrong process to manage them or apply inappropriate financial criteria for technology selection (Cooper, 2006). It is necessary for companies to manage their technology integration projects more effectively such that those projects truly do achieve their promised results.

The purpose of this chapter is to provide a literature review on different categories of technology, the features of technology (e.g. complexity, reliability, compatibility, maturity, etc) and the application of system dynamics modeling to understand new technology adoption activities. The literature review discusses the studies that have employed system dynamics as a tool to study the non-linear and complex relationship among elements of technology implementation activities. Different technology-related subjects from technology development capacity and commercialization of technology to technology resource management will be discussed. Moreover, this chapter provides overviews on the human-technology integration activities and the cost estimation techniques. Also it explains TOC and the total life cycle cost of a system.

The remaining part of this document is organized as follows. Section 2 and 3 briefly describe the technology definition, and the complexity associated with the technology activities. The maturity of technology as one of the main features of technology will be discussed in Section 4. Section 5 summarizes decision making methods available for selecting technology alternatives. Section 6 presents SD modeling technique. Section 7 reviews the studies that have used system dynamics to investigate the technology-related topics such as technology integration activities, technology selection, technology development capacity, technology resource management, commercialization of technology and technology assessment. Section 8 explains the critical success factors influencing technology adoption. Section 9 discusses the impacts of technology adoption on the human resource. The cost estimation techniques are reviewed in Section 10. Section 11 reviews the studies that have applied SD for cost estimation. Section 12 describes the concept of total ownership cost and the total life cycle cost of a system. The cost estimation of human related factors is briefly discussed in Section 13 and finally, Section 14 concludes the chapter.

2.2. Technology Definition

'Technology' is a fairly new word suggested by Jacob Bigelow, Professor in Harvard, in the 1820's. In modern English, technology comes from 'techne' meaning 'things technical' and 'ology' meaning 'an area of learning'. In Greek, technology comes from 'Techne' meaning 'art, craft, or skill' and 'logia' meaning 'word, or logic'. In indo-euro, the root of technology comes from the root of 'teks' meaning 'weave or fabricate'.

Technique and Technics are two related terms to technology. Technique means 'a method of accomplishing a desired aim' and Technics means 'the products of human fabrication for example a computer'. Merriam-Webster dictionary defines 'technology' as "The practical application of knowledge especially in a particular area." Technology ranges from a piece of knowledge, a method or technique to a complex system of machinery and its inherent intelligence (Geisler, 2000). Peter Drucker in 1992 defined technology as "the application of knowledge to human work". Kranzberg and Pursell mentioned that "Technology …deals with human work, with man's attempts to satisfy his wants by human action on physical objects" (Ormiston, 1990). Volti (2010) in his book '*Society and Technological Change'* presented technology as "A system based on the application of knowledge, manifested in physical objects and organizational forms, for the attainment of specific goals".

2.3. Technology Complexity

In practice, while some companies that implement new technologies announce significant profit, the technology implementation remains risky for others (Chuu, 2009). For example, 50%

to 75% of the advanced manufacturing technology implementation efforts in the US do not result in success (Chung, 1996). The failure rate especially is high in the IT investment projects. The Standish Group (a company that provides IT investment planning research and services) reports that only 28% of all IT application development projects have successfully implemented in 2000. About 23% of the projects have been stopped before completion or never completed, while 49% completed but failed to achieve the designated goals in terms of time, cost, or specifications (Camci & Kotnour, 2007). These examples of technology integration projects failures show how complex technology projects are. The complexity of the technology and the human-related issues are two impediments toward successful implementation of a new technology (Chung, 1996).

Organization theory defines complexity as an objective property of the system, their diversity and relationships (Li et al. 2010). According to Fioretti and Visser (2004) complexity is defined “in terms of inadequacy of the knowledge needed to solve a problem”. Technology complexity can be classified into two groups (Figure 4):

- Product complexity,
- Methods complexity.

Product complexity represents the complexity of the product or service that the technology integration project intends to deliver. This subcategory of technological complexity covers complexities associated with processes and products. While methods complexity relates to the complexity of the processes, tools, techniques and methods that the technology integration project employs to deliver its goals (Camci & Kotnour, 2007). In terms of complexity, Small (2007) divided technologies into three groups: high complexity, the moderate complexity and low complexity. For example in the manufacturing companies, the CNC and CAD are examples of the technologies with low complexity. The integrated information technologies such as MRP are among the technologies with intermediate level of complexity and the integrated process technologies (e.g. Flexible Manufacturing System, Computer Integrated Manufacturing) are technologies with high complexity.

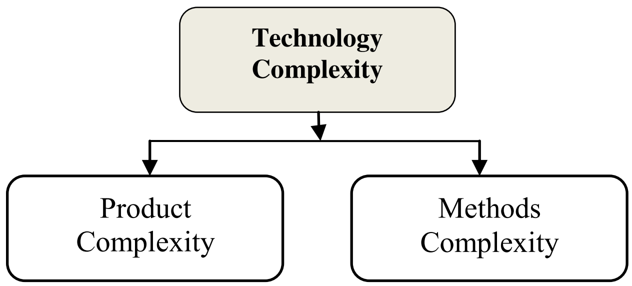


Figure 4. Technology Complexity (Camci & Kotnour, 2007)

2.4. Technology Maturity

In order to successfully integrate a new technology in the system, it is also necessary to first identify the level of the technology maturity. A technology is called mature if it has been in use for long enough time that most of its inherent problems and initial faults have been omitted or reduced by further development. For example, while CAD/CAM has been in use in manufacturing companies for several decades, the CIM systems are still new and require development of a large scale technology structure and high investment. Identifying the level of the technology maturity can be accomplished through the use of a generally understood metric. One such metric is Technology Readiness Level (TRL) (Sauser et al. 2010).

TRL was originally introduced by the National Aeronautics and Space Administration (NASA) to rate the readiness of technology for potential use in space flight. After that, the US

Department of Defense (DoD) started employing TRL to assess new technology for insertion into a weapon system. With the broad application of TRL within NASA and the DoD, other US government organizations such as Department of Energy (DoE) and Sandia National Laboratory have also used the TRL scale. Currently, TRL plays an important role in the decision making and development projects at both NASA and DoD (Sauser et al. 2010).

Technology has a life cycle from the incubation to the growth, maturity and decline. Different technology life-cycle stages are characterized by S curves shown in Figure 5. Technology maturity changes along different life cycle stages.

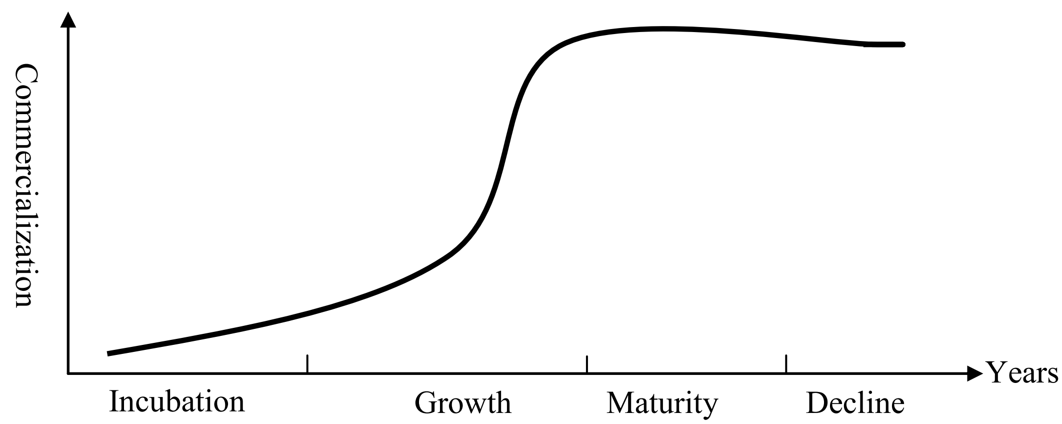


Figure 5. Technology maturity stages form an S curve [modified from (Altunok & Cakmak, 2010)]

Technology readiness consists of nine levels. Summary of TRLs are listed in Table 1. Project managers in defense projects usually select the technologies at TRL 6 or higher levels. The lower maturity for technology is not preferred since more effort is required to advance that technology to a readiness level which is appropriate for inclusion into an acquisition (Altunok & Cakmak, 2010).

Table 1. Definitions of Technology Readiness Levels by (Altunok & Cakmak, 2010)

TRL	Dentitions
1	“Basic principles observed”
2	“Technology concept and/or application formulated”
3	“Analytical and experimental critical function and/or characteristic proof of concept”
4	“Component and/or breadboard validation in laboratory environment”
5	“Component and/or breadboard validation in relevant environment”
6	“System/subsystem model or prototype demonstration in a relevant environment”
7	“System prototype demonstration in an operational environment”
8	“Actual system completed and qualified through test and demonstration”
9	“Actual system proven through successful mission operations”

Figure 6 shows the standard TRL scale developed initially by NASA.

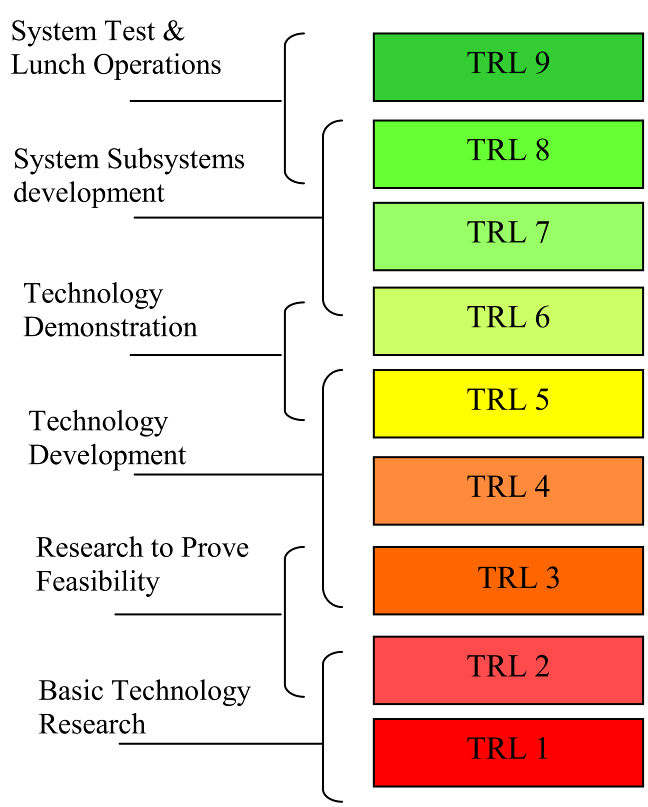


Figure 6. Graphical view of Technology Readiness Level scale [Modified from (Mankins, 2009)]

TRL is useful to identify the level of maturity toward systems applications that a technology has achieved. However, it is not able to address the problem of "difficulty" in R&D progress. For example, it is not clear how hard it will be to move from one TRL to another level for a given set of R&D objectives (Mankins, 2009). To address this issue, another figure of merit called 'R&D degree of difficulty' (R&D3) has been introduced. Table 2 lists different levels of this new technology management tool proposed by Mankins (2002).

Table 2. Research and development degree of difficulty scales defined by (Mankins, 2002)

R&D Degree of Difficulty scale	
$R\&D^3 = 1$	"Probability of Success in "Normal" R&D Effort Greater Than 95% to 99% : A very low degree of difficulty is anticipated in achieving research and development objectives for this technology area (including both the system concept, as well as performance, reliability and cost goals)."
$R\&D^3 = 2$	"Probability of Success in "Normal" R&D Effort Greater Than 90%: A moderate degree of difficulty should be anticipated in achieving R&D objectives for this technology area"
$R\&D^3 = 3$	"Probability of Success in "Normal" R&D Effort Greater Than 70% to 80%: A high degree of difficulty could be anticipated in achieving R&D objectives for this technology."
$R\&D^3 = 4$	"Probability of Success in "Normal" R&D Effort Greater Than 50% to 60%: A very high degree of difficulty could be anticipated in achieving R&D objectives for this technology."
$R\&D^3 = 5$	"Probability of Success in "Normal" R&D Effort Less Than 30% to 40%: The degree of difficulty should be anticipated in achieving R&D objectives for this technology is sufficiently high that a real "engineering breakthrough" in physics/chemistry/etc. is needed."

Table 3. Technology Need Values (Mankins, 2009)

TNV-1	"The technology effort is not critical at this time to the success of the program-the advances to be achieved are useful for some cost improvements, however, the information to be provided is not needed for management decisions until the far-term"
TNV-2	"The technology effort is useful to the success of the program-the advances to be achieved are meaningfully improve cost and/or performance, however, the information to be provided is not needed for management decisions until the mid- to far-term"
TNV-3	"The technology effort is important to the success of the program-the advances to be achieved are important for performance and/or cost objectives AND the information to be provided is needed for management decisions in the near- to mid-term"
TNV-4	"The technology effort is very important to the success of the program-the advances to be achieved are enabling for cost goals and/or important for performance objectives AND the information to be provided would be highly valuable for near-term management decisions"
TNV-5	"The technology effort is critically important to the success of the program at present-the performance advances to be achieved are enabling AND the information to be provided is essential for near-term management decisions"

The Technology Need Value (TNV) is a weighting factor based on the assessed importance of a particular technology development toward the ultimate systems application goals such as an improvement in performance and operability. Table 3 lists the TNV levels defined by Mankins (2009).

The TRL, R&D3 and TNV provide a common language by which technologists, senior managers and systems developers may communicate regarding three important considerations in technology investment decisions (Mankins, 2009).

(1) TRL can be used to determine the current level of maturity of the technology, and the maturity level target.

(2) R&D3 can be used to determine how hard it is to advance the current technology maturity level (current TRL) to the maturity target level (future TRL)

(3) TNV can be used to determine the importance of a given technology to the overall goals of the R&D program.

TRL supports assessment of the developmental maturity of individual technologies but is not able to address the integration issues between various technologies, which are unavoidable from a system's perspective (Tan et al. 2011). Therefore, in addition to the above mentioned metrics, some other figures of merit for technology have been developed to assess the risk associated with the development and operation of technologies and systems. Manufacturing Readiness Level (MRL), and Integration Readiness Level (IRL) are two examples of those metrics. The MRL is a 10 level scale applied to define current level of manufacturing maturity and identify maturity shortfalls and risks. The IRL is a 7 level scale used to systematically determine the compatibility, and readiness of interfaces between different technologies and consistently compare interface maturity between several integration points. Integration readiness levels are defined in Table 4.

Table 4. Definitions of Integration Readiness Levels by (Sauser et al. 2010)

IRL	**Definition**
7	"The integration of technologies has been verified and validated with sufficient detail to be actionable."
6	"The integrating technologies can accept, translate, and structure information for its intended application."
5	"There is sufficient control between technologies necessary to establish, manage, and terminate the integration."
4	"There is sufficient detail in the quality and assurance of the integration between technologies."
3	"There is compatibility (i.e. common language) between technologies to orderly and efficiently integrate and interact."
2	"There is some level of specificity to characterize the interaction (i.e. ability to influence) between technologies through their interface."
1	"An interface (i.e. physical connection) between technologies has been identified with sufficient detail to allow characterization of the relationship."

The use of these metrics is a method for making sure that unexpected results will not happen. The above mentioned techniques are categorized among qualitative metrics due to their descriptive nature defining each metric on a scale of 0-XX. These metrics simplify many aspects of readiness and maturity into one value. Moreover, the definition behind the description of each level of these metrics is subject to personal interpretation (Azizian, Sarkani, & Mazzuchi, 2009).

The pressure on field systems to reduce the time and cost of integrating new technologies without sacrificing system reliability and objectives has resulted in the need for more accurate techniques to assess the maturity of the complex systems and technologies. To respond to this need, several quantitative techniques have been developed. A review of some of these quantitative techniques is provided here:

System Readiness Level (SRL): The SRL method developed by Sauser et al. (2008) determines the maturity of a system and its status within a developmental life cycle through using a normalized matrix of TRLs and IRL pair-wise comparisons. This quantitative method provides awareness about system maturity as a product of IRL x TRL (Ramirez-Marquez & Sauser 2009).

The rationale behind the SRL is that in the development phase, companies are often interested in considering two points: (1) how the technology under the study is being integrated with every other technology. The SRL should be a function of both the connection of a technology with every other technology with which it has to be combined (e.g. IRL) and the maturity of the different technologies (e.g. TRL). (2) SRL should bring a system-level measurement of readiness. It means that if the system contains n technologies, the overall SRL of the system should be a function of various SRLs of each technology or in mathematical form (Ramirez-Marquez & Sauser 2009):

$$SRL = f(SRL1, SRL2, \ldots, SRLn) \quad (1)$$

The following is the SRL calculation procedure as explained by Sauser et al. (2008). The SRL is a function of the TRL and IRL matrices.

Matrix TRL gives an overview of the system status regarding the readiness of its technologies. TRL of a system with n components is defined as a vector with n components, where TRLi is the TRL of technology i.

$$[TRL]_{n\times 1} = \begin{bmatrix} TRL_1 \\ TRL_2 \\ \ldots \\ TRL_n \end{bmatrix} \quad (2)$$

Matrix IRL shows how the different technologies are combined with each other in the system. A system with n technologies has an IRL matrix as follows: where IRLij is the IRL between technologies i and j.

$$[IRL]_{n\times n} = \begin{bmatrix} IRL_{11} & IRL_{12} & \ldots & IRL_{1n} \\ IRL_{21} & IRL_{22} & \ldots & IRL_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ IRL_{n1} & IRL_{n2} & \ldots & IRL_{nn} \end{bmatrix} \quad (3)$$

As discussed before, TRL and IRL levels have values from 1-9, therefore, those values should be normalized. Based on the TRL and IRL matrices, an SRL matrix is calculated by multiplication of the TRL and IRL matrices:

$$[SRL]_{n\times 1} = [IRL]_{n\times n} \times [TRL]_{n\times 1} \tag{4}$$

$$[SRL] = \begin{bmatrix} SRL_1 \\ SRL_2 \\ \dots \\ SRL_n \end{bmatrix} = \begin{bmatrix} IRL_{11}TRL_1 + IRL_{12}TRL_2 + \dots + IRL_{1n}TRL_n \\ IRL_{21}TRL_1 + IRL_{22}TRL_2 + \dots + IRL_{2n}TRL_n \\ \dots \\ IRL_{n1}TRL_1 + IRL_{n2}TRL_2 + \dots + IRL_{nn}TRL_n \end{bmatrix} \text{ where } IRL_{ij}=IRL_{ji}. \tag{5}$$

As shown in the above matrix, each element of the matrix shows the SRL for each constituent technology. It should be noted that SRL values are within the interval (0, n), where n is the number of technologies in the complete system. To obtain a normalized value between (0,1), for each technology i, its associated SRL_i is divided by n_i where n_i is the number of connections that technology i has with other technologies. To find the SRL for the whole system, the mean of all normalized SRL values can be calculated as shown below:

$$SRL = \frac{\frac{SRL_1}{n_1} + \frac{SRL_2}{n_2} + \dots + \frac{SRL_n}{n_n}}{n} \tag{6}$$

The SRLMax: The SRLmax is an optimization model aims to maximize the SRL (which is a function of TRL and IRL) under constrained resources. The objective of the SRLmax method is to obtain the highest feasible SRL subject to the availability of resources such as schedule and cost. The general idea behind this method is that the technologies compete for resources and the optimal assignment of such resources can improve SRL. The general format of the optimization problem is shown below (Ramirez-Marquez & Sauser 2009):

$$
\begin{aligned}
&\text{Model SRL}_{\max} \\
&\text{Max} \quad \text{SRL}\,(\mathbf{TRL}, \mathbf{IRL}) \\
&\text{s.t.} \\
&R_1\,(\mathbf{TRL}, \mathbf{IRL}) \le r_1 \\
&\vdots \\
&R_H\,(\mathbf{TRL}, \mathbf{IRL}) \le r_H\,.
\end{aligned}
$$

Technology Readiness and Risk Assessment (TRRA): TRRA is another quantitative model that integrates three metrics: TRLs, the R&D degree of difficulty (R&D3), and Technology Need Value (TNV) within one frame work named the standard technical risk matrix. The TRRA formulates the risk matrix in a new way by considering 'probability of failure' on the y-axis and 'consequence of R&D failure' on the x-axis (Mankins, 2007)(Mankins, 2009). The probability of failure defines how likely it is that a given R&D effort will fail. How likely is it to succeed? Table 5 shows the probability ratings based on both quantitative and qualitative bases. Consequence rating on the other hand shows what the final consequences are if a given R&D or technology implementation effort does not succeed. What are the advantages if it succeeds? Table 6 illustrates the consequence rating suggested by Mankis (2009) for the consequence of R&D failure. The generic technology program risk matrix is illustrated in Figure 7.

Integrated Technology Analysis Methodology (ITAM): ITAM is a mathematical model that combines several system metrics together to find the overall maturity of a system based on the readiness of its make-up technologies. The metrics used in this method are TRLs, delta TRL, R&D Degree of Difficulty (R&D3), and Technology Need Value (TND).

Table 5. The probability ratings scale in TRRA method (Mankins, 2009)

Level		**Likelihood**
0.0-0.2	1	Remote
0.2-0.4	2	Unlikely
0.4-0.6	3	Likely
0.6-0.8	4	Highly Likely
0.8-1.0	5	Near Certainty

Table 6. The consequence ratings scale in TRRA method (Mankins, 2009)

Level		**Likelihood**
Quantitative	**Qualitative**	
0.0-0.2	A	Minimal Impact
0.2-0.4	B	Some Impact
0.4-0.6	C	Moderate Impact
0.6-0.8	D	Major Impact
0.8-1.0	E	Unacceptable

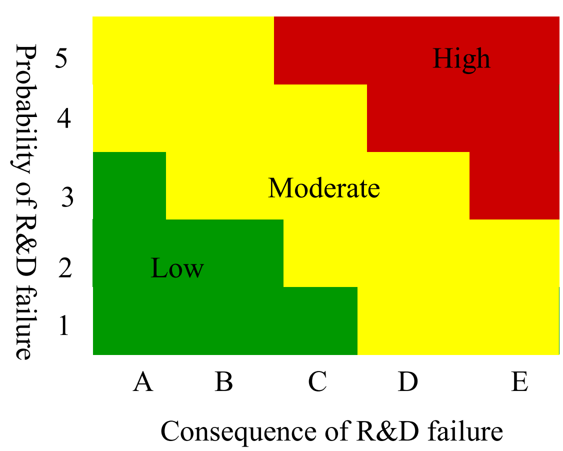


Figure 7. The generic technology program risk matrix [simplified from (Mankins, 2009)]

The Delta-TRL of a particular technology is the gap in TRLs between its existing level of maturity and its desired TRL. To calculate the overall maturity of the system, in the first step an individual technology index is calculated for each technology based on delta TRL, R&D3 and TNV. Then, the individual indexes are combined together to form the overall technology index for the complete system. The calculations are shown below (Mankins, 2002):

$$\text{Technology Index} = \Delta\text{TRL} \times \text{R\&D}^3 \times \text{TNV} \quad (7)$$

$$\text{Integrated Technology Index} = \text{ITI} = \frac{\sum_{\text{Subsystem Technologies}}(\Delta\text{TRL} \times \text{R\&D}^3 \times \text{TNV})}{\text{Total \# of Subsystem Technologies}} \quad (8)$$

The above mentioned maturity assessment techniques provide a criterion for decision makers to select the best fit technology for their system (Azizian et al., 2009).

2.5. Technology Selection Methods

Selection of appropriate technology is essential for the company's profitability and growth in the current competitive global market. If a company wants to survive in the current competitive market, the question is not whether to invest in technology or not. The decision making is about the type and the extent of technological investment (Da Costa & De Lima, 2009). The selection and justification of the technology require consideration of many economic as well as non-economic factors in the decision making process (Chan, Chan, & Tang, 2000).

Many quantitative methods have been developed to help decision makers select and justify possible technology alternatives. In general, the approaches presented in the literature for technology selection can be categorized into three groups (Small & Chen 1997):

1) Economic approaches that include methods such as Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PB) and Return On Investment (ROI). These methods evaluate technology options using economic factors (Slagmulder & Bruggeman, 1992).
2) Strategic approaches that study the impact of technology implementation on the strategic factors such as the attainment of industry leadership, the competitive benefits and the technical importance of applying new technologies (Kakati & Dhar, 1991).
3) Analytic approach including value and risk analysis.

Some studies moved toward integrating economic and strategic approaches and evaluate some weighted scoring methods (Sambasivarao & Deshmukh, 1997) (Soni, Parsaei, & Liles, 1990). The limitation of the methods mentioned above is that they all need accurate measurement and exact numerical evaluation. However, due to the uncertainty and lack of information, obtaining the exact evaluation data such as gross income, investment cost, salvage value, expenses, productivity and quality is so difficult if not impossible. Moreover, some of the factors involved in the decision making process are not easy to be quantified (for example, quality). In this situation, decision makers often try to rely on their own knowledge and past experience and make decisions based on their subjective judgments.

To overcome the difficulties of the classical methods of technology selection, several studies have applied fuzzy multiple attributes decision- making (FMADM) method for evaluating technology projects. Punniyamoorthy and Vijaya Ragavan (2003) considered both objective and subjective variables in their evaluation. Karsak (2000) applied FMADM to evaluate flexible manufacturing systems. Chuu (2009) believes that technology selection is a group decision making process. His model looks at the advanced manufacturing technologies selection problem as a multi-attribute group decision-making problem in a fuzzy environment. In another study, Abdel-Kader and Dugdale (2001) integrated the analytical hierarchy process and fuzzy sets theory to consider both objective (economic) and subjective (strategic) attributes. In a similar study, Chan et al. (2000) developed a systematic approach based on the concepts of fuzzy set theory and hierarchical structure analysis. The proposed method provides a tool for making decision under fuzzy environment and also allows decision makers to consider both objective attributes (e.g. investment cost, set up time) and subjective attributes (e.g. product quality, process flexibility). Figure 8 shows a schematic diagram of the proposed fuzzy method for technology selection.

The proposed methodology has eight steps. In the first step, a committee, consisting of decision makers from different managerial levels in the company, will be formed, and available technology alternatives and the selection criteria will be identified. In the second step, a proper linguistic scale (e.g. high, medium, low') are chosen and the decision makers are asked to give their judgment using triangle fuzzy numbers or pair wise comparisons. In the third stage, the criteria determined in the first step will be classified into two categories of subjective and objective criteria. In the fourth step, subjective criteria such as quality are evaluated using linguistic assessment and objective criteria are characterized applying economic terms and monetary expressions such as operating cost. In the fifth step, the linguistic variables will be transformed to triangle fuzzy numbers using a designed rating scale and a fuzzy appropriate index will be calculated for each alternative which finally can be used to rank the alternatives.

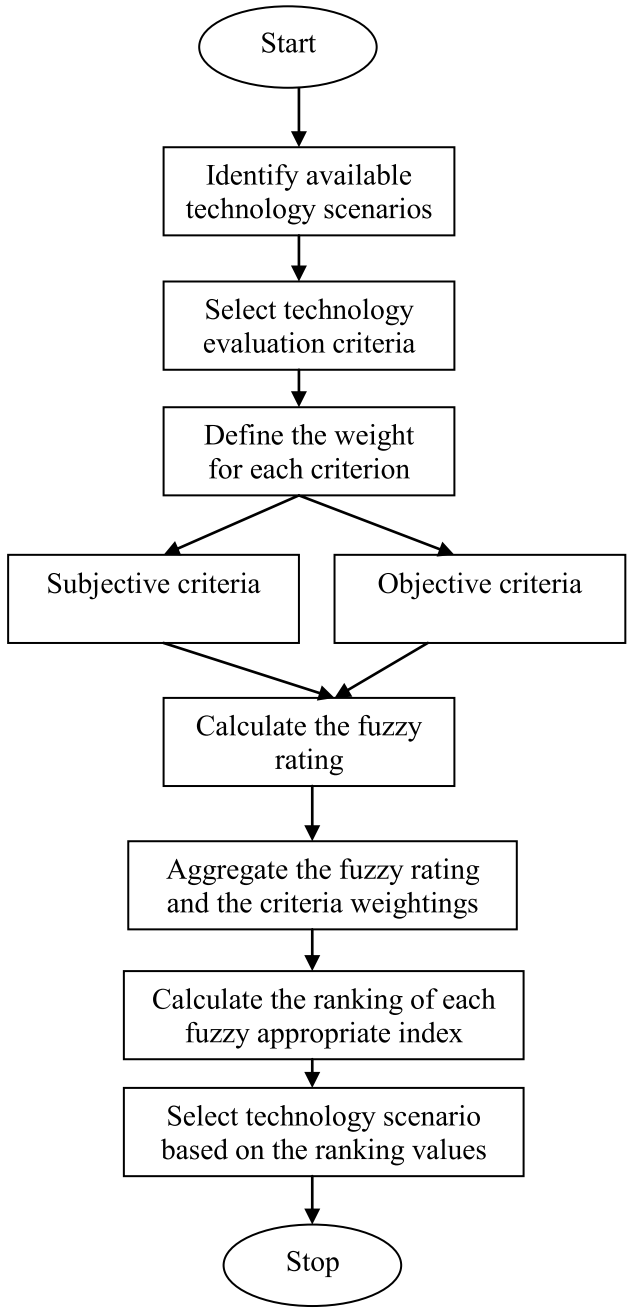


Figure 8. The schematic diagram of technology selection applying fuzzy set theory and hierarchical structure analysis [simplified from (Chan et al. 2000)]

Huang et al. (2009) conducted a Delphi survey among the members of Forum on Management Science and Engineering in China, participants of 2006 Annual Conference of

China Industrial Economic Association & Conference on Independent Innovation and Innovation Policies, and the participants of the 2nd National Conference on S&T Policy and Management. Based on the results of 110 questionnaires, they proposed an indexing system for evaluation of emerging technology options. The evaluation index system contains 5 criteria and 25 factors. Table 7 shows the 5 criteria applied in their method.

Table 7. The framework of the index system for new technology evaluation based on technology commercial potential (L Huang & Lu, 2009)

Criterion	**Weight**
Technology factors	0.240
Marketing factors	0.249
Qualification factors	0.186
Conformity factors	0.167

2.6. System Dynamics

The System Dynamics introduced by Forrester helps decision makers understand and visualize the dynamics behavior of the real world. System dynamics modeling provides a tool to predict possible outcomes and make appropriate decisions (Forrester 2007). As mentioned by Sterman (2000) the real world is a complex and dynamic system in which people are dealing with various issues. System dynamics provides decision makers a broad viewpoint to analyze and investigate problems of a complex system.

The typical human thinking for investigating problems is closer to the linear thinking in which most of the factors influencing existing problems are regarded as either independent variables, dependent variables, or both. However, system dynamics provides decision makers a different viewpoint of causal effects called feedback loop in which the feedback structure and relevance between different factors can be investigated (Hsieh, 2010).

In the case of feedback loops, the interrelations among factors are more than just linear-thinking model and factors have interactive effects. The behavior of a system depends on its structure. The complex behaviors in the system often are the results of the interactions among the system components (feedback structure), not the complexity of the components themselves.

System dynamics uses two main diagrams to model the dynamic complexity system: Causal Loop Diagrams (CLDs), and Stock and Flow Diagrams (SFDs). A CLD illustrates causal relationships and shows feedback within a system. All dynamics in the system are as a result of the interaction of just two types of feedback loops: positive loops and negative loops. It means that the impacts of feedback loops can lead to positive or negative results. The plus sign (+) shows the reinforcing or positive relation between two variables. It indicates that the effect is positively related to the cause. An increase in the independent variable results in an increase in the dependent variable and a decrease causes a decrease. In contrast, the negative sign (-) means that an increase (**decrease**) in independent variable results in a decrease (**increase**) in the dependent variable. The minus sign presents the balancing or negative relation among variables.

The positive feedback loop or "reinforcing loop," which may have even negative variables is to increase the value of a variable of the system. In contrast, the negative feedback loop or "balancing loop" is to decrease the value of a factor of the system. Figure 9 is a simple causal loop diagram with a single loop and two variables: hunger and amount eaten.

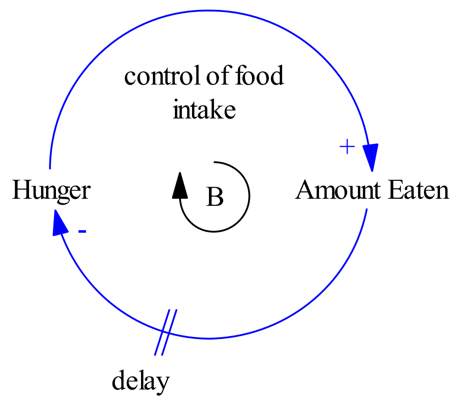


Figure 9. Simple causal loop diagram of food intake [simplified from (Morecroft, 2010)]

Another characteristic of the system dynamics is the ability to consider time delay in the model. Time delay means the effects of two variables on each other cannot be promptly brought. The impact is generated over time. For example product advertisement will affect customer mentality, but customer purchasing behaviors will not change immediately (Hsieh, 2010).

Agyapong-Kodua and Weston (2011) has listed several scientific methods which are popular for their wide usage in modeling dynamics and complexities in systems:

- Fuzzy logics
- Neural networks
- Bayesian networks
- Petri nets
- Causal loops
- Stock and Flow models (SF)

The deep mathematical base of modeling tools such as Bayesian networks, Fuzzy logics, Neural networks and Petri nets discourage many experts from deploying them. However, the

CLD does not include complex mathematical modeling and therefore they are applied to qualitatively show the cause and effects evident in a system. Another benefit of the CLD is that they can be combined together with other process modeling techniques to capture and analyze the causal effect of activities on different business performance measures. Therefore, Casual Loops could be applied for simplicity and as the first stage of qualitative analysis while simulating a system through the system dynamic approach. For more sophisticated analysis Casual Loops cannot be simulated in their natural state and the modeler needs to improve them to equivalent simulation models before comprehensive analysis.

There are several commercial and non-commercial simulation software packages that support CLD. The following are some examples:

- iThink
- Vensim
- InsightMaker
- OptiSim
- TRUE

CLDs originated from research in non-linear dynamics theories and control engineering. These techniques have been successfully employed in public policy making and implementation Agyapong-Kodua and Weston (2011) have summarized the advantages of CLDs as follows:

- Showing relationships between cause and possible effects
- Generating dynamic models of processes for alternative policy and scenario verification
- Capturing the opinions of team members during projects start and progress
- Illustrating the transformation from static modeling to dynamic modeling

CLDs are applied appropriately at the start of the modeling to catch mental models and show interdependencies and feedback structures. However, CLDs are unable to capture the stock and flow structure of the system. CLDs expand the boundary of human thinking and provide an effective tool for announcing interdependencies. But they are not appropriate for simulating the dynamics and performance of the system through time.

SFDs show the detailed flow structure of the system to facilitate the development of the mathematical model behind simulation (Gu & Chen 2010). Stocks accumulate changes over time. They are memory-kind variables, storing the results of previous actions. When, in a feedback structure, past decisions and actions want to impact current decisions and activities they do so through stocks (Morecroft, 2010). The flow diagram represents connections between variables which have the potential to alternate during time. Figure 10 shows the stock as a rectangle. There is an inflow consisting of a valve or tap on the left side of the stock. The inflow arrow originates from a source depicted as a pool or cloud. A similar combination of symbols represent outflow on the right side of the stock.

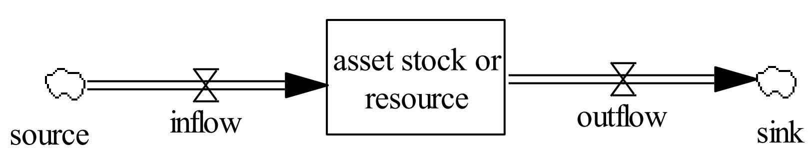


Figure 10. A simple representation of the stock and flow structure [modified from (Morecroft, 2010)]

A general research methodology often is used during system dynamics modeling. The methodology is based on the general concept of system dynamics shown in Figure 11. First the problems are defined and the system is conceptualized. Then, the casual loop diagrams and, the stock and flow diagram are developed and the equations among variables are built. Finally, the simulation will be run and the policies for improvement will be identified.

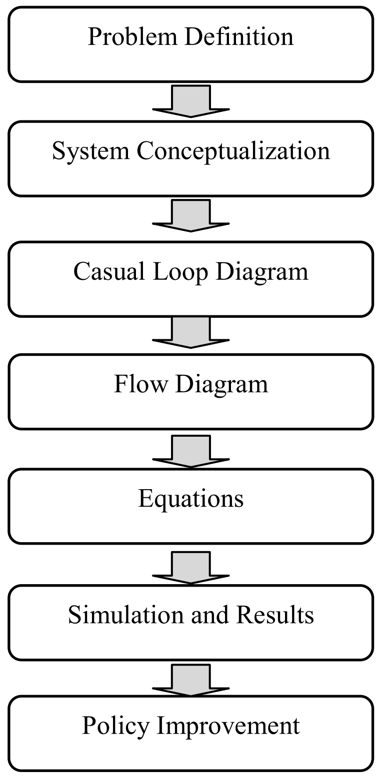


Figure 11. System Dynamics general procedure (Gu & Chen 2010)

2.7. System Dynamics Modeling to Analyze Technology Adoption

Technology adoption is regarded as a complex system that can be modeled using system dynamics. In general, technology integration has several features that make it a complex system. For example, a new technology is usually in interaction with other technologies (D. D. Wu, Kefan, Hua, Shi, & Olson, 2010). Therefore, changing one system or technology may affect other systems. These interactions among technologies are often time-dependant and can be simulated using systems dynamics.

Pretorius and Pretorius (2010) developed a system dynamics model to show the competition between two optical laser technologies (red laser and blue laser diode optical storage devices) in the market place. They have included the uncertainty of the market size into their model using a random variable with triangular distribution. Figure 12 shows a simplified schematic of their model.

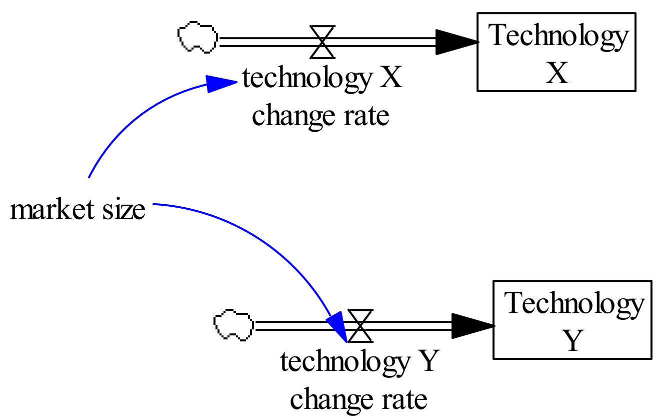


Figure 12. A SD model of two competing technologies [simplified from (Pretorius and Pretorius 2010)]

System Dynamics also can be applied to help organizations determine "which technologies they should focus to develop". The procedure in which a chain of long-term forward-looking events are conducted to recognize technologies critical to the success is called '*technology foresight'*. The term '*technology foresight'* originated in Europe in the 1990s where European countries looked for new policy tools to address problems in their science and technology systems (Miles, 2010). The final purpose of technology development is the optimization of the long-term impacts of technology on people, environment, and the society. The consequences of a technology are a function of technology features as well as the nature and extent in which the technology is used. The nature and extent of use refers to the concrete application of a technology by a specific user for a specific objective (Keller & Ledergerber, 1998).

Chen et al. (2012) uses a two-phase technology foresight model to identify technologies essential to the success of the Chinese ICT industry. In the first phase, they employed the Delphi method to collect opinions from hundreds of national experts and summarize a wide range of technology options to the top ten alternatives. The technologies were prioritized based on their impacts on the economic and social development of the country. This stage is shown in Figure 13. In the second phase, a system dynamics simulation model was applied to determine key factors in the development of the technologies and estimated the critical parameter values that influenced the successful diffusion of the chosen technologies. The values of the key factors were identified which would enable the selected technology to be integrated within the intended time frame. They also created and compared various scenarios for the technology development plan.

The SD modeling also has been used to determine the technology development capacity. Identification of the technology development capacity provides a good reference for organizations toward improvement. Wu and Liu (2010) applied the system dynamics simulation to identify the technological and scientific development capacity in Sichuan Province in China. They set up a dynamic structure model of the technology development system and ran simulation to analyze the elements of the technology development system, analyzed and made recommendations. Using the results of their model, they have recommended the following policies:

- Increasing funding and investment in science and technology
- Increasing the scientific and technological talents training
- Strengthening the science and technology intermediary service system through the construction of organizations such as productivity promotion centers and science and technology assessment agencies.
- Protecting intellectual property through encouraging research institutions located in universities to move toward more technology development. In addition, increasing implementation of the patent law to assure the intellectual property of research institutions in colleges and universities.

Whether to adopt a particular technology or not is affected by several factors including the maturity of the technology and how long the technology has been in use. New technologies are different from the traditional technologies due to their ambiguity, complexity and uncertainty. Therefore choosing and evaluating new emerging technologies are not as easy as justifying traditional technologies. Due to the uncertainty of emerging technologies, investors should consider the policies, technological and environmental changes when they want to decide whether to invest or to abandon a new technology. Therefore, a flexible decision making and monitoring tool is needed to help monitor the emerging technology's potential growth. According to Huang et al. (2009) the potential growth of emerging technology industrialization is influenced by five factors: (1) technology factor, (2) market factor, (3) industry factor, (4) conformity factor and (5) effect factor. The interdependency, interaction and mutual influence between these five factors determine the potential growth of emerging technology industrialization.

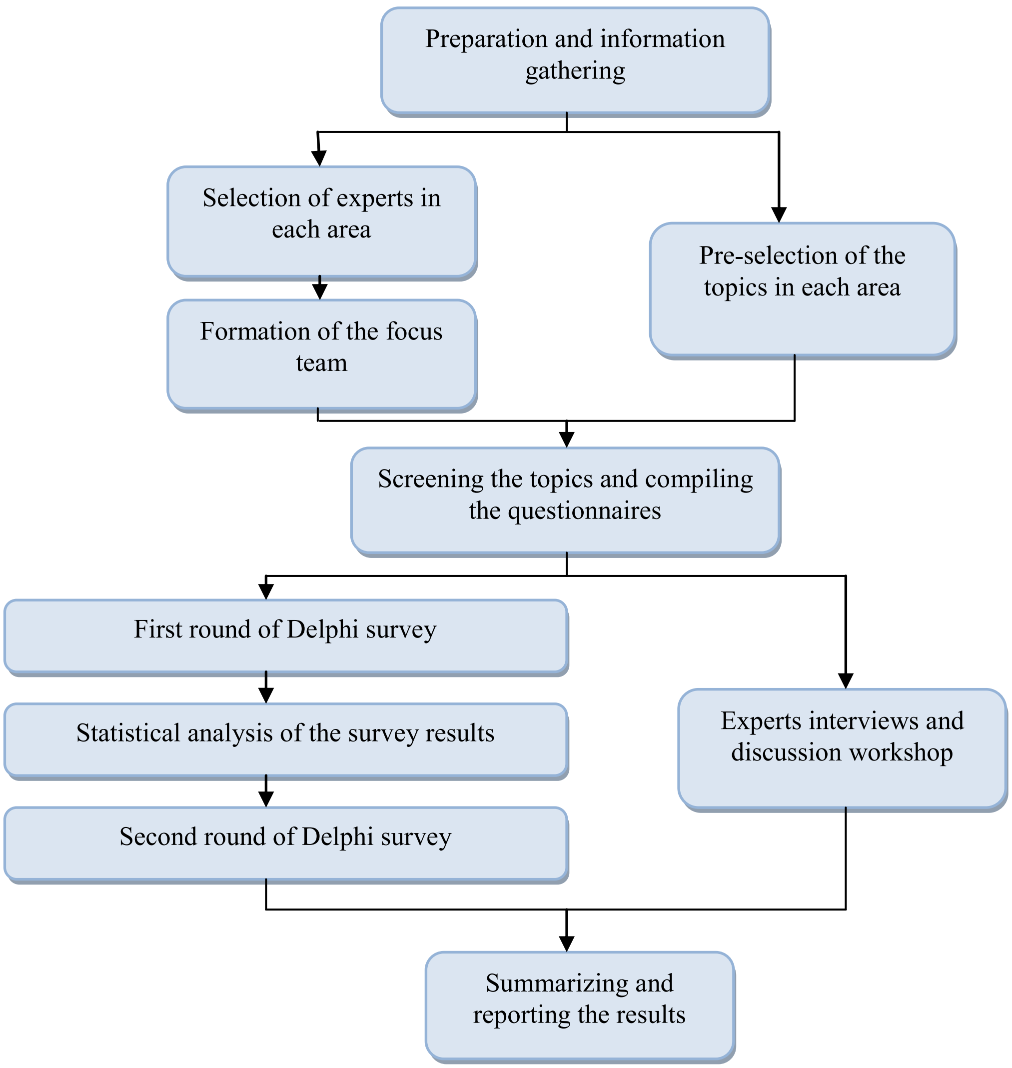


Figure 13. Delphi method used at the first phase of 'Technology Foresight' process [redrawn from (H. Chen et al., 2012)]

In another study Daim et al. (2005) applied the system dynamics method to estimate the trend of two different food safety technologies: testing technologies and elimination techniques.

The outputs for their analysis were several S-Curves depicted over thirty years illustrating the potential commercial success of investigated technologies.

Not only should the companies identify the appropriate technology options to implement, they also should be able to effectively manage the technology after its implementation. For example, it is important to effectively manage technology-related human resources and skills. Personal and organizational skills, knowledge, expertise and human resource commitments have critical impacts on the effectiveness of technology infrastructure (Broadbent & Weill, 1997). Choi et al. (2008) uses a system dynamics model to investigate the importance of skill management within the domain of IT human resource management. Figure 14 shows an overall structure of different parts of their model.

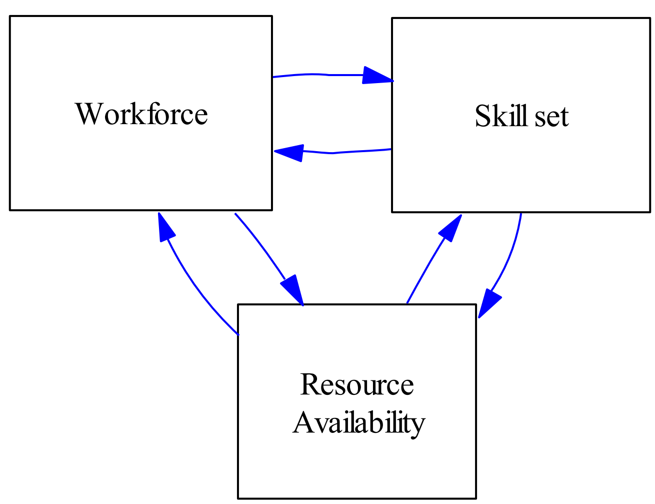


Figure 14. Overall structure of the SD model for IT skills human resource management suggested by (Choi et al., 2008)

Their model permits human resource managers to explore the implications of alternative staffing options when trying to manage skills required for IT-related activities. The key decision in their simulation model was the staffing decision. This decision is represented by the *Skill Augmentation Decision* variable in the model. This variable can take one of four values: (1) representing training, (2) recruitment, (3) contracting, or (4) no additional staffing during this period. The selected option is influenced by the resource availability.

Besides the benefits of the technologies identified, there are challenges toward the effective use of such technologies regarding the technology management activities, from planning stage to installation and implementation stage (Small, 2006)(Ungan, 2007). The companies often encounter problems in better identifying the dynamics of technology, for example when to exploit the current technology and when to explore new technologies. Dharmaraj et al. (2006) used principles of System Dynamics to determine the time in which a company should stop using the current technology and adopting the new technology developed by their R&D. They showed that at the early step of technology development, it is not effective to implement the new technology, therefore, the current technology is exploited and simultaneously the new technology is explored and the 'cost versus performance' measures are investigated. When the 'cost versus performance' of the new technology exceeds the 'cost versus performance' of the current technology, then the new technology can be implemented (Dharmaraj et al., 2006).

System dynamics also can be used to assess the impact of adopting a new technology on the performance measures of a system (Sikander, 2012)(Tran & Daim, 2008)(Wolstenholme, 2003). Musango et al. (2011) applied a system dynamics method to determine the potential impacts of biodiesel development on chosen sustainability measures for the Eastern Cape Province of South Africa. In the first step of their study they have tried to identify the requirements for increasing biodiesel production and the current characteristics of biodiesel production development in the Eastern Cape Province. The next step was to recognize the sustainability measures associated with such development. Land use change, air emission, water use, energy use, employment and profitability are several examples of the performance indicators they have used in the model. They have divided their model into eleven sub-models. The cost of operations and the profitability are two examples of those sub models. In another study, Chen (2011) applied a system dynamics approach to explore the dynamic behavior of Radio Frequency Identification (RFID) technology adoption. Based on the results of the model, some recommendations have been made to the decision-makers to facilitate the RFID adoption. Interaction and persuasion by word of mouth, promotion efforts, advertising campaign, and training efforts are among policies that facilitate the adoption.

In addition to the above mentioned studies, several researchers tried to present some general frameworks that facilitate making decision on technology adoption. Wolstenholme (2003) suggested a three-stage methodology as a tool for technology evaluation. The methodology is based on creating dynamic simulation models of the application domain of the technology. These three stages are:

Stage I: model the domain of application

Stage II: technology assessment

Stage III: technology accommodation in the domain

In the first stage of the methodology an appropriate system dynamics model of the domain of application of the technology is created and validated. The model building process by itself should improve the understanding of the application domain. The base model should analyze the domain experts' knowledge and represent people's mental models of the structure of the domain. The second stage is to apply the model created in the first stage as a test bed to justify the impacts of the new technology. The third stage of the method is the most important stage in which the model is used to identify the changes, procedures, and policies to accommodate that are required to make the best use of the new technology. The model assists in conducting experiments to redesign the application domain to take benefits from technology implementation. Any aspects of the model can be modified and the effects of the modification on the performance of the system can be studied. In another study, Gregory (1995) proposed a model with five fundamental processes for technology management. These processes are: (1) identification, (2) selection, (3) acquisition, (4) exploitation and (5) protection. The five-process technology management procedure is depicted in Figure 15.

The identification process involves recognizing all the technologies which are critical to the business, or may be critical in the future. The selection process includes the selection of technologies that should be adopted within the organization. This process is critical since it needs the large commitment of human and financial resources. The acquisition activity refers to the decisions about the appropriate tools of achieving chosen technologies. Technologies may be acquired internally through R&D activities or may be acquired externally through licensing and joint venture activities. Exploitation is the process in which the technology is converted into marketable products or services. Protection refers to the maintaining the knowledge and expertise that are embedded in products and technology systems (Gregory, 1995).

While the studies mentioned in this section have used the SD modeling to investigate the technology adoption, there is no specific study that includes different aspects of the technology adoption process from the implementation stage to the upgrade and maintenance stage. Moreover, the previous studies are mainly focused on investigating the technology diffusion and technology development rather than technology implementation. Therefore, a SD model can be created to integrate various aspects of technology adoption activities and provide a decision making tool for managers in the manufacturing companies to analyze the impact of new technology implementation on their production system performance and the total cost of the system.

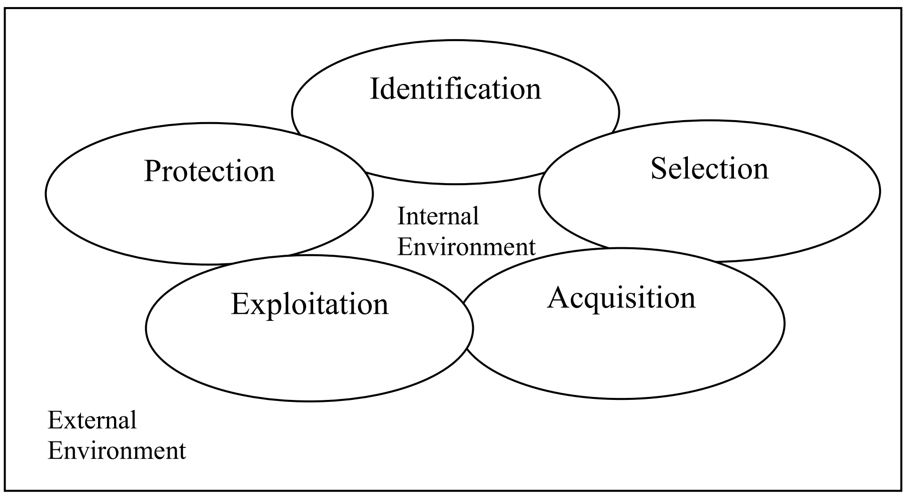


Figure 15. Five-process technology management framework [simplified from (Probert, Phaal, & Farrukh, 2000)]

2.8. Critical Success Factors of Technology Adoption

Technology adoption generally includes the process starting from collecting required knowledge until the actual technology implementation (Teng & Nelson, 1996). One important point before adopting a new technology is to determine the factors that impact the adoption process. Once an organization knows the key success factors, they can apply the knowledge to facilitate or lead the adoption procedure. Several studies have dealt with the concept of successful factors in technology implementation projects. Suebsin and Gerdsri (2009) presented seven factors impacting technology adoption process. These factors include functional performance, operating cost, ease-of-use, reliability, compatibility, acquisition cost, and serviceability.

Small and Chen (1997) conducted a study to investigate the impact of technology justification technique on the successful adoption of new technology projects. They concluded that the companies applying hybrid justification strategies including both economic and strategic justification approaches attain more success from their technology adoption projects compare to firms only applying one of those methods. Udo and Ehie (1996) also tried to study the impediments toward successful technology implementation. They listed the lack of planning for technology implementation, lack of experience with modern technologies, and lack of top management support as a result of not having a clear and believable cost justification for technology implementation as several reasons for technology adoption failures. In another study, Udo and Ebiefung (1999) considered eight human related factors (morale, satisfaction, reward system, belief in new technology, top management commitment, response to workers concerns, effective facilitators and training) and showed that there is a positive association between those factors and technology adoption benefits.

Altameem et al. (2006) analyzed the factors leading to success and failure of e-government technology implementation. They categorized those factors into three groups: technical factors, organizational factors and, governing factors. Governing factors include factors such as top management support, leadership, and funding. Technical factors include information technology infrastructure, citizen collaboration and security. Finally, the organizational factors for e-government adoption include elements such as training, organization structure and the availability of technical staff. Wallace and Keil (2004) used a different approach. They divided the framework influencing technology implementation into four parts: customer, scope and requirements, execution, and environment. In another study Al-Mabrouk (2006) determined the factors that affect knowledge management implementation projects. Management leadership, organization culture, efficient performance measurement system, availability of resources, training, and human resource management are among those factors. In a similar study, Ayman et al. (2008) discussed the twenty four factors important to IT adoption success. Several examples of those factors are: financial resources, top management support, user involvement, training, project management, business case, organization culture, compatibility of the technology with the existing socio-cultural values and other systems, complexity of the technology, IT vendor/software selection, and IT expertise.

A significant number of studies have concentrated on analyzing the Technology Acceptance Model (TAM). Davis and his colleagues proposed TAM as a tool for predicting the likelihood that a new technology is adopted by a group or organization (Davis, 1989)(Davis, Bagozzi, & Warshaw, 1989). Based on TAM, the “perceived ease of use” and “perceived usefulness” are two variables that influence the user’s acceptance of a new technology (Ghazizadeh et al. 2012)(Brangier & Hammes-Adele, 2011)(Turner et al. 2010)(Sun & Zhang, 2006).

2.9. The impacts of Technology Adoption on Human Resource

The degree in which many modern complex technologies can successfully meet their planned objectives highly depends on the performance of the humans who operate, maintain, support, monitor, and manage the systems (Malone et al. 2007). Traditional approaches to technological implementation concentrate on mechanical, hardware, and software design challenges and often not enough attention is paid to the end users and their limitations and capabilities. An assumption is made that the introduction of the technology automatically will be acceptable to the users and will improve their job performance. However, this assumption is not always true (Reinach, 2007).

Even the most sophisticated technologies may not reach their intended performance if designed without enough consideration of user needs and requirements. To improve the overall performance of a designed technology, the human operator should be regarded as a key part of the system. Concise consideration of an operator's interaction with a system at the early stage of the design eliminates potential cost occurring as a result of mismatching the system's implementation and users capabilities and limitations (Reinach, 2007). The importance of considering human factors at the design stage becomes more obvious knowing the fact that human error is either a root cause or at least one of the main contributing causes of work sites accidents. Human error contributes to 80–90% of all accidents (Landsburg et al., 2008). Therefore, manpower and personnel managers should work closely with technology sponsors, system developers and industry to ensure life cycle costs reflect manpower and training requirements early in the technology development phase.

In addition to considering the human resource at the early stage of the technology development, the manpower concepts, training system plans and human resource requirements should be determined and approved for every technology implementation plan. The companies implementing a new technology should be capable of providing the right level of skill sets for system design, and they should be able to design systems that provide the right level of knowledge for their personnel. Neither the technology nor people can be overextended; therefore organizations implementing a new technology should find the right balance between technology and people (Holness et al. 2011)(Lieber & Fass, 2011).

Human Systems Integration (HSI) is the process by which human performance considerations are completely coupled with the acquisition and design of complex systems (Stark & Kokini, 2010)(Mack et al. 2007). HSI includes nine domains where the influence of a new technology should be considered before the technology is acquired and implemented. These domains are: manpower, personnel, training, human factors engineering, safety and occupational health, personnel survivability, and habitability. A brief explanation of each domain is provided here (Reinach, 2007):

Manpower considers the personnel required to operate, maintain, support, and train for the system or technology under consideration. The staff requirements should be taken into account under all operating conditions and within current and/or planned staffing levels. For example, a company may set a particular staffing limit which impacts the number of workforce available to use and maintain the new equipment. Therefore the new equipment's design is affected by the proposed staffing level policy.

Personnel focuses on the knowledge, skills, abilities and other characteristics required to operate the new modernized technology. The manpower and personnel domains are closely related; manpower discusses staffing levels, while personnel domain discusses the quality and qualifications of individuals who will operate the system. This domain focuses on the talent management: how to efficiently recruit, train and retain the workforce.

Training discusses the training requirements essential to create the knowledge, skills, abilities and other characteristics necessary to operate, maintain, and sustain the new or modernized technology.

Human factors engineering concentrates on designing human system interfaces to improve user performance and reduce the chance of occurring user errors. This goal is conducted through creating designs compatible with user capabilities and limitations.

System safety and health hazards tends to design systems that minimize the likelihood of occurring accidents and injuries through evaluation of potential failures and their harmful outcomes. Risk assessment techniques are useful methods in this domain. This domain also concentrates on checking the potential occurrence of bodily harm problems (injury, illness, and death) related to harmful exposure to vibration, noise, and ambient temperature. It focuses on designing features that minimize human error and reduce risk of injury.

Habitability ensures that all aspects of the living and working spaces are designed with the end user capabilities and limitation in mind.

Survivability ensures that the end user will have all personal protection needed.

HSI incorporates all the aforesaid domains and tries to put together them in one single framework. It is not common to apply human factors to a product in its development phase and the focus usually has been on product reliability issues rather than human-related issues (Rizvi, Singh, & Bhardwaj, 2009). The final purpose of HSI analyses is to satisfy as many requirements as possible relevant to the seven HIS domains considering the life cycle cost, performance, and development and delivery schedule. Sometimes depending on the requirements, the analysis needs within a particular HSI domain or between domains can be challenging and complex (Lively, Seman, & Kirkpatrick, 2003)(Holness et al., 2011). Booher (1999) listed 10 elements as HIS success factors. These factors are as follow:

- Top-level managers' support and understanding
- Human-centered design not just the hardware and software design
- Assign HSI evaluation factors as much weight as technical and cost factors while selecting systems procurement sources
- Involve people from various domains in the HSI aspect of system design
- Integrating HSI-related requirements into the system documentation
- Quantitative definition of human performance in system design calculations
- MANPRINT technology including tools, and techniques that assist in system design
- Test and evaluation integration
- Presence of skilled practitioners within the system as well as skilled HSI practitioners in system design
- Education and training of practitioners and non-practitioners

The implementation of a new technology is often leads to a significant change in human resource management policy. Several reasons are behind this change. First, new technologies often allow for the replacement of labor with capital. Also, automation and computerization result in changes in the composition of the personnel in favor of workers with higher skill sets. Second, new technologies can significantly change the work environment toward a more integrative and information intensive environment. In addition, new technologies may enhance workers knowledge by giving them more information about activities in other functional areas (Siegel et al. 1997).

In general, human resource and technological capabilities go hand in hand. A firm's capability to acquire, nurture, retain and deploy human resources creates the basis for successful implementation of new technologies (Zahari & Thurasamy, 2012)(Cooke, 2007). In order to operate a given technology a worker should acquire the required knowledge. Prior researches have emphasized training as one of the important factors in developing required skills within human resource (Gao & Feng, 2010)(Liu 2010)(Yu & Weinan 2011)(Tome, 2011).

Human resource development activities should be conducted with the aim of increasing the knowledge, skills, and capacities of all the people in the organization. Human resource development can be obtained in several ways including training the workforce and delivering the practical and appropriate education to them (Bada & Madon, 2006). Moreover, adoption of advanced technologies will influence the employment rate and increase employee empowerment and result into increasing educated workers (D. S. Siegel et al., 1997)(Chung, 1996).

Musango et al. (2011) developed a system dynamics model to determine the potential effects of biodiesel development on sustainability. As part of their model, they have explored the employment from biodiesel plant to determine the number of jobs provided in the Eastern Cape Province as a result of establishing the biodiesel plant. The number of job created is important in improving the economy of the province. Their model calculates the desired employment from biodiesel plant and simulates the recruitment process. The model is shown in Figure 16. There are two stock variables in the model: workforce in training and employment biodiesel plant and there are two flow rates: recruiting for training and new trainees. The target employment in the biodiesel plant is restricted to the plant size.

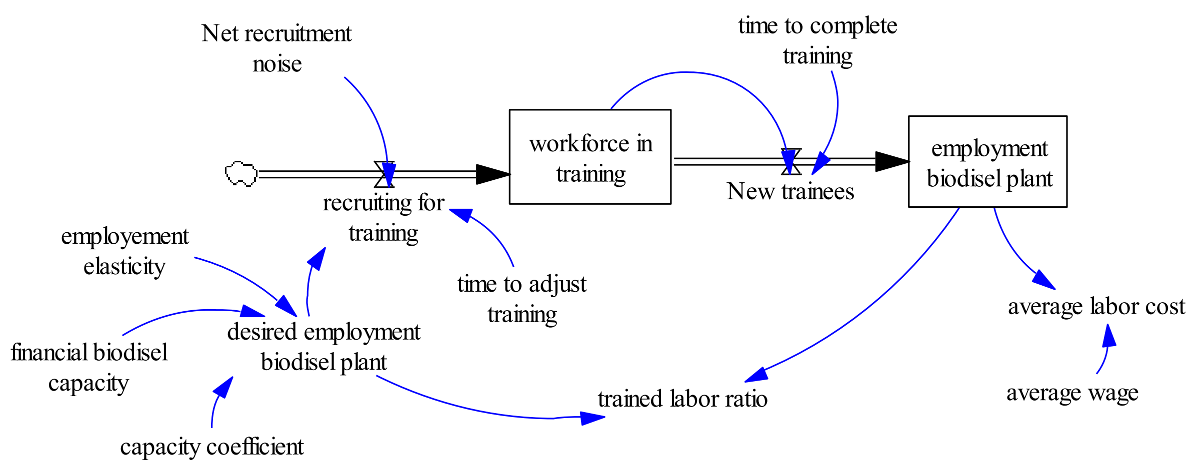


Figure 16. Establishment of biodiesel plant stock and flow diagram [redrawn from (Musango et al., 2011)]

In another study Gu and Chen (2010) represents the human resource management using a system dynamics model shown in Figure 17.

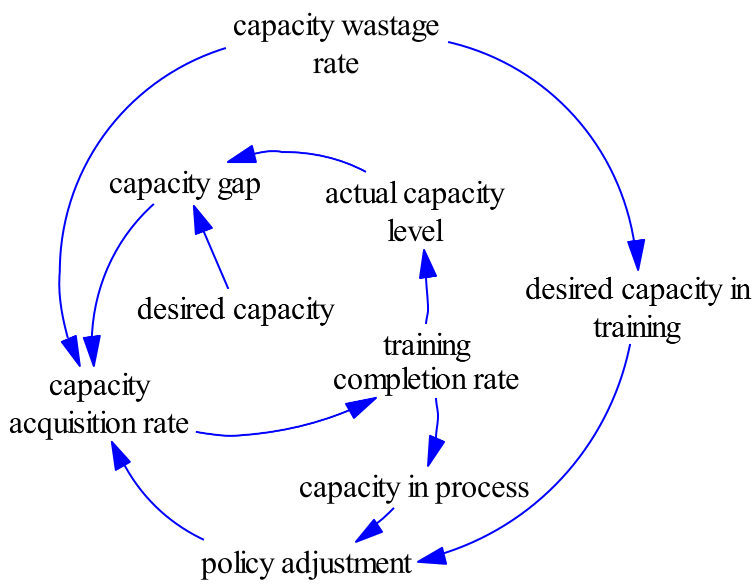


Figure 17. Casual Loop Diagram of Human Resource Management [modified from (Gu & Chen 2010)]

The CLD consists of two main feedback loops: creating capacity gap and filling capacity gap by training. In the real world, current capacity and knowledge in an organization deteriorate over time due to the technology development and market changes. The more the capacity wastage rate, the more the organization's capacity loss. Therefore, appropriate actions such as training or recruitment employees should be taken to leverage the capacity level (Gu & Chen 2010). The flow diagram of their model represented in Figure 18 shows an inter-link between capacity and training. Variables T1, T2 and T3 represent the time period in which the capacity gap is to be eliminated, mean time to estimate the capacity loss rate and training average delay time respectively. In another study Hafeez and Abdelmeguid (2003) discussed the importance of applying training and human resource retraining scenarios for organizations to stay at the cutting edge of technology. They employed system dynamics to show the relationship among recruitment, training, skills, and knowledge (Figure 19).

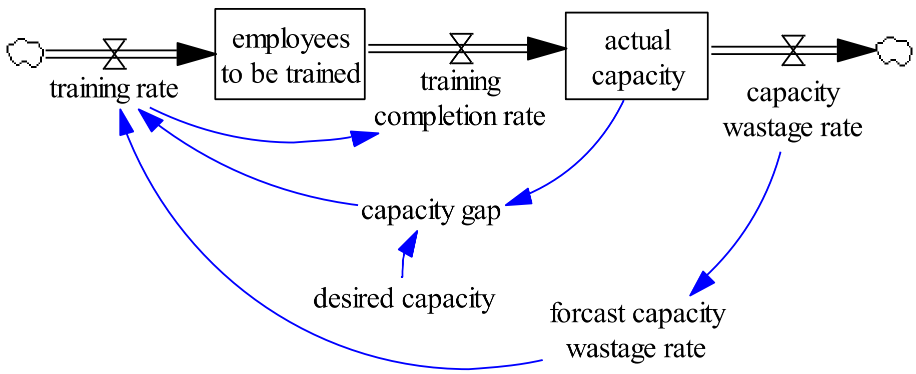


Figure 18. Human Resource Management stock and flow diagram [simplified from (Gu & Chen 2010)]

The model help decision makers capture the dynamics of skill acquisition and retention, especially when a company is planning some major changes such as implementing a new technology or developing a new product.

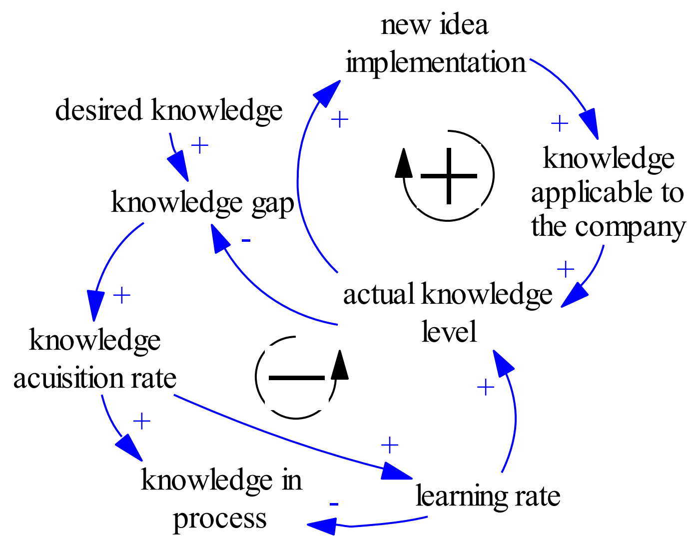


Figure 19. CLD of the inter-link between knowledge, skill, and training [simplified from (Hafeez & Abdelmeguid, 2003)]

2.10. Cost Modeling Techniques

Cost plays a significant role in the success of any technology implementation plan. The primary goal of technology implementation in any industry from manufacturing companies to service industry is to meet the required performance at the target cost. In addition, cost is the primary criterion for many decision making processes. Alternative or options are usually evaluated based on their upcoming costs and the timeframe in which they will be incurred. Therefore, effective cost modeling is an important element of any technology implementation process since it enables decision maker to justify their decision via accurate cost reporting and forecasts of estimated future costs. Moreover, accurate cost modeling helps determining the appropriate budgeting strategies.

When implementing a new technology it is important that the companies assess the actual cost of the technology over its expected life, or its total cost ownership.

To determine the TOC of a particular technology, a number of cost components should be considered including the cost of the hardware/infrastructure, the cost of service required for technology implementation, the maintenance cost, the human resource –related cost such as training cost and some additional cost components.

Prior researches suggest various methods and techniques for cost estimation and modeling. Niazi et al. (2006) categorized these methods into qualitative and quantitative techniques. They further subdivided qualitative techniques into analogical and intuitive techniques, and the quantitative techniques into analytical and parametric techniques. Figure 20 gives an overview of the classification of cost estimation techniques.

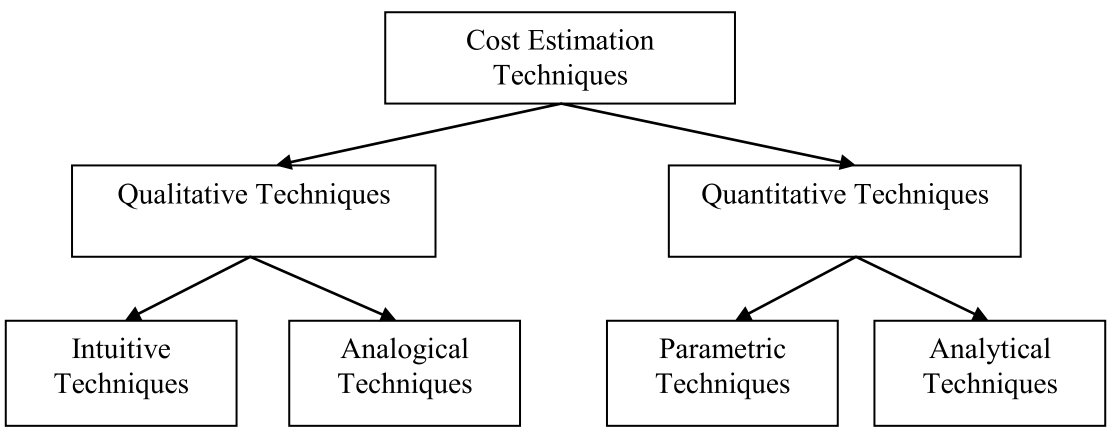


Figure 20. Classification of the cost estimation techniques (Niazi et al., 2006)

The intuitive cost estimation techniques are relied on the past experience and domain expert's knowledge. The knowledge usually is stored in the form of rules, judgments and decision trees in databases to help companies improve the decision-making process and develop cost estimates based on certain input information. The two subcategories under intuitive techniques are: Case-Based Methodology (Rehman & Guenov, 1998) and Decision Support Systems (Kingsman & De Souza, 1997).

Analogical cost estimation techniques apply similarity criteria by using the historical cost data for activities or equipments with known cost. Two examples of such methods are Regression Analysis (Rifat Sonmez, 2004)(Adalier, Ugur, Korukoglu, & Ertas, 2007) and Back Propagation Neural-Network methods in which a neural network stores the required knowledge to infer the cost (Chen & Chen 2002).

Parametric techniques are a category of quantitative methods that are focused on the application of statistical methods to formulate the cost as function of its constituent variables. Parametric techniques are particularly useful in situations where the cost drivers or parameters are known or easily can be identified. A considerable number of studies have used parametric method to estimate the cost. Jiang et al. (2007) showed how parametric methods can be applied to estimate the cost of an equipment from design stage to usage stage. They have adopted regression analysis to establish the parametric model. Regression analysis methods are adequate in cases with a large number of sample data (Heping Liu, 2010). In another study Fragkakis et al. (2011) used parametric models for conceptual cost estimation of concrete bridge Foundations. Caputo and Pelagagge (2008) compared artificial neural networks and parametric functions for calculating the manufacturing cost of large and complex pressure vessels. Mittas and Angelis (2010) used a semi-parametric model to estimate the cost of a software package. Sonmez and Ontepeli (2009) estimated the cost of urban railway projects using parametric modeling.

Analytical cost estimation techniques are another category of quantitative techniques that are focused on decomposing a system into elementary subsystems, operations, and activities that represent different resources consumed during the creation and operation of the system and expressing the cost as a summation of all these elements. These techniques can be further classified into techniques such as Activity-Based Costing (ABC) and Breakdown Approaches.

Breakdown approach estimates the total cost of a product or equipment by summing all the costs incurred during the production cycle, including material costs as well as overheads. Breakdown method requires detailed knowledge about the resources employed to manufacture a product or equipment including purchasing, processing, and support and maintenance details (Niazi et al., 2006). Son et al. (2011) applied a type of breakdown approach called Configuration estimation method for initial cost of ships calculated based on engineering bills of materials.

ABC method concentrates on estimating the costs occurred on executing the activities to produce a product or equipment. ABC is based on the point that products or equipments require activities and activities require resources that result in costs (Waghmode, Sahasrabudhe, & Kulkarni, 2010). This method is an appropriate technique to distribute the overhead costs in proportion to the activities performed on a product or equipment to manufacture it. A wide range of the application of activity-based costing method can be found in the literature. Roztocki and Weistroffer (2004) applied ABC to evaluate information technology investments in emerging economies. In another study, Park and Kim (1995) used ABC for an economic evaluation of advanced technologies in manufacturing companies. Liu et al. (2008) shows the application of ABC in the refinery industry. Al-Tahat and Abbas (2012) applied activity-based cost estimation method in foundry systems manufacturing steel castings.

Depending on the purpose of cost estimation, the selected technique would be different. For example, qualitative techniques are useful in providing rough cost estimates and usually are used as a decision-aid tool for designers during the early stages of design process. However, if more accurate estimates are needed (e.g. profit margin determination), then quantitative techniques are applied (Niazi et al., 2006). To get faster and more accurate estimations, the integrated systems combining two or more techniques have been developed in recent studies. Integration of Parametric and neural methods (Caputo & Pelagagge, 2008), parametric cost estimation using simulated annealing (Xing et al., 2010), hybrid cost estimation approach applying decision trees and fuzzy logic (Papatheocharous & Andreou, 2012), hybrid genetic algorithm and neural network approach in activity-based costing (Kim & Han 2003), and fuzzy-activity-based costing (Nachtmann & Lascola Needy, 2001)(Dogan & Sahin, 2003) are among those techniques. An extensive review of the cost estimation modeling and techniques can be found in Rush and Roy (2000), Curran et al (2004) and Niazi et al (2006).

The above mentioned cost estimation methods have several limitations. For example, some of these methods require users with high level programming skills and moreover these methods are unable to consider uncertainties. To overcome these shortcomings, Scanlan et al. (2006) created a knowledge based cost modeling system. The Knowledge based cost modeling system still has some limitations. The main shortcoming is the inability of static models to fully show dynamic systems (Jinks, Scanlan, Reed, & Wiseall, 2010). A system representation at a particular point in time is defined as static model. However, the real world is a dynamic system in which many components are interacting over time, therefore methods such as discrete event simulation (Asiedu, Resant, & Gu, 2000)(J.-S. Chou, Yang, & Chong, 2009) and system dynamics are developed to overcome the limitations of the existing cost modeling techniques.

The following section gives an overview of studies on the application of system dynamics for cost modeling.

2.11. System Dynamics Model for Cost Estimation

The focus of this section is to discuss how SD can be applied to assess the cost associated with technology integration process. Applying the SD, the parameters affecting life cycle cost can be analyzed and the importance of these factors on life cycle cost is studied.

When deciding about the adoption of new technologies, not only the purchase price should be considered, but also the maintenance, support, upgrade and operational costs which occur during the equipment lifecycle are among the factors need to be considered. There are many factors affect total life cycle cost of an equipment such as the reliability of equipment, the system efficiency, the human-related cost, the capability index of equipment, the equipment age, the risk, the maintenance policies and so on (Chen et al. 2011). All the factors are correlative, influencing and interactive with each other. Therefore, clarifying the degree in which these factors affects total cost is very important before integrating a new technology. What is needed is not another version of the current cost estimation methods, but something that covers the limitation of the current cost estimation methods and provides feedback relationships among various factors. SD provides the ability to model feedback loops and dynamic behaviors and influences. The ending point of one unit of time is the starting point of the next unit of time, therefore the SD provides the ability to model dynamic influences and the possibility to check the effects of the decision that we make today on the system at various points in the future (Purvis, 2001).

Several studies in various areas have proved the applicability of SD for cost estimation. Yi and Xiao (2008) applied a SD model to investigate the effect of employing incentive methods in reducing the project cost. They studied the effects of using incentive methods to decrease cost and risk while considering a fixed project duration and quality level. In another study Kollikkathara et al. (2010) explored the impact of implementing a city-wide waste prevention program on the generation of waste in the city and on the cost or benefit resulted by different waste processing options. Loutfi et al. (2000) conducted a study to study the economic affect of tourism revenue and also government policies on the Egyptian Economy. Kiani et al. (2009) developed a SD model to analyze different quality cost factors. Prevention and appraisal costs are the two effective cost factors. They illustrated that prevention cost has the most important impact on the total quality cost, especially external failure costs. Manataki and Zografos (2009) applied SD to access the economic performance of Air Traffic Management programs. The focus of their analysis was on the cost analysis of European air traffic services in 20 years and their recruitment plan.

Several studies have applied SD for investigating the cost estimation of a specific equipment or product. Purvis (2001) used SD to estimate the Operation and Support costs for the C-17 Globemaster III cargo aircraft. Chen et al. (2011) applied system dynamics to prioritize twelve factors that have influence on the life cycle cost of a ship diesel oil mainframe. Based on their analysis, the order of these 12 factors is as follow: the service year and every year working hours, mean time between failures, mean cost of maintenance, mean time between the whole mainframe's dismantlement and repair, mean cost of dismantlement and repair, the power and fuel consuming rate, lube consuming rate, the purchase cost, failures repair cost and dismantlement and repair cost.

A few studies have applied SD modeling approach for Cost Estimation of Technology Integration Activities. Monga (2001) built a SD model based on Navy experts' opinions. He characterized the technology development process through two dynamic behaviors: oscillation and goal seeking. He showed that an increase in the complexity of new technologies results into an increase in the total costs. However, increasing the technology maturity results into total cost reduction. Further, according to his model an increase in the training results into a decrease in total costs.

2.12. Life Cycle Cost/Total Ownership Cost Breakdown

Before the organizations accept new technology, they must be convinced that the new technology will not lead to cost overrun in their system. The National Institute of Standards and Technology (NIST) Handbook 135, 1995 edition, defines Life Cycle Cost (LCC) as "the total discounted dollar cost of owning, operating, maintaining, and disposing of a building, equipment or a system" over a period of time. For a new technology acquisition plan, the LCC consists of the following components:

(1) research and development costs

(2) investment costs

(3) operating and support costs

(4) disposal costs over the entire life cycle

Figure 21 provides an overview of the cost categories. These costs include both the direct and indirect costs that would be logically assigned to the technology acquisition plan.

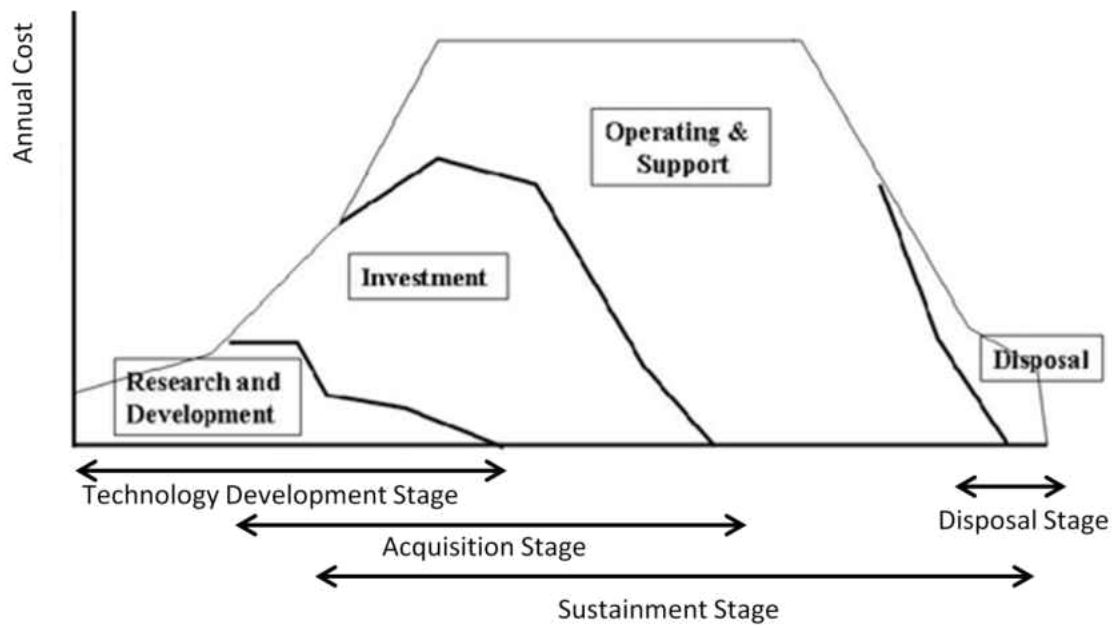


Figure 21. Comparison of cost areas during the system life cycle [modified from (DAU, 2012)]

The research and development costs associated with the Technology development stage, investment costs associated with the acquisition stage, operating and support costs associated with the sustainment stage, and disposal costs occur at the end-of-life stage. Equation 9 provides a breakdown of the LCC of a system:

$$LCC = DC + IC + OSC + DC \quad (9)$$

where,

LCC: Life Cycle Cost

DC: Development Cost

IC: Investment Cost

OSC: Operating and Support Cost

DC: Disposal Cost

Development costs are estimated using the research, engineering and manufacturing development costs. Investment cost occurs at the acquisition stage and typically includes procurement costs associated with purchasing hardware, planning activities, system test and evaluation, infrastructure construction, and initial operations and maintenance associated with the technology deployment activities (Singh 2004). Operation and Support costs occur from the deployment stage through the end of system operations. This cost consists of the costs of equipment, consumable, manpower, software, training and services associated with operating, maintaining, modifying, and supporting a system through its life cycle (DAU, 2012). Equation 10 provides a breakdown of the Operation and Support costs:

$$OSC = OC + PC + MC + EMC + TC \qquad (10)$$

where,

OC: Operation Cost

PC: Personnel Cost

MC: Maintenance Cost

EMC: Energy and Materials Cost

TC: Training Cost

Disposal costs occur at the end of the system useful life and include elements such as collection, disassembly, materials recovery, decontamination, disposal of hazardous materials, safety precautions, and transportation to and from the disposal sites. It is important to consider the disposal cost before the technology is adopted because these cost elements can be high, depending on the features of the system. Sometimes technologies receive credit depending on the cost estimation of the material recovery and recycling considerations.

The concept of TOC is related to LCC but it is broader in scope. TOC takes into account the components of life-cycle cost. Moreover, it includes other infrastructure costs not necessarily assigned to the LCC. In general, traditional LCC estimates are sufficient to decisions made as part of the technology acquisition plan. However, in special cases depending on the importance of the issue at hand, it may be better to use the broader perspective of TOC rather than the LCC. As discussed before, LCC consists of both the direct costs and some indirect costs that are logically assigned to the technology adoption plan. In a typical LCC estimate, the estimated indirect costs consist of only the costs of infrastructure support attributed to the new technology such as primarily safety support for personnel, technology-specific training, and the technology related facilities or installations. However, there are some other support or infrastructure activities such as hiring and training of new personnel, individual training other than technology-specific training, and most management and planning activities that normally are not included in the scope of a traditional LCC estimate but are included in TOC (DAU, 2012).

One purpose of TOC estimation is to use the results of the analysis to find out how the TOC can be reduced while keeping or improving the current performance of the system. There are several solutions that may help organizations reduce the TOC of the system. Adoption of new technologies and management practices, and improving the reliability and maintainability of the system are among the options that may provide significant opportunities to reduce TOC (Reed & Reed 2003).

2.13. Cost Estimation of Human Related Activities

It is recommended to address the human resource issues early in the technology development phase (Wallace et al. 2007). Therefore, there is no specific way to separate out the costs of human resource from the rest of development costs. Liu (2010) suggested that the human related efforts can be estimated by counting the number of HSI-related requirements.

Kopardekar, and Hewitt (2002) discussed three methods for human factors cost estimation: (1) Expert judgment approach, (2) Parametric cost estimation, and (3) cost estimation based on a Heuristic approach. In order to estimate the human factors cost using parametric method, the following steps could be used: in the first step the human related aspects that may impact (or be impacted by) the new technology implementation program, are identified. In the second step the level of impacts (from 'no impact' to 'very high impact') for each factor is determined. Then based on the level of impact, an estimated cost for covering HSI issues will be provided in Step 3. Finally in Step 4 the total human cost is estimated by the sum of all costs identified in Step 3. Several human factors that can be used in the first step and could impact (or be impacted by) the technology modernization program are: Workload, Training, Equipment Design, Standardization of Computer-Human Interface, Staffing, Safety and Health, Special Skills and Tools, Compatibility of Input and Output Devices, and Environmental factors that may impact human-system performance.

Human Factors have an essential contribution not only during the technology development, but also after implementation and during the system operation (Ives, 2007). One purpose of the SD model developed in this study is to investigate the human related aspects (e.g.

the number of workforce and the required skill set) and the corresponding costs impacted by new technology adoption.

2.14. Conclusion

Companies are often excited about implementing advanced technologies and they look at new technology solutions as a way for survival and growth. Unfortunately, not all technology implementations succeed. Making smart decisions about how to acquire a new technology, when to trade, and how much budget to invest in adopting the new technology is still a challenge for many organizations. All of these decisions require appropriate understanding of technology implementation and operations activities.

Assessing the relationships among various aspects of technology implementation plan is a complex task which requires the identification of the complexity features of new technology adoption process.

System Dynamics approach is a useful modeling technique that can be applied to better understand the behavior of complex systems over time. System Dynamics can be used to obtain the non-linear and complex relationship among elements of technology implementation activities. It is an effective approach for technology-related policy analysis in complex and uncertain systems. Dynamic technology systems with interdependent factors can be modeled and analyzed via system dynamics technique. Accurate modeling of technology-related activities provides decision makers with appropriate information needed to make better decisions. Managers and stakeholders at different levels of the organization can all benefit from the technology modeling results.

The current document provided a literature review on the technology features and the system dynamics modeling of technology management activities. It reviewed the studies that have employed System Dynamics to study different aspects of technology-related activities from technology development capacity to technology resource management.

The chapter further discussed the critical success factors of technology implementation and then reviewed the studies that have discussed the impact of the technology implementation on the human resource. Finally the chapter discussed the available cost estimation techniques and the application of SD modeling for cost estimation.

CHAPTER 3
MODEL, RESULTS AND DISCUSSION

3.1. Introduction

The result of this study is a System dynamics Model (SDM) that can be used to justify the investment in new technology adoption projects and to advance the understanding of TOC drivers. The purpose of the model is the identification of drivers for cost overruns and assess the level of their impact on total ownership cost. The developed model defines causal linkages and relationships between various elements of the system and ultimately helps leaders in their decision making efforts and in identifying the critical factors that cause unwanted and unforeseen behaviors in the systems.

This chapter starts with an overview of the general model including the sub-models that are embedded in the general model. Subsequent sections provide further details for each sub-model including the technology implementation activities, maintenance activities to support the new technology and the training activities required as a result of implementing new technologies.

3.2. Overview of the Model

The diagram illustrated in Figure 22 below shows the high level overall structure of the model. The overall model integrates three major areas:

1. Technology Implementation activities
2. Technology-System Interaction
3. Human-Technology Interaction

Each area has an effect on others. The further descriptions of Technology, System and Training areas are provided in the subsequent sections of this chapter.

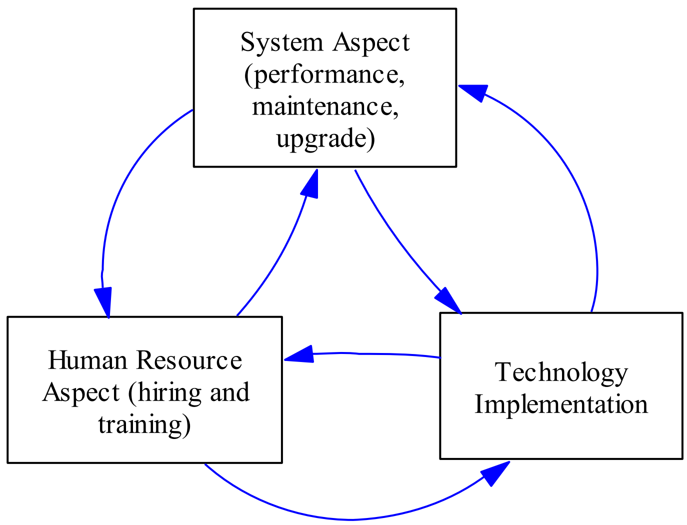


Figure 22. An overview of the three major areas covered in the System Dynamics modeling of integrating new technologies

3.3. Sub-System 1: Technology Implementation

Technology as one of the main blocks of the model includes various interconnected variables. For example, variables such as automation level, implementation time, technology maturity, and required investment can be used to describe the technology integration process. The technology integration activities are initially driven by model requirements. The cost of these activities is continuously checked in the SDM model. In general, the technology can be described through several key features. These key features represent the key concepts behind the model. The following features were identified as key characteristics and the whole model will be build around these features.

Complexity: determines the degree of being difficult to analyze, understand, or implement. Complexity is measured on a scale from 0 to 10, where 0 being the best or the most easy to plan and implement and 10 the worst or totally complicated technology to plan and implement. The complexity degree is typically determined by the experts and through considering several variables, each weighted according to their importance in technology implementation.

Maturity: determines for how long the technology has been in used. The longer the technology has been in use, the more inherent problems and initial faults have been omitted. More description about maturity can be found in Section 2.4 of this document. The level of the technology maturity can be determined through using the generally understood metric. Technology Readiness Level is one of those metrics on a scale from 1 to 9.

Implementation time: The amount of time it takes from initial planning stage to the final fully implementation and testing of the technology.

Reliability: The probability that a system or equipment performs its desired performance under stated conditions for a specified period of time.

Life Span: or design life of a system or equipment is the period of time during which the equipment is expected to work within its specified standards; in other words, the life expectancy of the equipment.

Upgradeability: determined the degree to which the system or equipment can be promote to equipment that provides greater performance than an earlier model. The upgradeability degree is typically determined by the designers and is measured on a scale from 0 to 10.

Automation Level of the technology: is considered as the ratio of the number of equipments needed to implement the system to the number of employees needed to run the system.

Required capital investment: money invested in the technology implementation with an expectation of an income.

Compatibility: determines the degree of efficient integration and operation with other existing systems with no further modification or conversion required. Compatibility is measured on a scale from 0 to 10, where 0 being the worst or too many modifications required and 10 the best or no modification is required. The compatibility degree is typically determined by the experts through conducting some initial analysis about the cost of the required modifications to make the new system capable of working with existing systems.

Each above mentioned feature should be investigated further through identifying its key variables. After recognizing the key variables, they will be connected in a form of a casual loop diagram. In general, building a system dynamics model for each block of the model (Technology, System, Human resource) starts with model conceptualization. Following are the steps of SDM model conceptualization:

1. Define the TOC model boundary and identify key variables.
2. Describe the behavior or draw the reference modes of the key variables.
3. Diagram the basic mechanisms, the feedback loops, of the TOC system.

General variables of interest to the system dynamics technology sub-model were identified through brainstorming session.

The next step would be to fully define each of these variables. For example, funding is the amount of money allocated by the management to conduct all the effort required in implementing the new technology or Technology Implementation Risk can be defined as a measure of the risk integrated in implementing the new technology. It can be defined as a dimensionless variable measured applying a scale changing from 1 to 10; changing from a very low risk at 1 to a very high risk at 10.

Casual Loop Diagram (CLD)

The feedback structure of the model can be qualitatively shown using causal loop diagrams. Causal Loop Diagram lists the variables and connects them by causal links, shown by arrows. Each link has a polarity: a positive or negative. Positive link (denoted by '+') link implies that by increasing (decreasing) the cause, the effect will increase (decrease). A negative link (denoted by '-') means that by increasing (decreasing) the cause, the effect will decreases (increases). There are also two types of loop in the CLD: Positive or Reinforcing loop and Negative or Balancing loop.

The Causal Loop Diagram was developed from the team modeling sessions. The significant benefit of casual loop diagram is that it allows the decision maker to understand and explain the feedback structure between variables. CLD is the casual map of the feedback processes that the decision makers believe are responsible for the dynamics in the system. The following figures (23-24) are the snapshots of the initial set of major causal loops thought to be relevant to technology implementation. Moreover, several examples of the loops and their elements are listed in APENDIX A.

R1 Loop: Technology implementation requires resource involvement

Story of the loop: Technology Implementation requires special effect by all involved human resource and even requires using tools and equipment. The longest the Technology implementation period, the highest is the amount of work required to implement technology and therefore the startup resource level allocation. The amount of work required refers to the number of man-hour needed to implement technology.

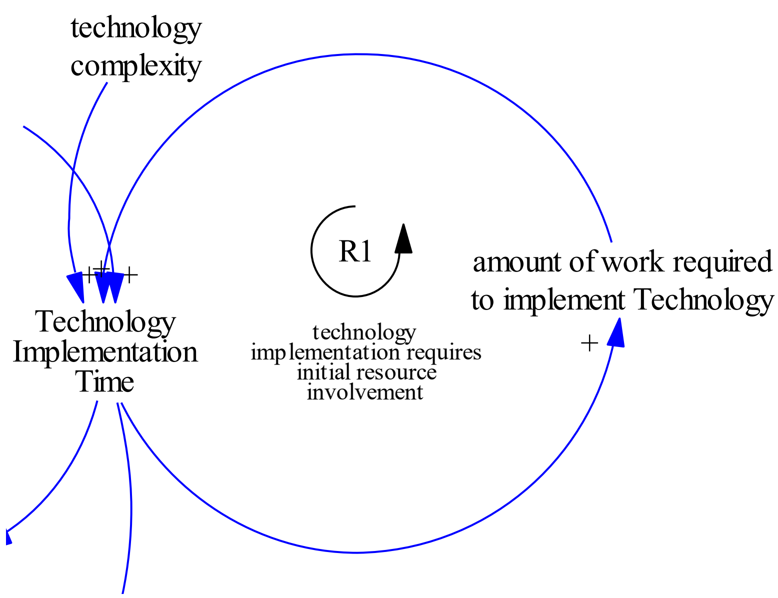


Figure 23. Reinforcing Loop R1: indicating the technology implementation requires time and resource involvement

B1 Loop: Technology implementation requires budget

Story of the loop: The budget drives technology implementation schedule (Timeline). The governmental policies and the technology price determine the amount of budget allocated to technology implementation. The higher the budget allocated to the technology, the shorter the technology implementation time. The time to implement technology affects the implementation cost. The higher is the cost of implementation, the more is the pressure to increase the budget allocated to technology.

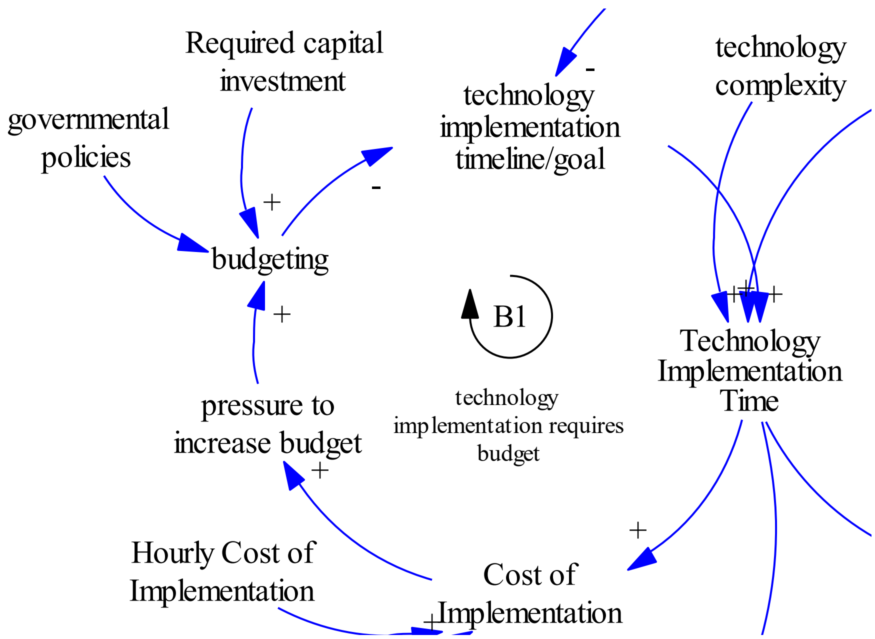


Figure 24. Balancing Loop B1: indicating the technology implementation requires budget

In addition to using CLD, the interrelations between variables further can be shown using ‘Causes tree’ and ‘Uses tree’ diagrams. Causes tree of a variable lists those variables that have direct or indirect impacts on the variable. ‘Uses tree’ on the other hand lists the variables that are influenced by the variable under the study. Figures 25 and 26 show the ‘Causes tree’ and ‘Uses tree’ diagrams of ‘technology implementation time’ respectively.

Based on the Causes tree, ‘technology implementation time’ is influenced by the ‘amount of work required to implement the technology’, the ‘complexity of the technology’ and the ‘technology implementation timeline’. On the other hand, based on the Uses tree, ‘technology implementation time' affects implementation cost and the amount of efforts implemented toward technology adoption.

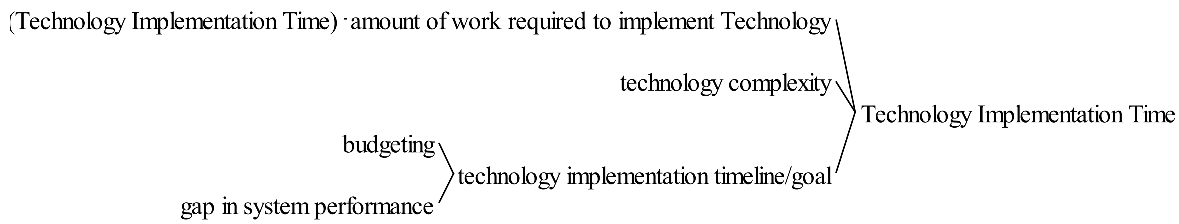


Figure 25. 'Causes tree' diagram for 'technology implementation time'

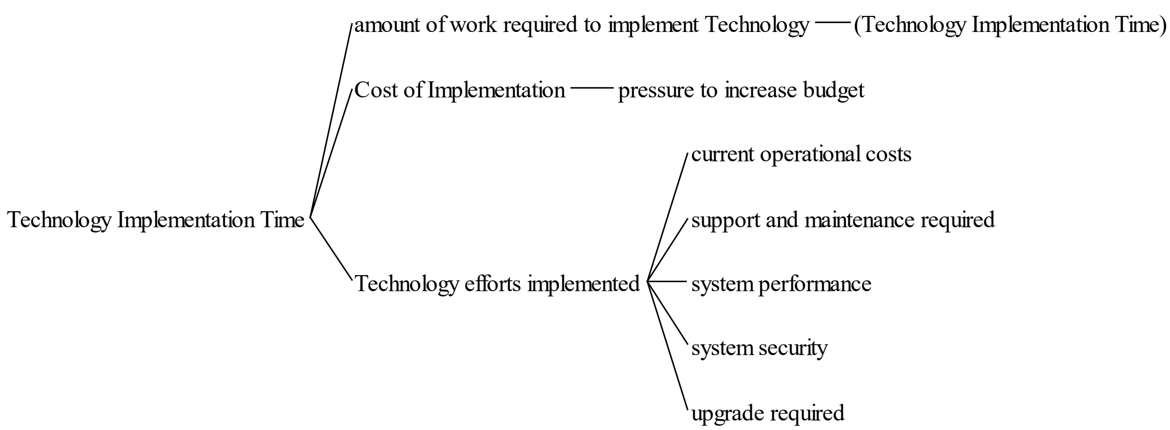


Figure 26. 'Uses tree' diagram for 'technology implementation time'

3.4. Sub-System 2: System Aspects

The second subsystem mainly represents the benefits and impacts of the technology implemented on the system performance as well as the support, upgrade and maintenance efforts required to operate the technology based on its intended goals. In an effort toward modeling the system part, four areas have been selected for analysis:

(1) Maintenance and support activities;

(2) Upgrade activities required over the technology life span;

(3) Impact of the technology on the system performance;

(4) Impact of the technology on the operational costs.

The related variables are identified and connected through CLD. Figures 27-30 show the snapshots of the set of major causal loops relevant to the sub system-2.

B2 Loop: Technology requires maintenance

Story of the loop: Once a technology system has been implemented it should be maintained and supported through its entire life. The amount of maintenance required can be determined based on the technology life span. The amount of maintenance implemented improves system's reliability. The higher is the systems reliability, the lower is the gap in systems reliability and the lower is the required long term support and maintenance.

B3 Loop : Technology requires upgrade over its life cycle

Story of the Loop: System upgrades should be part of the system support activities. When a new version of the technology supersedes the old version, it becomes preferred to upgrade the technology. In some cases it may be logical to completely replace the technology with the new version. However, in most cases it is economical to just upgrade the technology to the higher version. In fact, upgrading the technology becomes a part of its lifetime plan. The number of upgrade implemented for a technology influences the technology readiness level (TRL). The higher is the technology TRL, the lower is the TRL gap from the TRL target and therefore the lower is the upgrade required.

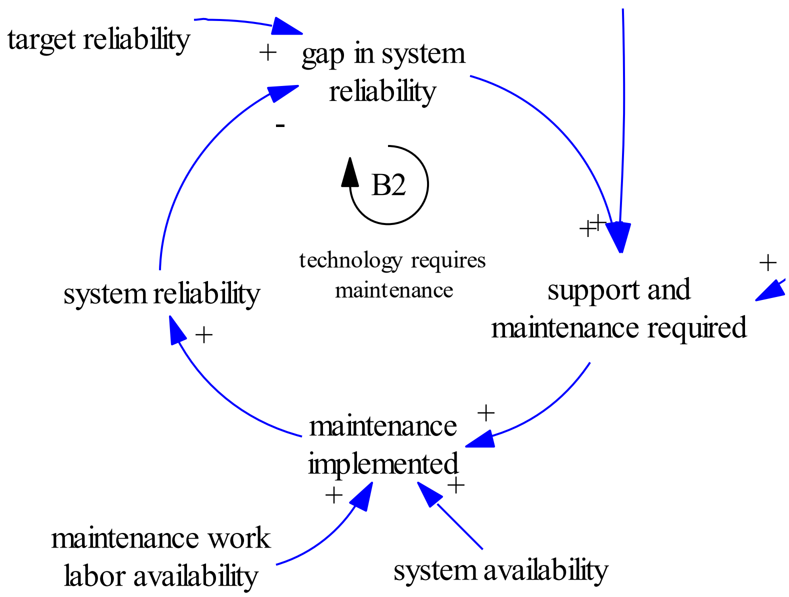


Figure 27. Balancing Loop B2: indicates that more system reliability results in less support and maintenance and vice-versa

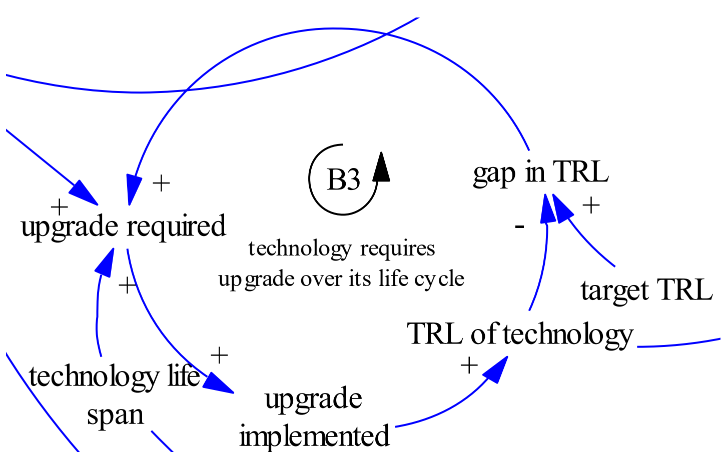


Figure 28. Balancing Loop B3: indicates that more upgrade activities results in more technology maturity and vice-versa

B4 Loop: Technology implementation affects system performance

Story of the Loop: One of the main objectives of technology implementation is to improve system performance. The higher the amount of technology efforts implemented the greater is the systems performance. The better is the system performance the lower is the gap in system performance from the target.

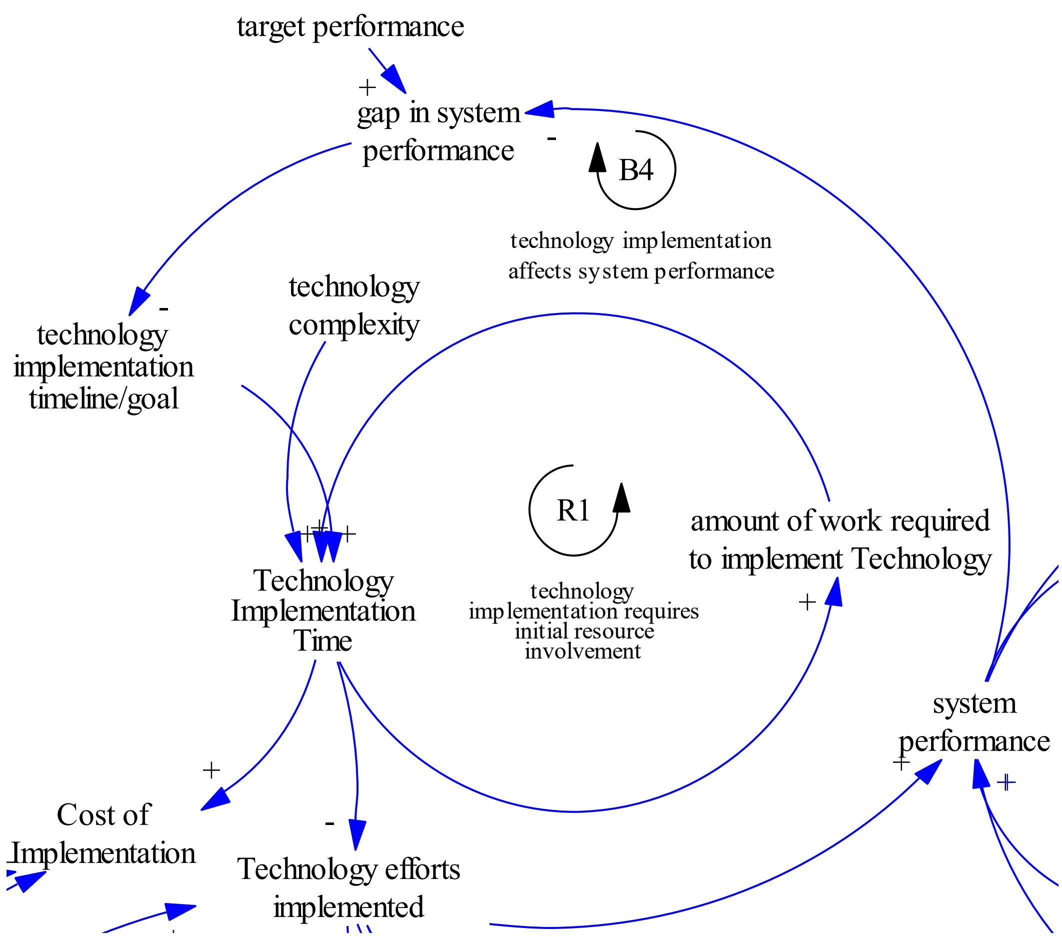


Figure 29. Balancing Loop B4: indicates that the more the technology efforts implemented, the better is the system performance

B5 Loop: Technology implementation results in reducing operational costs

Story of the Loop: Companies can make themselves more competitive by adopting technologies that result in lower operational costs and finally lead to lower cost price. Technology adoption can reduce cost of the systems in several ways: through improving the productivity, improving the quality of the product or service, through increasing the automation level and reducing the labor cost. Loop B5 is based on the hypothesis that the more is the amount of technology efforts implemented, the more is the improvement in operational costs. The lower is the operational cost the lower is the gap in operational cost from the target.

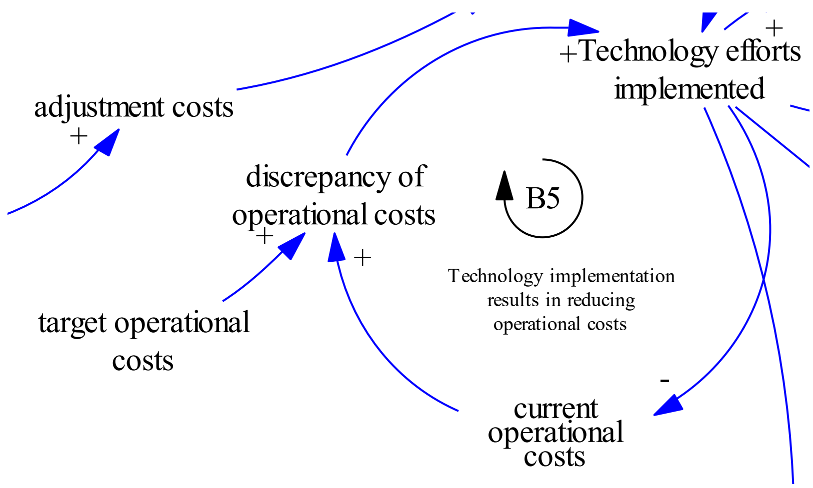


Figure 30. Balancing Loop B5: indicates that the more the technology efforts implemented, the lower will be the system operational costs (technology implementation improves the operational cost of the system)

3.5. Sub-System 3: Human Resource Aspects

The third subsystem discusses the impact of the technology implementation on the workforce. The technology implementation may impact the number of personnel in the company. Moreover, every technological change requires at least a little training. In fact, the implementation process could be improved with user involvement and training (Griffith, Zammuto, & Aiman-Smith, 1999).

Training is an integral part of almost any technology implementation project. Both current and new staff recruited should be trained to get the skill set required to use the new technology. This section presents the mental model of the impact of the technology implementation on the required training and the employees' satisfaction. Figure 31 shows two loops corresponding to the human resource aspects of the technology implementation.

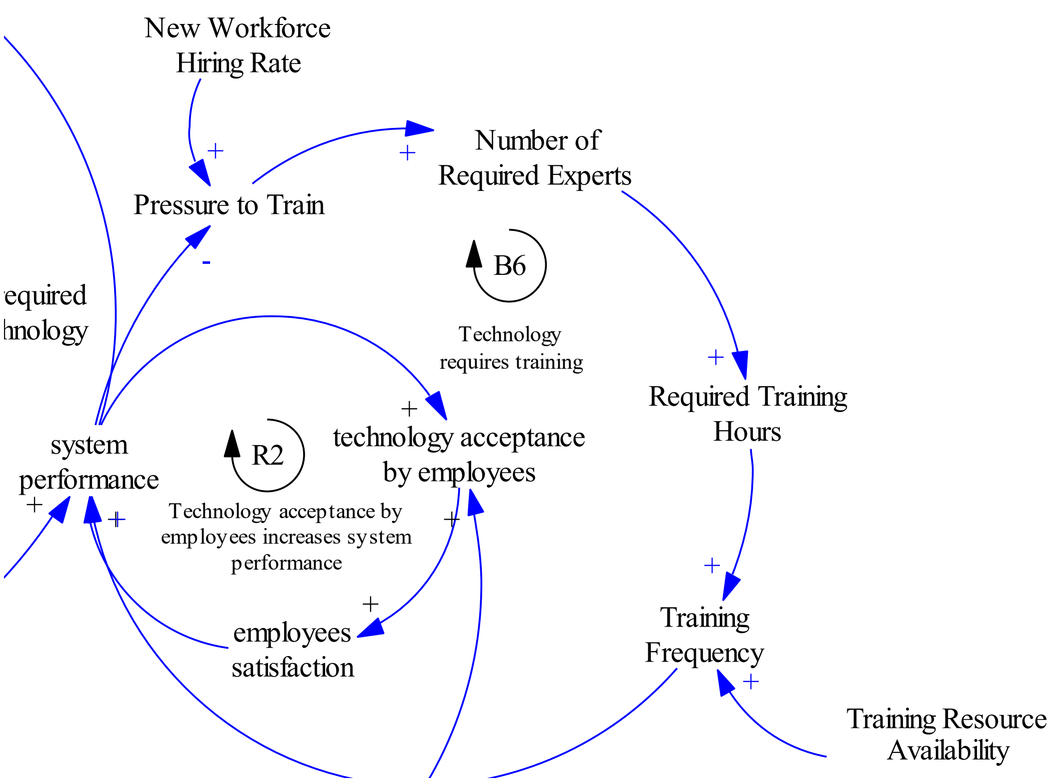


Figure 31. Loops R2 and B6: indicate the technology changes require training and the technology implementation impacts employees' satisfaction

R2 Loop: Technology acceptance by employees increases system performance

Story of the Loop: As discussed before, many companies use technology implementation as a vital tool to improve their system performance. The point is that one of the challenges toward successful adoption of the technology is the employees' resistance against the change. Understanding root causes of resistance allows companies to develop solutions to improve the acceptance of the technology. For example, Training initiatives can help companies increase the employees' satisfaction and technology acceptance. Employees can receive motivation to apply a new technology by engaging in appropriate training programs (Siegel 2008).

The hypothesis behind loop R2 is that the better is the system performance the higher is the technology acceptance by employees. On the other hand, technology acceptance by employees results in employees' satisfaction which further increases the system performance.

B6 Loop: Technology requires training

Story of the Loop: Technology implementation sometimes requires a high level of skill and education on the part of employees. According to Boothby et al. (2010) companies that implement new technologies and at the same time spending on training and improving technical skills are expected to gain more productivity than others. In addition, sometimes in order to successfully adopt new technologies new skills should be hired. The skill level of newly hired workforce and the existing personnel could be improved through training. Moreover as discussed before, training can improve employees' attitude towards new technologies and increase the user acceptance, which is important for improving the performance of the system and the appropriate use of new technologies (Ouadahi, 2008). Loop B6 is built based on this concept that the lower the system performance is the higher the pressure for training will be. The pressure to train results in increasing the number of skill set required. Further, increasing the number of required experts increases the need for the number of training hours. Once the employees receive the required training, the system performance improves.

The set of major casual loops discussed so far in this chapter is summarized in Table 8. In addition, Figure 32 represents the overall CLD model including all loops and the connections among them. Note that all links are named and the loop identifiers show which loops are clockwise or counterclockwise. Loop polarity signs and ‘R’ and ‘B’ labels represent the positive (Reinforcing) and negative (Balancing) loops.

Table 8. The initial set of major loops in the CLD

Loop Name	**Major interrelated elements**	**Loop type**	**Concept behind loop**
B1	Technology implementation timeline, technology implementation time, cost of implementation, pressure to increase budget, budgeting	Balancing	Technology Implementation requires budget
B2	Support and maintenance required, maintenance implemented, system reliability, gap in system reliability	Balancing	Technology requires maintenance
B3	Upgrade required, upgrade implemented, TRL of technology, gap in TRL	Balancing	Technology requires upgrade over its lifetime
B4	Technology efforts implemented, system performance, gap in system performance, technology implementation timeline, technology implementation time	Balancing	Technology implementation affects system performance
B5	Technology efforts implemented, current operational costs, discrepancy of operational costs	Balancing	Technology implementation results in reducing operational costs
B6	System performance, pressure to train, number of required experts, required training hours, training frequency	Balancing	Technology requires training
R1	Technology implementation time, amount of work required to implement technology	Reinforcing	Technology implementation requires initial resource involvement
R2	System performance, technology acceptance by employees, employees satisfaction	Reinforcing	Technology acceptance by employees increases system performance

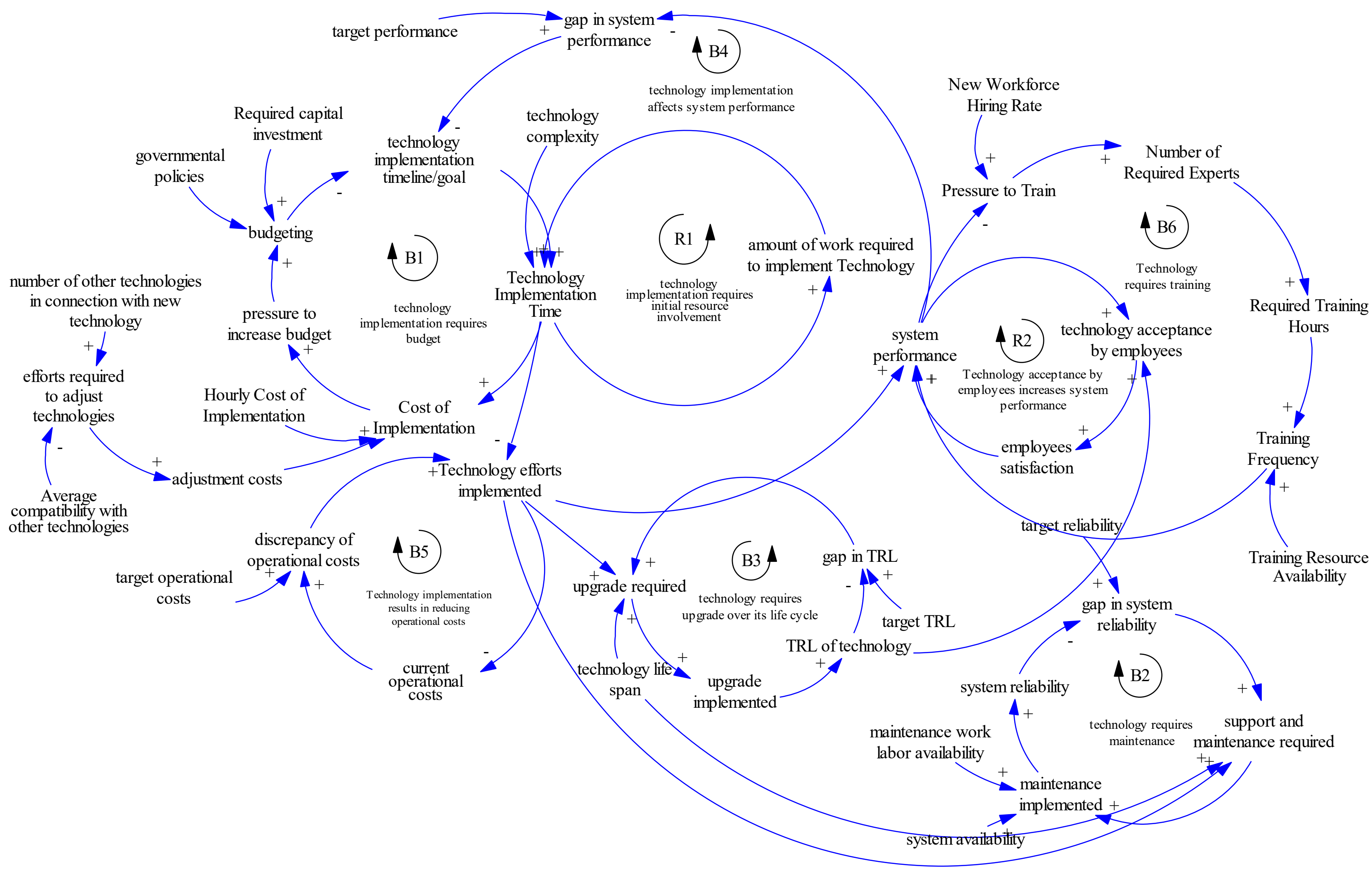


Figure 32. The Casual Loop Diagram of Technology Adoption Process

3.6. Stock and Flow Diagram

CLD are helpful in many situations. They are widely used to represent the interdependencies and feedback processes. They are also often used at the beginning of modeling process to capture the mental models of decision maker. However, CLDs suffer from several limitations. One limitation is that CLD can never be final and comprehensive. As the understanding of the decision makers improves, the CLD evolves. Moreover, the CLD cannot capture the stock and flow structure of the model which is one of the central concept of the dynamic systems theory. Stocks play a vital role in generating the dynamics of systems for several reasons (Sterman 2000, p.195-197):

(1) Stocks represent the state of the system at each point of the time and create the basis for corrective actions. Without the knowledge about the state of the system, the decision makers will not be able to take required actions.

(2) Stocks accumulate over time and provide a memory for the system.

(3) Stocks create delays in the system. There is a lag between the time an input enters the stock and the time it leaves the stock.

(4) Stocks provide decision makers the ability to model disequilibrium dynamics in the system. Often the total inflow to a stock is not equal to the total outflow from the stock since the inflow and outflow rates are usually influenced by various decisions. Stocks help decision makers model these situations.

This section explains the SD simulation approach to model the complexity of technology adoption process and explore technology features influencing the total cost of the system. SD relies on casual loops and information feedback and is a powerful approach in modeling any complex system identified by nonlinear causality, interdependency and information feedback (Sterman, 2000)(Scholl, 2001). The overall structure of the SD model suggested in this dissertation was formulated in Vensim software. Table 9 lists different parts of the SD model and their association with three sub-systems described in the previous section.

Table 9. The list of six different sub models of the Stock and Flow Diagram

	Sub Systems	Stock and Flow Sub Models
Total Ownership Cost	Technology Implementation	Technology Implementation Process
	Human-Technology Interaction	Workforce Hiring
		Workforce Training Process
	Technology-System Interaction	The Impact of Technology on the System Performance
		Service, Maintenance and Support Process
		Upgrade and Technology Maturity

The representation of the model itself consists of six sub models, each representing a different sub set of activities: technology implementation activities, workforce training, workforce hiring, support and maintenance activities, upgrade and technology maturity and finally the impact of technology on the system performance.

To make it easier to read, each part of the model is depicted in a separate figure. The complete model is shown in further in this Chapter.

The inflows and outflows variables are the driving forces of the dynamics of the model and are referred to as rate or flow variables. On the other hand the state variables shown by rectangles are referred to as levels or stocks. The stock variables will increase and decrease by inflows and outflows. It should be noted that there is a mathematical mapping behind the stock and flow diagram. The general concepts behind each part of the model are discussed in the following subsections.

3.6.1. Sub-Model 1: Technology Implementation Process

Companies often implement new technologies as an ongoing effort. Therefore, they need to make sure that the technology implementation activities consistently are integrated with other existing business processes (Gerdsri, Assakul, & Vatananan, 2008). The technology implementation stock and flow diagram is represented in Figure 33. This part of the model shows the process of generating technology implementation efforts and the completion rate of those activities. The technology implementation starts with an 'Estimated Implementation Efforts Backlog' determined based on the number of man hours work required to implement the technology. This number is often determined by conducting feasibility studies and using consultants' opinions. If the technology is not developed inside the company, the number of man hours implementation activities is determined by the company selling the technology. It should be noted that, the efforts required to implement technology are generated over time with a rate called 'Implementation Initiation Rate'.

The 'Implementation Initiation Rate' is determined based on the 'Estimated Implementation Efforts Backlog' and the standard time to implement the technology, 'Standard Implementation Time'. This rate is adjusted by the 'Complexity of the Technology' and the 'unexpected rework rate'. The higher the complexity of the technology, the higher the amount of

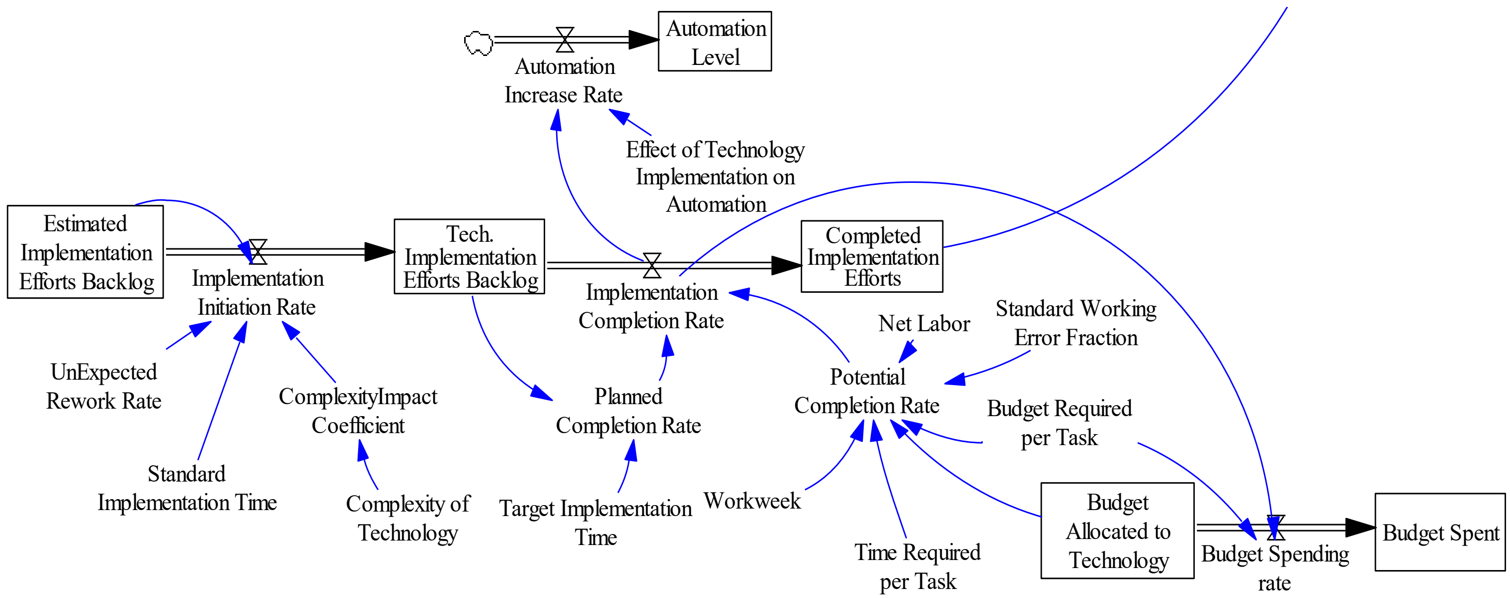


Figure 33. Sub-Model 1: Technology implementation and budget allocation process

efforts required to implement the technology. A (1-9) scale is employed to represent the technology complexity. To include the impact of the technology complexity on the rate of the activities required to implement the technology, the variable ‘Complexity Impact Coefficient’ is defined. This variable is a sort of lookup table that links the technology complexity with the rate of required implementation activities. Figure 34 shows one example of the look up function that can be applied to connect the complexity of the technology and the implementation initiation rate.

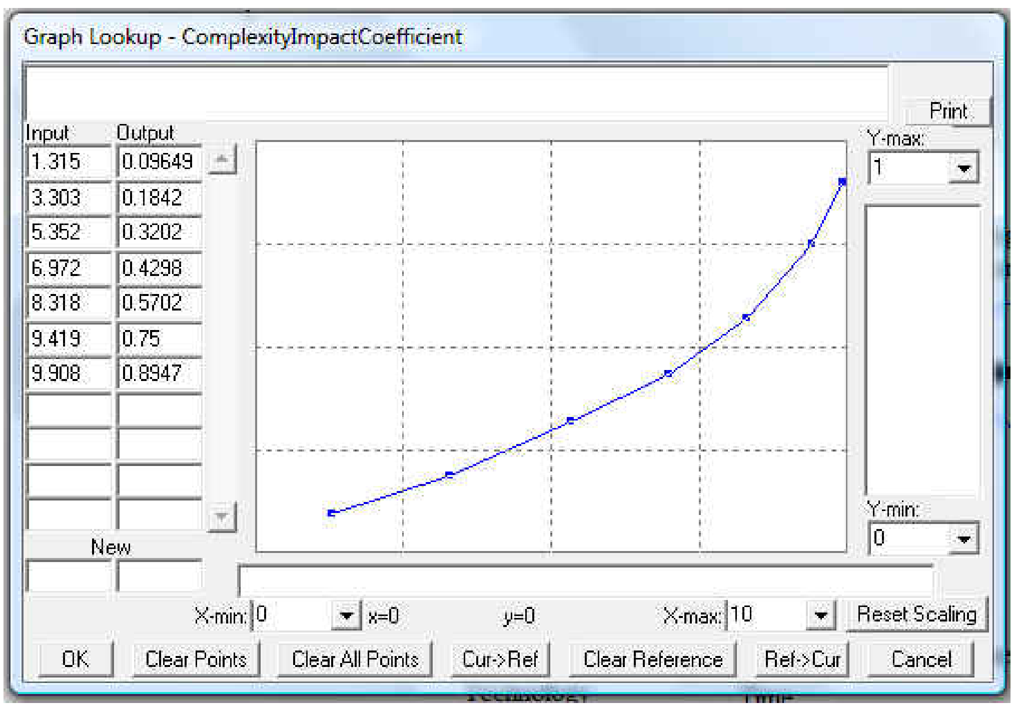


Figure 34. Effect of ‘technology complexity’ on the ‘Implementation Initiation Rate’

The higher is the technology complexity, the higher will be the generation rate of activities that need to be implemented. The ‘Implementation Initiation Rate’ is defined as follow:

Implementation Initiation Rate = (Estimated Implementation Efforts Backlog/Standard Implementation Time)(1+UnExpected Rework Rate)*(1+ComplexityImpactCoefficient)*

The amount of man-hour work generated over time through the ‘Implementation Initiation Rate’ is accumulated in the ‘Tech. Implementation Efforts Backlog’ variable. This stock connects the ‘Implementation Initiation Rate’ with the ‘Implementation Completion Rate’. Therefore, the level of this stock variable at each point of the time indicates the amount of man-hour work that is waiting to be implemented:

Tech. Implementation Efforts Backlog = INTEG (Implementation Initiation Rate-Implementation Completion Rate, 0)

The rate of conducting the ‘Tech. Implementation Efforts Backlog’ is modeled using ‘Implementation Completion Rate’. This variable is determined based on two other variables: ‘Planned Completion Rate’ and ‘Potential Completion Rate’. ‘Planned Completion Rate’ is calculated from the ‘Tech. Implementation Efforts Backlog’ and the ‘Target Implementation Time’ (e.g. the company plans to implement 1000 man-hour implementation efforts in six months). The typical formula to calculate the rate of planned completion efforts is:

Planned Completion Rate = Tech. Implementation Efforts Backlog/Target Implementation Time

On the other hand, ‘Potential Completion Rate’ considers the impact of the resource availability and budget allocated to technology on the implementation rate. A typical equation for calculating the ‘Potential Completion Rate’ is:

Potential Completion Rate = IF THEN ELSE (Budget Allocated to Technology>=Budget Required per Task, Net Labor(Workweek/Time Required per Task)*(1-Standard Working Error Fraction), 0)*

Based on the above formula, if the budget required for a task is less than the available budget, then the task is conducted and the completion rate is calculated based on the number of work hour available in each week (e.g. 40 hours), the 'Time required per Task' and the number of available workforce. To include the amount of rework and work errors, a 'Standard Working Error Fraction' has been used to adjust the completion rate.

The actual 'Implementation Completion Rate' is the minimum of 'Planned Completion Rate' and 'Potential Completion Rate':

Implementation Completion Rate = MIN (Potential Completion Rate, Planned Completion Rate)

The amount of the work done is accumulated in the 'Completed Implementation Effort' stock.

Completed Implementation Efforts = INTEG (Implementation Completion Rate, 0)

The remaining level of 'Budget Allocated to Technology' is influenced by the 'Implementation Completion Rate'. The 'Budget Allocated to Technology' is spent with the 'Budget Spending Rate' calculated from the completion rate of implementation activities and the amount of budget required per task:

Budget Spending rate = (Implementation Completion Rate)(Budget Required per Task)*

The budget spent during implementation is accumulated in the 'Budget Spent' stock:

Budget Spent = INTEG (Budget Spending rate, 0)

Later in this chapter we will discuss how the amount of implementation efforts completed impacts the performance of the system. In addition, the implementation efforts affect the 'Automation Level' in the system. The assumption here is that the higher is the number of man hours work implemented, the more increase is in the automation level. Table 10 lists the main variables in the technology implementation sub-model and the input variables and the corresponding mathematical equations.

Table 10. 'Technology Implementation' Sub-model variables and equations

	Main Variables	**Input Variables**	**Equations**
Technology Implementation	Implementation Completion Rate	Planned Completion Rate Potential Completion Rate	*MIN(Potential Completion Rate, Planned Completion Rate)*
	Potential Completion Rate	Budget Allocated to Technology Budget Required per Task Net Labor Standard Working Error Fraction Time Required per Task Workweek	*IF THEN ELSE(Budget Allocated to Technology>=Budget Required per Task, Net Labor*(Workweek/Time Required per Task)*(1-Standard Working Error Fraction) , 0)*
	Planned Completion Rate	Tech. Implementation Efforts Backlog Target Implementation Time	*(Tech. Implementation Efforts Backlog) / Target Implementation Time*
	Implementation Initiation Rate	Estimated Implementation Efforts Backlog Complexity Impact Coefficient Standard Implementation Time UnExpected Rework Rate	*(Estimated Implementation Efforts Backlog/Standard Implementation Time)*(1+UnExpected Rework Rate)*(1+ComplexityImpactCoefficient)*
	Budget Spending Rate	Budget Required per Task Implementation Completion Rate	*(Implementation Completion Rate*Budget Required per Task)*
	Automation Increase Rate	Implementation Completion Rate Effect of Technology Implementation on Automation	*Implementation Completion Rate*Effect of Technology Implementation on Automation*

3.6.2. Sub-Model 2: Workforce Training Process

The function of the training process is to transform the trainees into qualified workforce that can work with the new technology implemented. According to Riddell and Song (2012) the speed of technology acceptance by employees depends on the amount of the knowledge they have about the technology. In fact having a technology without enough knowledge on how to use it is useless. In general, training the personnel reduces the technology adoption cost and increases the probability of technology acceptance by the users (Wozniak, 1987). Therefore, the companies need to train their personnel on how to properly use the capabilities of their new technologies. The 'Workforce Training' sub model is depicted in Figure 35.

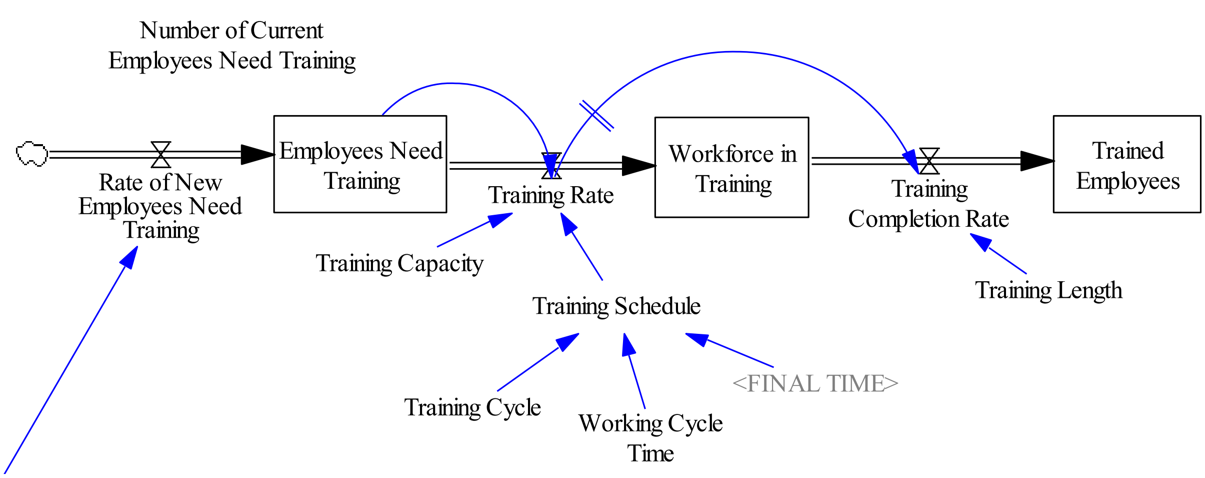


Figure 35. Sub-Model 2: workforce training process

The list of the main variables in the workforce training sub-model and the corresponding mathematical equations are listed in Table 11.

Table 11. ‘Workforce Training’ Sub-model variables and equations

	Main Variables	**Input Variables**	**Equations**
Workforce Training Process	Rate of Employees Need Training	New Employee Hire Rate	New Employee Hire Rate
	Training Rate	Employees Need Training Training Capacity Training Schedule	*IF THEN ELSE(Employees Need Training>0, Training Capacity*Training Schedule, 0)*
	Training Completion Rate	Training Rate Training Length Training Rate	*DELAY3I(Training Rate, Training Length , Training Rate)*
	Training Schedule	*Training Cycle* *Working Cycle Time* *FINAL TIME*	*PULSE TRAIN(Training Cycle, Working Cycle Time, Training Cycle + Working Cycle Time, FINAL TIME)*
	Training Cost Rate	Training Completion Rate Training Unit Cost per Employee	*Training Completion Rate*Training Unit Cost per Employee*

The Stock variable, ‘Employees Need Training’ describes the number of workforce that need training at any given point of time. The number of ‘Employees Need Training’ will rise by the inflow of workforce recruited, and fall by the outflow of ‘Training Rate’. The initial value for the ‘Employees Need Training’ Stock is equal to the number of current employees that should be trained. In this model, it is assumed that all of the newly hired personnel need to receive training.

Employees Need Training = INTEG (Rate of New Employees Need Training-Training Rate, Number of Current Employees Need Training)

The other two stock variables are ‘Workforce in Training’ and ‘Trained Employees’. The ‘Workforce in Training’ is fed by the ‘Training Rate’ and is depleted by the ‘Training Completion Rate’.

Workforce in Training = INTEG (Training Rate-Training Completion Rate, 0)

‘Trained Employees’ level is replenished by trainees who successfully complete their training, i.e., Training Completion Rate.

Trained Employees = INTEG (Training Completion Rate, 0)

‘Training Rate’ is determined based on the ‘Training Capacity’ and ‘Training Schedule’ applying the following equation:

*IF THEN ELSE (Employees Need Training>0, Training Capacity*Training Schedule, 0)*

If there are some employees who need training, depending on the capacity of the training sessions, they are sent for training. To distinguish the training period from the working shifts, a ‘Training Schedule’ variable has been used. This variable is defined based on the training and working cycle times:

Training Schedule = PULSE TRAIN (Working Cycle Time, Training Cycle, Training Cycle + Working Cycle Time, FINAL TIME)

It is assumed that training is completed periodically within equal intervals. ‘Training Schedule’ is a binary variable (0, 1). It gets the value of 1 over the training period and 0 otherwise.

It is assumed that all employees pass the training period, therefore the 'Training Completion Rate' is simply determined based on the initial 'Training Rate' and taking into account the training period, i.e. 'Training Length'. 'Training Completion Rate' further can be used to calculate the 'Training Cost'. A third order exponential delay equation in Vensim is applied to determine the rate of the employees that finish training period:

Training Completion Rate = DELAY3I (Training Rate, Training Length, Training Rate)

3.6.3. Sub-Model 3: Workforce Hiring Process

Sometimes adopting a new technology has a significant impact on the number of workforce in the company. Implementation of a new technology may reduce the number of workforce as a result of increasing the automation level, or may increase the need for hiring professionals. Figure 36 shows the hiring new employees and the promotion process.

Most companies contain different promotion chains that show the various levels in the hierarchy within the company (Sterman, 2000). A typical promotion chain is represented in Figure 5. There are total four employee ranks: employees with 1-3 years experience within the company, employees with 3-5 years experience, employees with 5-7 years experience and employees with more than 7 years experience. The distribution of the employees across these four ranks depends on the average emplacement time in each category, the promotion fraction as well as the hiring rate of new employees.

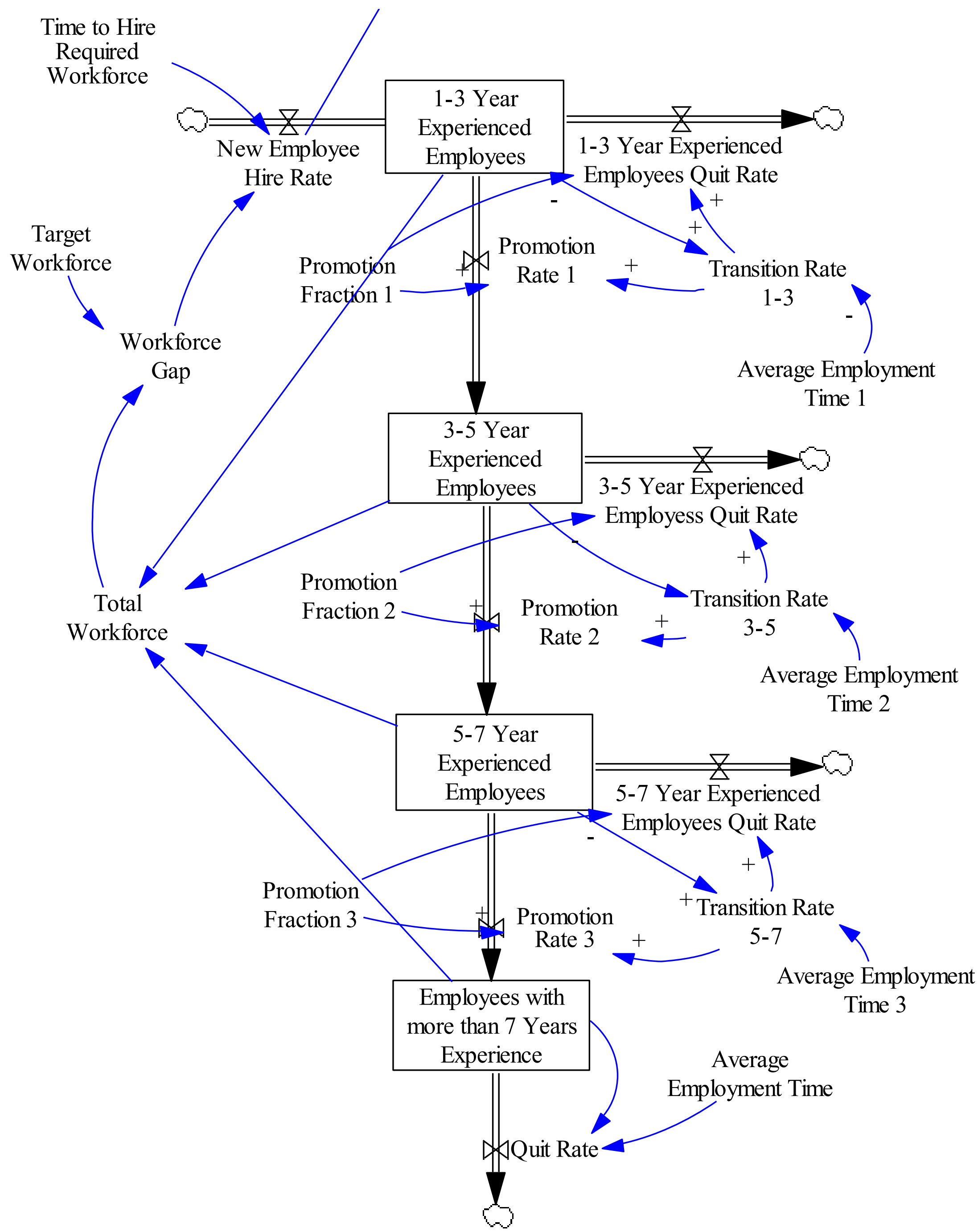


Figure 36. Sub-Model 3: workforce hiring process

Employees are moved to another experience level based on a transition rate and a promotion fraction. Those employees not promoted quit the company. The 'Transition Rate' in each level is determined based on the number of the employees in the corresponding experience level and the average employment time. For example, the 'Transition Rate 1-3' is calculated as follow:

Transition Rate 1-3 = (1-3 Year Experienced Employees)/Average Employment Time 1

Then, the 'Promotion Rate 1' that represents the rate of workforce promoted from the 1-3 years experience level to the 3-5 year experience level is calculated applying both the 'Transition Rate' and the 'Promotion Fraction':

*Promotion Rate 1 = (Transition Rate 1-3) * (Promotion Fraction 1)*

Therefore, the percentage of employees who are not promoted and leave the company is:

*'1-3 Year Experienced Employees Quit Rate' = (Transition Rate 1-3) * (1-Promotion Fraction 1)*

It should be noted that the 'New Employees Hire Rate' is determined from the 'Workforce Gap' calculated based on the current 'Total Workforce' and the 'Target workforce'.

Workforce Gap = Target Workforce-Total Workforce

New Employees Hire Rate = (Workforce Gap)/ (Time to Hire Required Workforce)

The ‘Target Workforce’ is determined based on the number of employees needed to work with the new technology. Table 12 gives more detail on the variables and equations associated with the ‘workforce hiring’ sub-model.

Table 12. ‘Workforce Hiring’ Sub-model variables and equations

	Main Variables	**Input Variables**	**Equations**
Workforce Hiring	New Employee Hire Rate	Workforce Gap	*IF THEN ELSE(Workforce Gap>=0, (Workforce Gap)/Time to Hire Required Workforce , 0)*
		Time to Hire Required Workforce	
	1-3 Year Experienced Employees	New Employee Hire Rate	*INTEG((New Employee Hire Rate)-(Promotion Rate 1)-(1-3 Year Experienced Employees Quit Rate))*
		Promotion Rate 1	
		1-3 Year Experienced Employees Quit Rate	
	Transition Rate 1-3	1-3 Year Experienced Employees	*(1-3 Year Experienced Employees)/(Average Employment Time 1)*
		Average Employment Time 1	
	Promotion Rate 1	Transition Rate 1-3	*(Transition Rate 1-3)*(Promotion Fraction 1)*
		Promotion Fraction 1	
	1-3 Year Experienced Employees Quit Rate	Transition Rate 1-3	*(1-Promotion Fraction 1)*(Transition Rate 1-3)*
		Promotion Fraction 1	
	Total Workforce	1-3 Year Experienced Employees	*(1-3 Year Experienced Employees)+(3-5 Year Experienced Employees)+(5-7 Year Experienced Employees)+(Employees with more than 7 Years Experience)*
		3-5 Year Experienced Employees	
		5-7 Year Experienced Employees	
		Employees with more than 7 Years Experience	
	Workforce Gap	Target Workforce	*Target Workforce-Total Workforce*
		Total Workforce	

3.6.4. Sub-Model 4: Service, Maintenance and Support Process

The maintenance sub model consists of two main parts: the first part models the preventive maintenance process and the second part models the corrective maintenance activities. Preventive Maintenance is often performed in a routine basis designed to keep machinery in good condition to prevent unexpected failure and equipment downtime. Therefore, preventive maintenance is schedule to occur regularly as system operates. On the other hand, corrective maintenance is performed to fix and repair the failed equipment and machines. Figure 37 indicates the general structure of the preventive maintenance process.

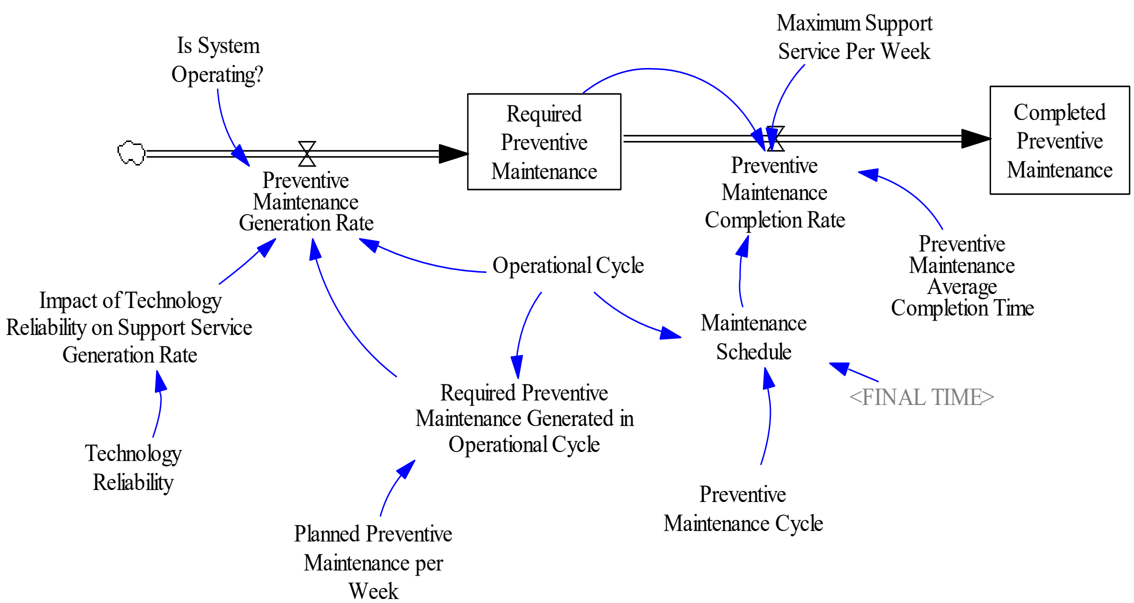


Figure 37. Sub-Model 4: Preventive Maintenance part

The preventive maintenance arrival rate called 'Preventive Maintenance Generation Rate' is determined based on the amount of man-hours maintenance required in each operational cycle. To calculate the 'Required Preventive Maintenance Generated in Operational Cycle' we need to know the length of the 'Operational Cycle' and also the amount of man-hours preventive maintenance planned per week:

Required Preventive Maintenance Generated in Operational Cycle = (Planned Preventive Maintenance per Week)(Operational Cycle)*

The ‘Planned Preventive Maintenance per Week’ is usually restricted by the maintenance crew size available for preventive maintenance. The generation rate of scheduled preventive maintenance is calculated based on the ‘Required Preventive Maintenance Generated in Operational Cycle’ and is adjusted based on the technology reliability.

*Preventive Maintenance Generation Rate= (IF THEN ELSE ("Is System Operating?"=1, Required Preventive Maintenance Generated in Operational Cycle, 0)/Operational Cycle) * (1+Impact of Technology Reliability on Support Service Generation Rate)*

The ‘Impact of Technology Reliability on Support Service Generation Rate’ lookup-type variable can be used to determine the impact of the reliability on the preventive maintenance generation rate. There is a non-linear relationship between technology reliability and the ‘Preventive Maintenance Generation’ rate. The rate decreases as reliability increases. The lookup table shown in Figure 38 represents this non-linear relationship in graphical format.

The ‘Required Preventive Maintenance’ stock is created continuously as the technology is applied. The stock level rises by the inflow of ‘Preventive Maintenance Generation Rate’ and is depleted by the outflow of ‘Preventive Maintenance Completion Rate’:

Required Preventive Maintenance = INTEG (Preventive Maintenance Generation Rate-Preventive Maintenance Completion Rate, 0)

The completion rate of the preventive maintenance activities is a function of ‘Maintenance Schedule’ and the ‘Average Completion Time’. The completion rate is also affected by the maximum support service available per week (Kothari, 2004):

Preventive Maintenance Completion Rate = MIN (Maximum Support Service Per Week, Required Preventive Maintenance/Preventive Maintenance Average Completion Time)(Maintenance Schedule)*

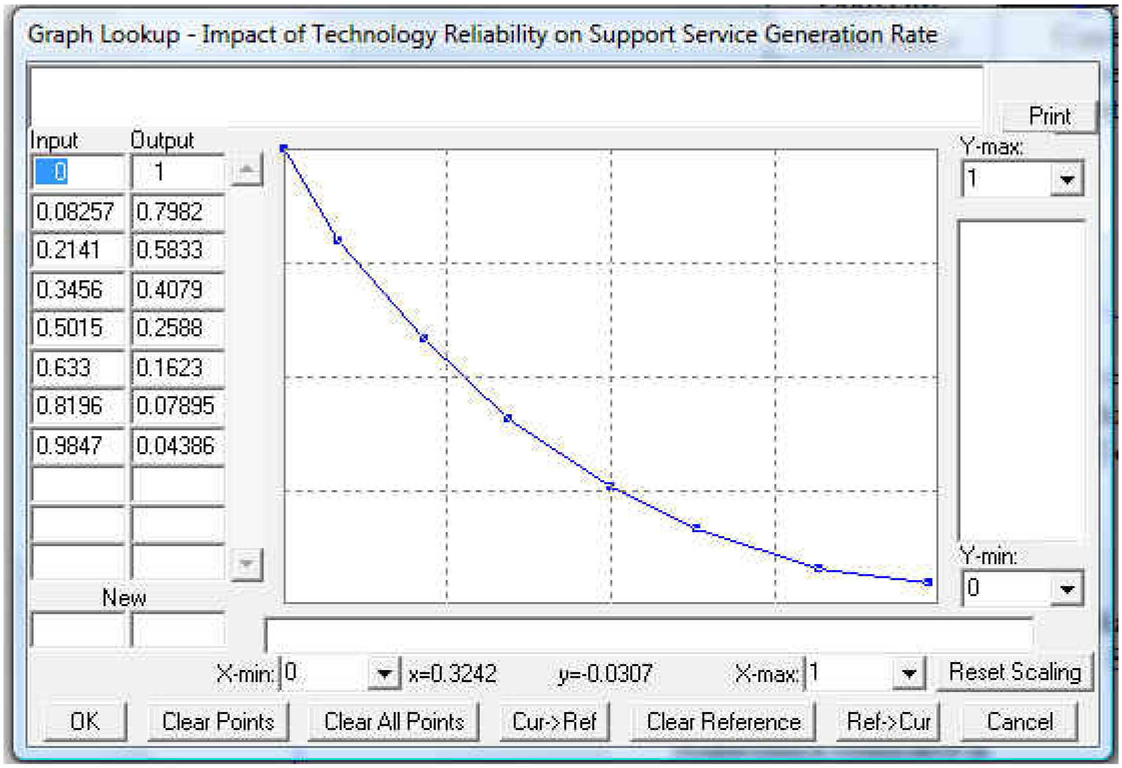


Figure 38. The impact of technology reliability on preventive maintenance generation

The 'Maintenance Schedule' is a binary variable that distinguishes the maintenance cycle (1) from the operational cycle (0). This variable ensures that the preventive maintenance activities are only got done during the maintenance cycle. A PULSE TRAIN function can be used to determine the maintenance schedule (Kothari, 2004):

Maintenance Schedule = PULSE TRAIN (Operational Cycle, Preventive Maintenance Cycle, Preventive Maintenance Cycle + Operational Cycle, FINAL TIME)

Finally, the 'Completed Preventive Maintenance' stock is created continuously as the preventive maintenance activities are done. The second part of the maintenance sub model is shown is Figure 39.

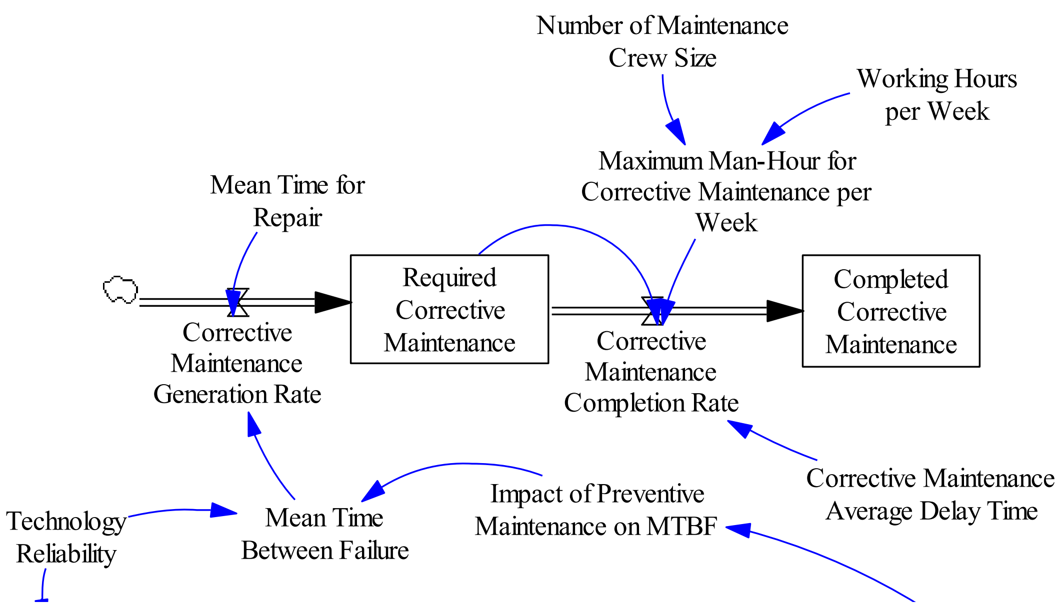


Figure 39. Sub-Model 4: Corrective Maintenance part

'Required Corrective Maintenance' is created continuously as the technology is applied. The 'Corrective Maintenance Generation Rate' or the amount of corrective maintenance man-hours generated is estimated from the 'Mean Time Between Failure' (MTBF) and the 'Mean Time for Repair' (MTTR) using the following formula:

*((1/Mean Time Between Failure)*Mean Time for Repair)*

One divided by the MTBF gives the rate of system failures over time. Multiplying the rate of system failures by the average time needed for repair gives the rate of man-hours corrective maintenance required over time. The 'Required Corrective Maintenance' stock is depleted by the 'Corrective Maintenance Completion Rate' outflow rate:

*Required Corrective Maintenance = INTEG (-Corrective Maintenance Completion Rate, (Technology Life Span/Mean Time Between Failure)*Mean Time for Repair))*

The 'Corrective Maintenance Completion Rate' is determined based on the 'Corrective Maintenance Average Completion Time' and the maximum available workforce for corrective maintenance per week. Unlike the preventive maintenance, the corrective maintenance activities are not necessarily getting done during the planned maintenance cycle. Therefore, we do not have a corrective maintenance schedule variable similar to what we have used in the model presented in Figure 37. In this case, we assume that the corrective maintenance activities should be done as soon as they occur as long as we have enough resource to perform the activities. Therefore the 'Corrective Maintenance Completion Rate' is calculated as (Kothari, 2004):

Corrective Maintenance Completion Rate = MIN (Maximum Man-Hour for Corrective Maintenance per Week, Required Corrective Maintenance/Corrective Maintenance Average Delay Time)

The 'Maximum Man-Hour for Corrective Maintenance per Week' is calculated from the 'Number of Maintenance Crew Size' available for corrective maintenance per week and the number of working hours per week:

*Maximum Man-Hour for Corrective Maintenance per Week = Number of Maintenance Crew Size*Working Hours per Week*

Finally, the 'Completed Corrective Maintenance' backlog is created by the 'Corrective Maintenance Completion rate' inflow.

Completed Corrective Maintenance = INTEG (Corrective Maintenance Completion Rate, 0)

Table 13 summarizes the variables and equations associated with the 'maintenance' sub-model and Figure 40 illustrates both preventive and corrective maintenance parts of the sub model.

Table 13. ‘Maintenance’ Sub-model variables and equations

	Main Variables	Input Variables	Equations
Maintenance and Support Activities	Preventive Maintenance Generation rate	Operational Cycle Required Preventive Maintenance Generated in Operational Cycle Impact of Technology Reliability on Support Service Generation Rate	*(1+Impact of Technology Reliability on Support Service Generation Rate)*(IF THEN ELSE ("Is System Operating?"=1, Required Preventive Maintenance Generated in Operational Cycle , 0)/Operational Cycle)*
	Required Preventive Maintenance Generated in Operational Cycle	Planned Preventive Maintenance per Week Operational Cycle	*Planned Preventive Maintenance per Week*Operational Cycle*
	Maintenance Schedule	Operational Cycle Maintenance Cycle FINAL TIME	*PULSE TRAIN(Operational Cycle, Preventive Maintenance Cycle , Preventive Maintenance Cycle + Operational Cycle , FINAL TIME)*
	Preventive Maintenance Completion Rate	Maximum Support Service Per Week, Required Preventive Maintenance Required Preventive Maintenance Preventive Maintenance Average Completion Time	*MIN(Maximum Support Service Per Week, Required Preventive Maintenance/Preventive Maintenance Average Completion Time)*(Maintenance Schedule)*
	Required Preventive Maintenance	Preventive Maintenance Generation Rate Preventive Maintenance Completion Rate	*INTEG (Preventive Maintenance Generation Rate-Preventive Maintenance Completion Rate)*
	Completed Preventive Maintenance	Preventive Maintenance Completion Rate	*INTEG (Preventive Maintenance Completion Rate)*
	Corrective Maintenance Completion Rate	Maximum Man-Hour for Corrective Maintenance per Week Required Corrective Maintenance Corrective Maintenance Average Delay Time	*MIN("Maximum Man-Hour for Corrective Maintenance per Week", Required Corrective Maintenance/Corrective Maintenance Average Delay Time)*
	Required Corrective Maintenance	Corrective Maintenance Generation Rate Corrective Maintenance Completion Rate	*INTEG (Corrective Maintenance Generation Rate - Corrective Maintenance Completion Rate)*
	Corrective Maintenance Generation Rate	Mean Time Between Failure Mean Time for Repair	*(1/ Mean Time Between Failure) *(Mean Time for Repair)*
	Maximum Man-Hour for Corrective Maintenance per Week	Number of Maintenance Crew Size Working Hours per Week	*Number of Maintenance Crew Size*Working Hours per Week*

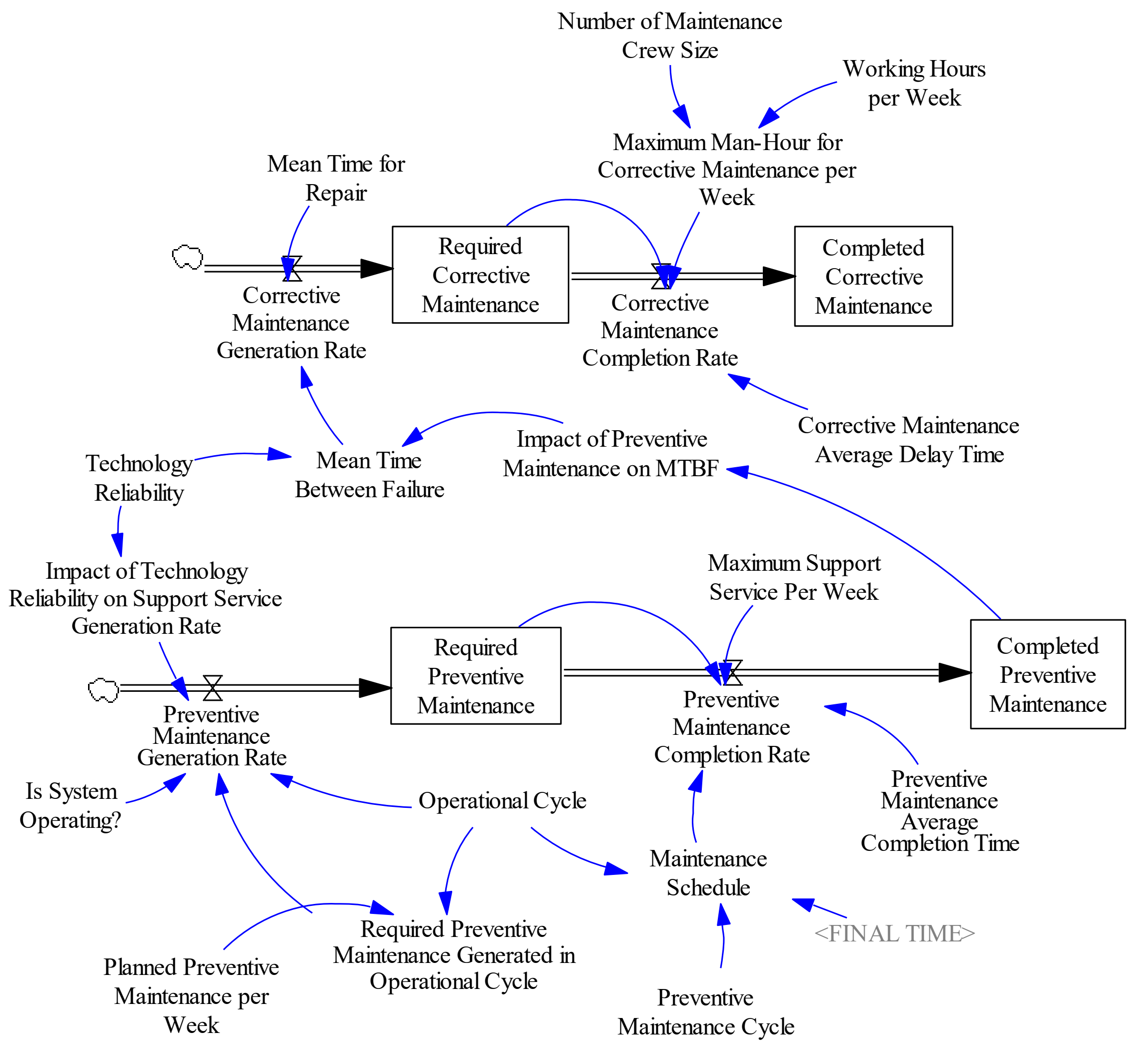


Figure 40. Sub Model 4: Maintenance and Support activities

3.6.5. Sub-Model 5: Upgrade and technology maturity process

In order to successfully integrate a new technology in the system, it is important to first identify the level of the technology maturity and moreover to regularly upgrade the technology.

A technology is called mature if it has been in use for long enough time that most of its inherent problems and initial faults have been omitted or reduced by further development. Identifying the level of the technology maturity can be accomplished through the use of a generally understood metric. One such metric is Technology Readiness Level (TRL). As discussed in Chapter 2, TRL consists of nine levels (1-9) and was originally introduced by the National Aeronautics and Space Administration (NASA) to rate the readiness of technology for potential use in space flight (Sauser et al. 2010). The SD model presented in Figure 41 shows the changes of the technology maturity over time and the amount of upgrade efforts required over technology life span.

The 'Technology Maturity' is defined as a stock fed by the 'Change in TRL' inflow rate.

Technology Maturity = INTEG (Change in TRL, Initial Technology Readiness Level Index)

The 'Change in TRL' rate is determined based on the 'Target TRL', the current 'technology Maturity' and the 'Time Required to Improve TRL'. Suppose that the company's goal is to improve the current technology TRL (let say 7) to a target TRL (say 9) during the next six months. Therefore the change in TRL rate per week is $\frac{(9-7)}{6\times4}$:

Change in TRL = (Target TRL-Technology Maturity)/Time Required to Improve TRL

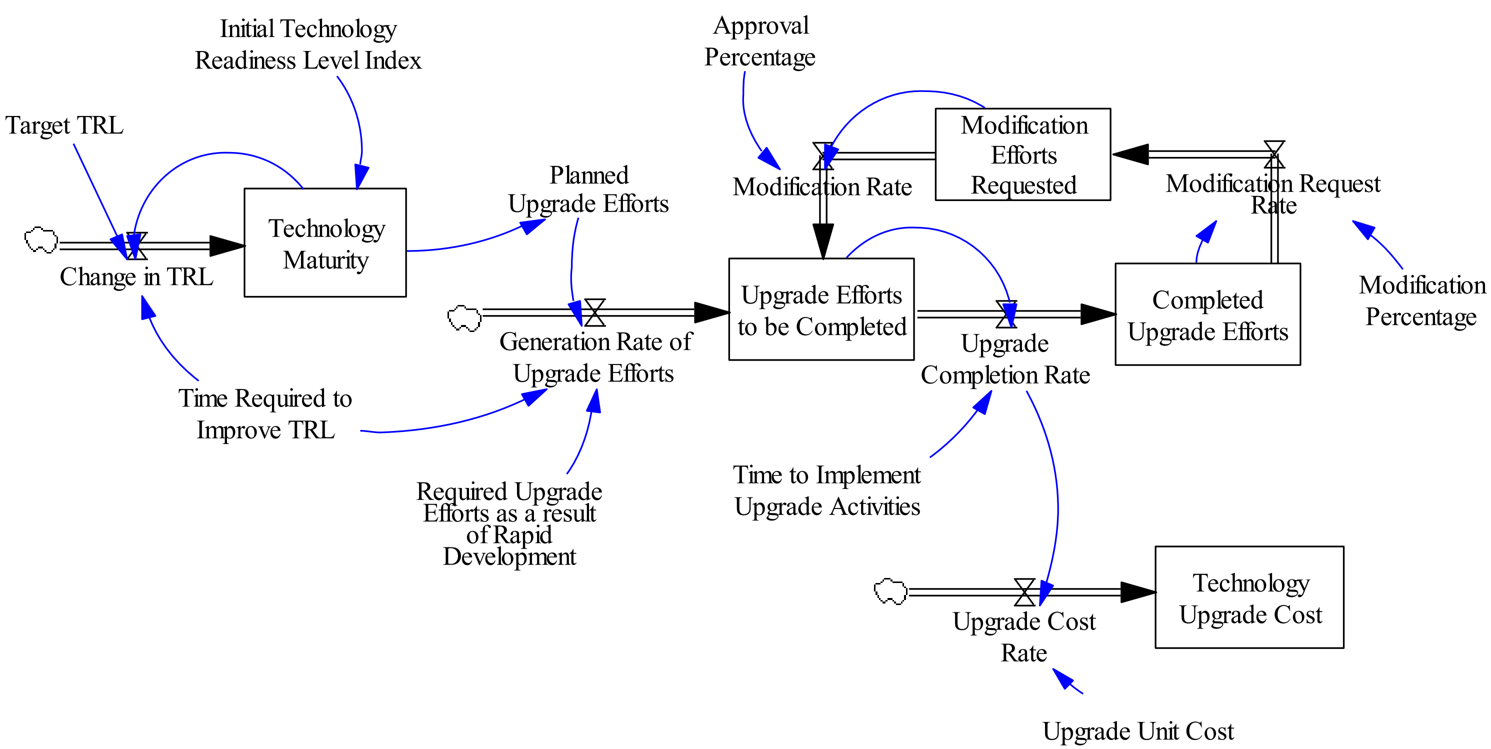


Figure 41. Sub Model 5: Upgrade and technology maturity process

In order to improve the current maturity level, the company needs to get done some upgrade efforts. A look up table has been used to find the amount of efforts required to upgrade the technology based on the 'Technology Maturity' level. The amount of the efforts needed is represented through 'Planned Upgrade Efforts' variable. The lower is the current TRL, the more is the amount of 'Planned Upgrade Efforts'. Figure 42 depicts an example of the LOOKUP function used to determine the number of man-hours upgrade efforts. It should be noted that depending on the type and complexity of the technology, the estimated amount of upgrade efforts to improve the TRL is different.

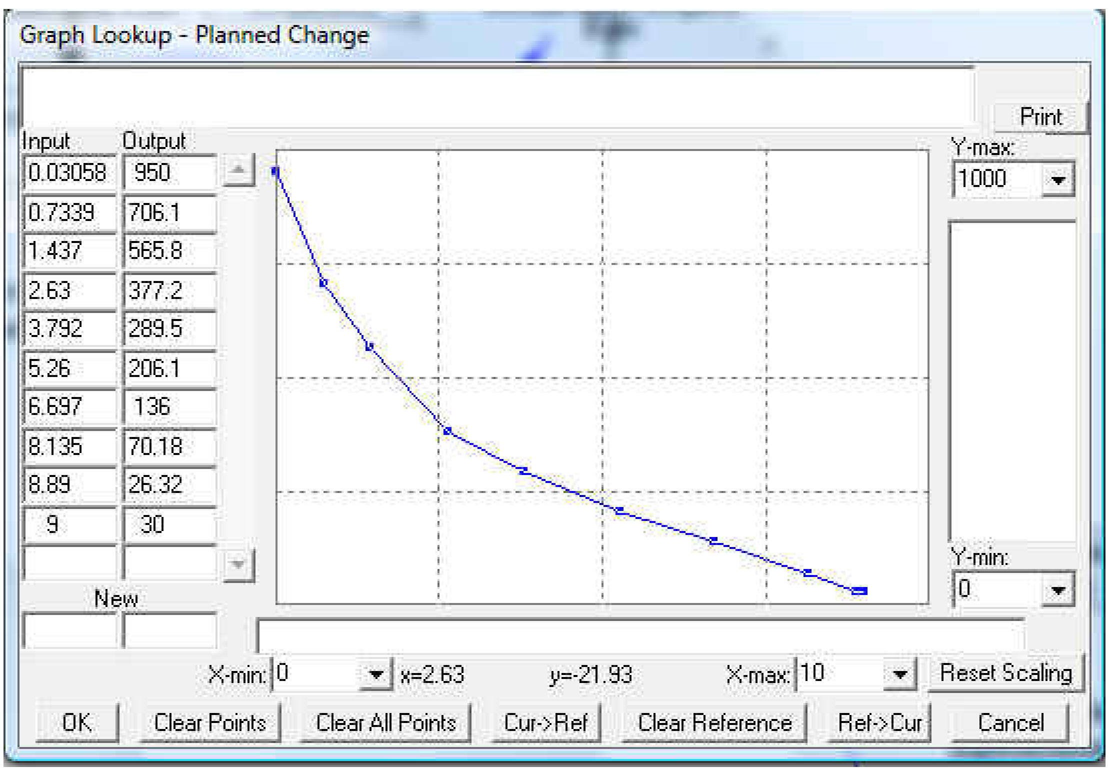


Figure 42. The effect of technology maturity (1-9) on the amount of required upgrade activities

In addition to the ‘Planned Upgrade Efforts’, sometimes the companies need to conduct some upgrade activities as a result of technology rapid development. This amount of work has not been included on the panned upgrade activities. Therefore, the rate of upgrade efforts generation can be calculated considering both the amount of planned upgrade activities and the amount of upgrade activities required to be done as a result of technology rapid development:

Generation Rate of Upgrade Efforts = (Planned Upgrade Efforts + Required Upgrade Efforts as a result of Rapid Development)/Time Required to Improve

On the other hand, the ‘Upgrade Completion Rate’ is calculated based on the average time that is assigned to implement upgrade efforts and the amount of upgrade efforts to be completed:

Upgrade Completion Rate = Upgrade Efforts to be Completed /Time to Implement Upgrade Activities

The completed upgrade efforts are accumulated in the ‘Completed Upgrade Efforts’ stock. Often after conducting upgrade activities, some modifications are required. The ‘Modification Request Rate’ is determined based on the amount of upgrade efforts completed and the ‘Modification Percentage’ variable:

*Modification Request Rate = Completed Upgrade Efforts*Modification Percentage*

It is assumed that not all requested modification efforts are accepted, therefore an 'Approval Percentage Rate' is used to model the rate of modification efforts which is approved:

Modification Rate = Modification Efforts Requested Approval Percentage*

The amount of 'Upgrade Efforts to be Completed' is calculated based on the upgrade efforts generation rate, the modification rate and upgrade activities completion rate:

Upgrade Efforts to be Completed = INTEG (Generation Rate of Upgrade Efforts + Modification Rate - Upgrade Completion Rate)

Further, the 'Upgrade Completion Rate' along with the 'Upgrade Unit Cost' can be used to calculate the total 'Technology Upgrade Cost' level. Table 14 lists the main variables and equations behind the 'technology upgrade process' sub model.

3.6.6 Sub-Model 6: Impact of Technology on System Performance

This part of the model represents the impact of technology implementation on the system performance. Depending on the type of the system under investigation, different measures can be used to represent the system performance. Cycle time, scrap rate, and production volume are some examples of them. In the current research, the number of work errors has been applied as a proxy of the system performance.

Table 14. ‘Upgrade and Technology Maturity’ Sub-model variables and equations

	Main Variables	**Input Variables**	**Equations**
Upgrade and Technology Maturity	Change in TRL	Target TRL Technology Maturity Time Required to Improve TRL	*(Target TRL-Technology Maturity)/Time Required to Improve TRL*
	Technology Maturity	Change in TRL	*INTEG (Change in TRL, Initial Technology Readiness Level Index)*
	Planned Upgrade Efforts	Technology Maturity	*LOOKUP function*
	Generation Rate of Upgrade Efforts	Planned Upgrade Efforts Required Upgrade Efforts as a result of Rapid Development	*(Planned Upgrade Efforts + Required Upgrade Efforts as a result of Rapid Development)/Time Required to Improve TRL*
	Upgrade Efforts to be Completed	Generation Rate of Upgrade Efforts Modification Rate Upgrade Completion Rate	*INTEG(Generation Rate of Upgrade Efforts + Modification Rate-Upgrade Completion Rate)*
	Upgrade Efforts Completed	Upgrade Completion Rate Modification Request Rate	*INTEG (Upgrade Completion Rate-Modification Request Rate)*
	Modification Efforts Requested	Modification Request Rate Modification Rate	*INTEG(Modification Request Rate-Modification Rate)*
	Technology Upgrade Cost	Upgrade Cost Rate	INTEG(Upgrade Cost Rate)

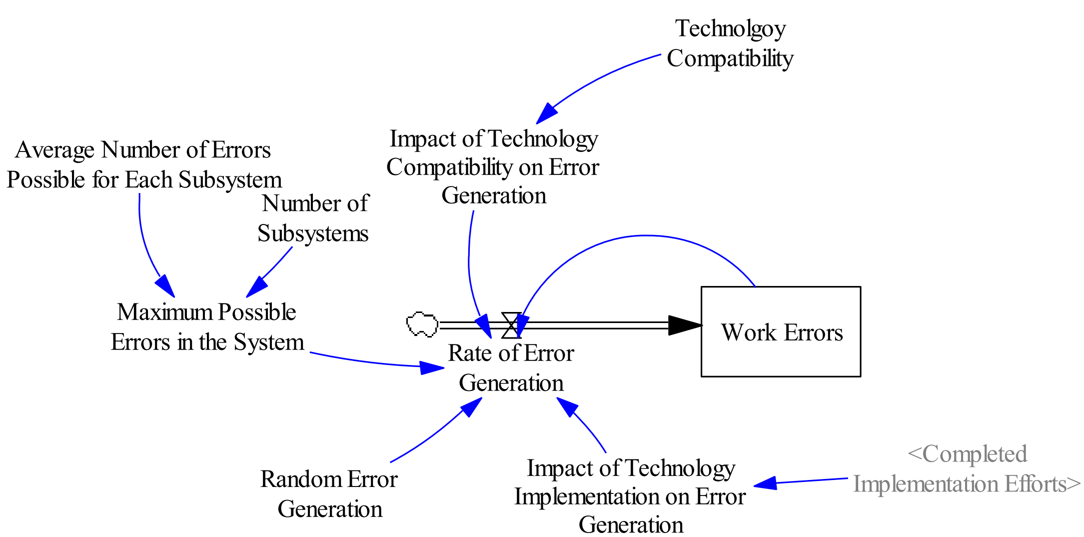


Figure 43. Sub Model 6: Impact of Technology Adoption on System Performance

The sub model 6 is shown in Figure 43. It has been assumed that the work errors are randomly generated in the system. The 'Random Error Generation' variable has been used to represent the number of work errors generate in each unit of the time. To avoid the unrealistic rate of error generation, a new variable has been defined to bound the 'Work Errors' level with the 'Maximum Possible Errors in the System'. The maximum errors in the system are a function of the 'Number of Subsystems' and the 'Average Number of Errors Possible for Each Subsystem'.

Maximum Possible Errors in the System = (Average Number of Errors Possible for Each Subsystem)(Number of Subsystems)*

The 'Rate of Error Generation' is also affected by the technology implementation efforts. The higher the amount of technology implementation efforts, the lower is the work error generation. The 'Impact of Technology Implementation on Errors generation' variable links the technology implementation efforts with the error generation rate. A type of lookup function shown in Figure 44 can be used to connect the amount of technology implementation efforts with the error generation rate. Moreover, the error generation rate is also affected by the degree of technology compatibility with other technologies. A (1-10) scale is used to measure the technology compatibility with other systems. The lower is the technology compatibility, the higher is the error generation rate. One example of 'Impact of Technology Compatibility on Error Generation" look up variable that can be used to show the impact of compatibility on the error generation rate is depicted in Figure 45. The mathematical equation behind the 'Rate of Error Generation' is as follow:

*IF THEN ELSE (Work Errors<Maximum Possible Errors in the System, Random Error Generation*Impact of Technology Implementation on Error Generation*(1+Impact of Technology Compatibility on Error Generation), 0)*

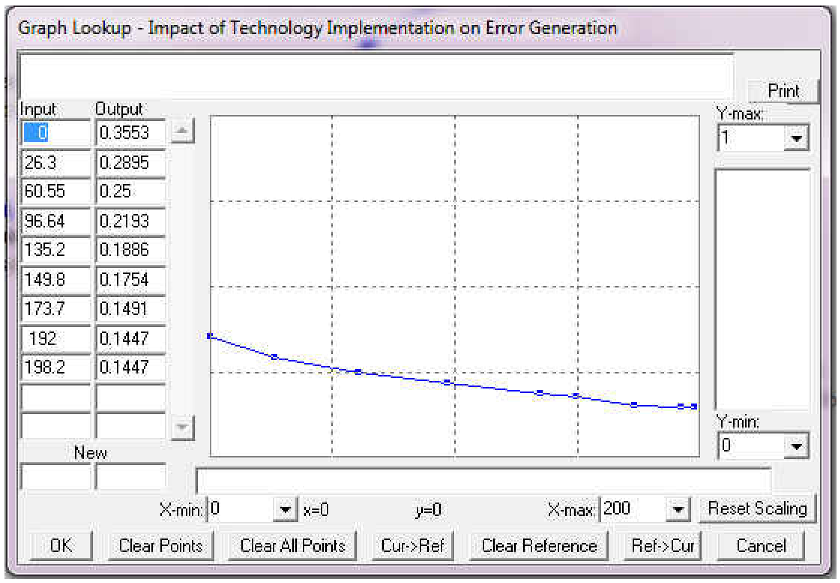


Figure 44. The impact of technology implementation man-hours efforts on the error generation rate

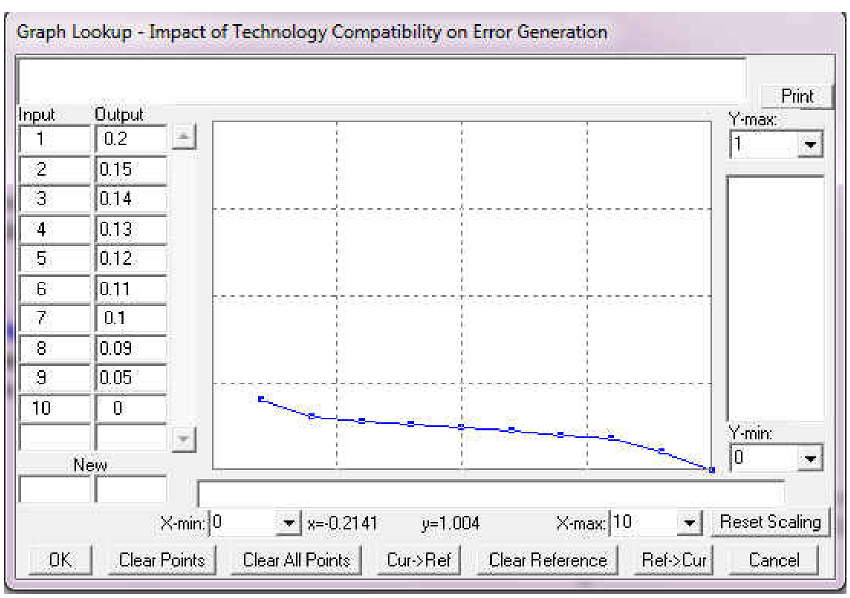


Figure 45. The impact of technology compatibility on the error generation rate

3.6.7. Sub Model 7: Total Ownership Cost

TOC calculated in this research composed of seven main cost components including: Initial investment/ technology purchase price, implementation cost, service and maintenance cost (preventive and corrective maintenance costs), cost of hiring new employees, workforce training cost, technology upgrade cost and other costs. Table 15 lists some examples for each cost category. Figure 46 shows the SD model part associated with TOC calculation.

Table 15. Components of the Total Ownership Cost of the new technology

	Cost Components	**Examples**
Total Ownership Cost of new technology	Technology Implementation Costs	Infrastructure Cost (Hardware and Software)
		Consulting Cost
		Labor Cost/Internal Resource
		Project Management Cost
	Workforce Costs	Training Cost
		New Employee Hiring Cost
	Maintenance and Service Costs	Labor Cost
		Tools and Equipment Cost
		Cost of Spare parts
	Technology Upgrade Costs	
	Purchase Costs	Initial Investment
	Other Costs	Operational Cost

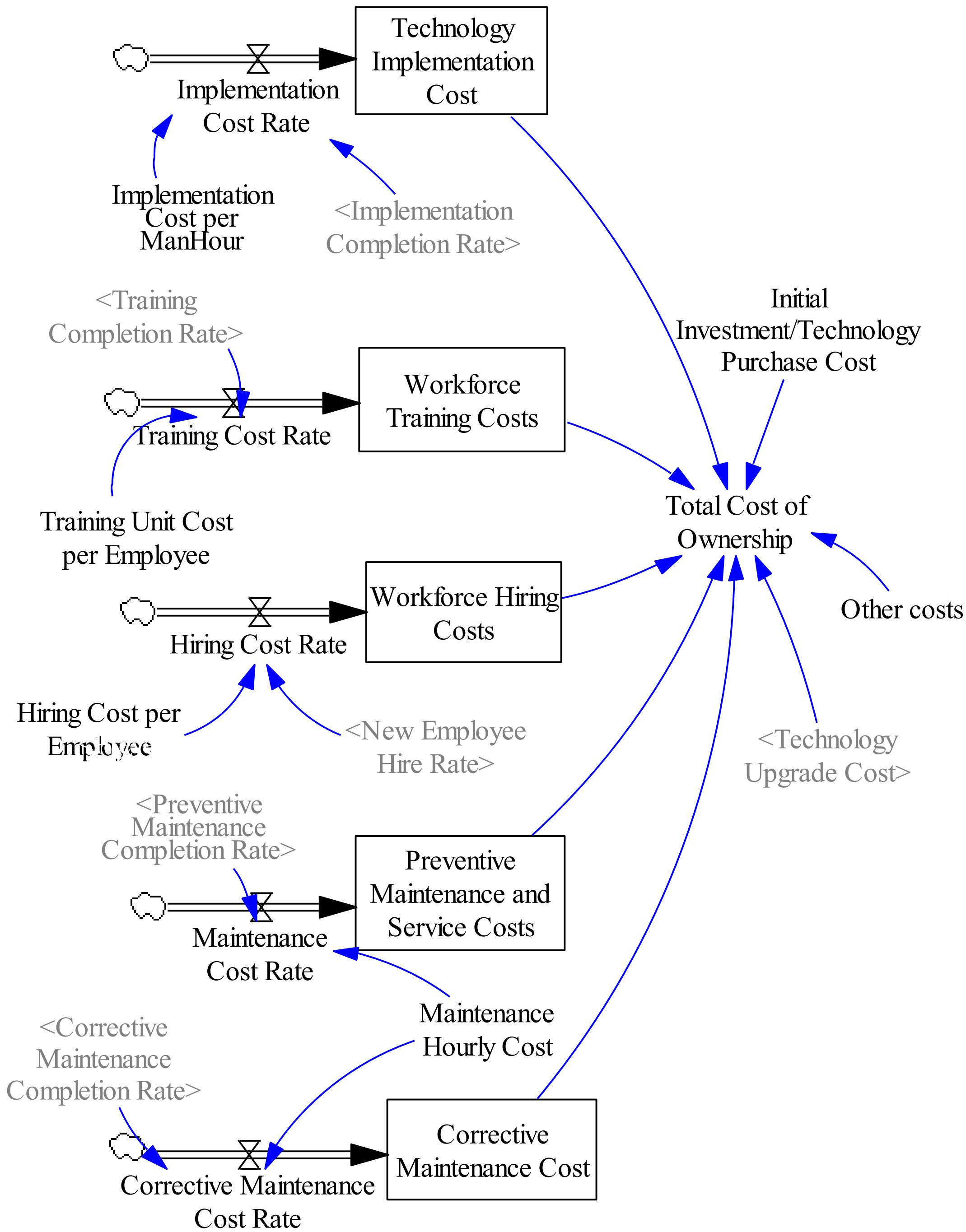


Figure 46. Sub Model 7: Components of Total Ownership Cost

3.7. Conclusion

This chapter details the general overview of the SD Model. The model includes three main parts: (1) the variables corresponding the new technologies *implementation stage*, (2) variables corresponding to the *system aspects* including technology upgrade, support and maintenance activities (3) variables corresponding to the *human* resource aspects (e.g. training and required skill set). Several primarily casual loop diagrams of these three parts have been discussed. Causal loops are developed at the beginning of a modeling project to record mental models. To capture the stock and flow structure of systems, the Stock and Flow diagrams should be used. The final result of the dissertation is a model that determines the important parameters and the relationships that exist between different elements that make up TOC when integrating a new technology. Figure 47 shows the general overview of the expected stock and flow model.

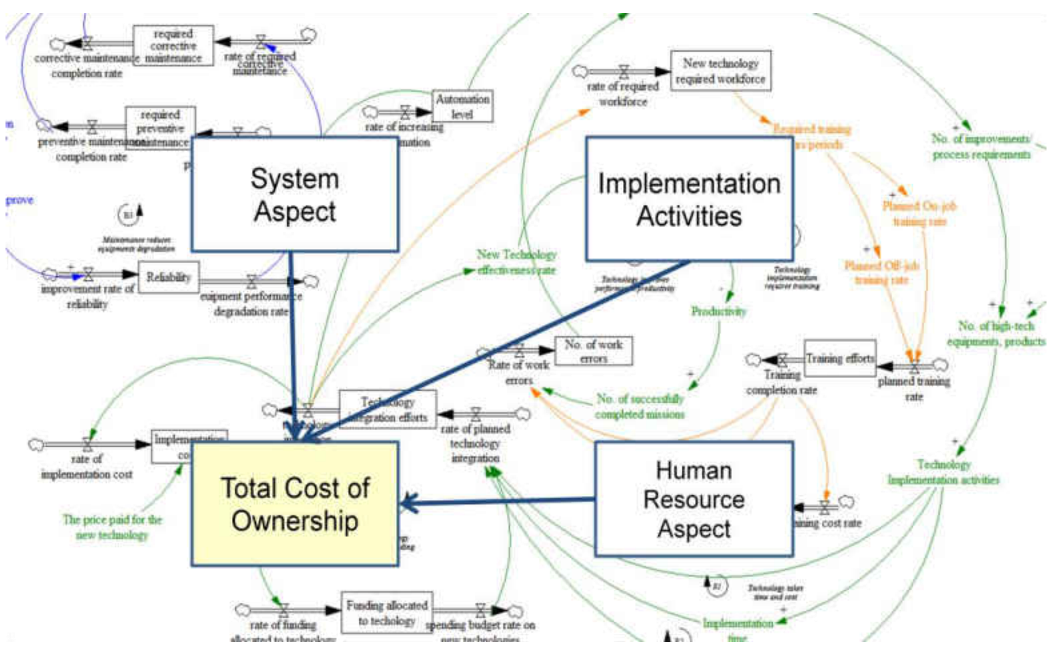


Figure 47. General overview of the SDM

CHAPTER 4
CASE STUDY: ENTERPRISE RESOURCE PLANNING ADOPTION

4.1. Introduction

This chapter shows the application of the SD model for an Enterprise Resource Planning (ERP) system implementation. Chapter starts with a brief introduction of ERP systems and the critical issues affecting an ERP implementation. Further the chapter discusses the institution data that have been used to calibrate the SD model. Finally, the results of running the simulation and the resulting dynamic behavior are discussed.

4.2. Enterprise Resource Planning Systems

ERP systems are defined as "computer-based information systems designed to process an organization's transactions and facilitate integrated and real-time planning, production and customer response" (O'Leary, 2000). The core concept behind ERP is to have a single database where all the departments of a company can communicate and share information (Shehab, Thomassin, & Badawy, 2011).

The term ERP backs to the 1960s when the software engineers tried to write computer programs to create inventory reports. By 1970s this effort has resulted in developing the Material Requirements Planning (MRP) systems. MRP systems mainly have been applied for facilitating the scheduling in the production lines. Later in 1980s, the MRP systems were further promoted to include other aspects of manufacturing processes. The new version was called MRP II. The MRP-II has been evolved to cover other office-based efforts such as accounting and human resource management rather than the inventory control and production planning. The new system created what we call ERP today. The exact term ERP was created by Gartner, the global leader in IT services, in 1990 (Jacobs & Weston 2007).

According to Bingi et al. (1999), ERP market is one of the fastest growing industries in the software market. They predicted that the $15 million ERP market at the time will grow to the $50 billion market within five years. The growth rate of ERP systems was estimated to be around 40%.

Jacobs and Weston (2007) believed that ERP systems have achieved a level of maturity where many companies have realized the benefits of ERP implementation as well as the human and financial resources required to implementation and ongoing support of the system. In fact, ERP systems have entered an era of 'easy configuration' where many corporations are interested in implementing these systems. According to Yen et al. (2001) more than 20,000 companies around the globe have spent billions of dollars in ERP systems implementation. In fact, by 1997, 70 percent of the Fortune 1,000 firms installed ERP systems in different areas including human resource, financial processes, production planning and engineering process.

Every aspect of business including production, sales, and human resource management can be integrated through ERP system. ERP combines the databases and functions of different departments in a single database to facilitate the following processes (Chou et al. 2005):

- Finance Resource Management
- Supply Chain Management
- Human Resource Management
- Customer Relationship Management

- Manufacturing Resource Planning

Enterprise Resource Planning is a useful approach that helps most companies to improve the efficiency and productivity. It is essential that managers and owners of a company have a broad look at the benefits and risks related with the implementation of the ERP system.

Although ERP implementation projects are becoming popular, the failure rate of these projects is still high (Chen et al. 2009). ERP implementation is not only a complex process but also a resource intensive process. According to Bansal and Negi (2008) an ERP implementation project lasts anywhere from 1 to 3 years and spends 1-3% of the company's turnover. The point is that, it was estimated that at least 90% of ERP projects were over budget and exceeded their planned implementation time (Noudoostbeni, Yasin, & Jenatabadi, 2009). The following section discusses some of the challenges facing companies during ERP systems implementation.

4.3. Challenges in ERP Systems Adoption

Despite the popularity of ERP implementation, the failure rate of ERP projects is very high. Around 75% of the ERP implementation projects in the US encounter some sort of failure. The project failure can be due to the cost overrun, schedule overrun and failure to meet the expected objectives (Bansal & Negi, 2008).

Traditionally, literature discussed the uncertainty of cost drivers as a challenge in ERP implementation projects (Daneva, Wettflower, & De Boer, 2008). Hidden costs such as employees training and the cost of maintenance and support activities are among the factors that make ERP implementation risky. To alleviate the risk associated with cost overrun, companies have looked at solutions such as outsourcing the ERP implementation. Although outsourcing in some cases can save money, the fact is that ERP systems are so critical to be outsourced. The risk of data loss and downtime are among the biggest concerns for companies (Shehab et al., 2011).

Therefore, development of a cost estimation method for ERP systems is critical. Elragal and Haddara (2010) suggested using a group of ERP experts as a panel to develop a cost estimation model for ERP adoption. Daneva (2007) applied a portfolio management perspective along with a Monte Carlo simulation to estimate the cost of ERP implementation. In general, the cost of implementing ERP systems can be categorized into investment cost and the cost of maintenance and operation. The platform cost and the employees training cost can be counted as the investment cost, while the cost of system maintenance and upgrade including both software and hardware maintenance is regarded as routine cost during the usage stage of the system (Xue, 2012). Therefore, at the initial implementation stage the companies mainly deal with the initial investment and the human resource costs, however they should not ignore the maintenance and upgrade cost that will occur after the system is implemented.

As discussed before, the uncertainty in both revenue and cost is an important point that should be appropriately considered while evaluating the ERP systems (Wu & Liou 2011). In addition, ERP adoption is a complex process which involves technical and organizational complexity and requires evaluating the cost of the system during a long-term horizon. To sum up the ERP implementation projects have several features that make them good examples to show the application of the SD model proposed in this research:

- The failure rate of ERP implementation is high. Therefore it is critical for companies to understand the total cost that an ERP system may bring into the organization (Chen et al. 2009)(Bansal & Negi, 2008).
- The ERP implementation project is risky and costly. Companies may spend millions of dollars and many years on implementing ERP systems. Moreover, when an ERP system is adopted, going back is too expensive and difficult (Bingi et al., 1999).
- The ERP adoption involves complex context dynamics and the ERP justification requires considering a long-term horizon (Wu & Liou 2011). The total cost of the system does not occur at the initial stage and the total cost can be three to five times the purchase cost of the software (Bingi et al., 1999).
- There is a high degree of uncertainty on cost drivers (Daneva et al., 2008)(Wu & Liou 2011)

The following section explains a case study of ERP system implemented in a university.

4.4. Case Study: ERP Implementation at the University at Albany

The case study discussed in this section is the one applied in a PhD dissertation by Meg Fryling (2010). She has developed a SD model to study the users' acceptance and perceived success of ERP systems and she has used a case study of ERP implementation at the University at Albany to evaluate her model. In this section we have applied some data presented in her work to show the application of our model.

4.4.1. Project History and Background

The history of the ERP project implemented at the University at Albany refers back to the Integrated Administrative Systems (IAS) project started in 1996 to overcome the limitations of the existing administrative information systems. At the time, there were eight different disparate legacy systems operating on multiple separate platforms (Fryling, 2010):

- System 1: Enable to facilitate activities associated with 'Undergraduate Prospects'
- System 2: ADM to facilitate activities associated with 'Undergraduate Admissions'
- System 3: GAS to facilitate activities associated with 'Graduate Admissions'
- System 4: SIRS to facilitate activities associated with 'Student Records'
- System 5: DARS to facilitate activities associated with 'Degree Audit and Transfer Credit'
- System 6: SAM to facilitate activities associated with 'Financial Aid'
- System 7: RS 6000 to facilitate activities associated with 'Student Financials, Orientation, Housing, Parking'
- System 8: PDS to facilitate activities associated with 'Human Resources'

However, these systems were not efficient enough for two main reasons: first, the data exchange between different sections has required using batch interfaces which results in creating data redundancy and delay in updating and accessing the data. Second the students and faculty did not have access to update and use the data appropriately. To solve these issues the IAS project was launched to overcome the limitation of the existing administrative information system. To facilitate data management, it was decided to integrate all the information systems listed above into one single system and further it was decided to integrate all those systems via an ERP system.

4.4.2. ERP Solution

The University at Albany started calling for technical proposals from different vendors for an ERP system. After reviewing the proposals, the IAS executive level steering committee decided to purchase PeopleSoft developed by Oracle Corp in 1997.

4.4.3. Project Scope and Resource

The project scope was determined to implement PeopleSoft ERP modules to replace the existing human resources, legacy student, and financial systems. Since the cost of outsourcing implementation activities was high (7-10 million dollars bids), it was decided to assign the implementation activities to the university staff. It was argued that implementing the ERP modules by internal staff results in a significant cost saving, however the implementation time was longer compare to the case in which the implementation activities are outsourced. In order to make sure that implementation team is able to successfully implement the system, it was mentioned in the project charter that specific training sessions should be offered to both implementation team and end users group. The UAlbany central IT department took the responsibility of offering training to the user community (Fryling, 2010).

4.4.4. Software Customization, Support and Upgrade

Since the PeopleSoft software has been created based on “best business practices”, the project charter specifically mentions that the Ualbany policy is to employ these practices as much as they can and limit the customization of the packaged software. This policy reduces the initial budget required for implementation activities, however transfers the cost to future software upgrades (Fryling, 2010). Oracle, the ERP vendor, offers software support four times a year in order to:

- fix bugs and bundling issues
- make governmental mandated requirements and changes
- offer some customer requested changes

Later in this chapter we explain that these support efforts are considered as planned preventive maintenance in the SD model. Moreover, every several years Oracle releases a new version of PeopleSoft in order to solve major software issues and offer new functionality. In order to remain on the supported version of the ERP system, the vendors need their clients to upgrade their systems regularly. Although it is not mandatory for clients to upgrade their ERP systems, they remain on the unsupported version of the software if they decide to not upgrade their system. Therefore, UAlbany decided to keep upgrading the former Peoplesoft ERP to its new version called Oracle's Campus Solutions Version 9.0 in August 2009. Similar to ERP initial implementation activities, ERP upgrade also requires significant amount of resource and commitment. The 'upgrade and technology maturity' sub-model was developed to model the upgrade activities. Table 16 lists the timeline of the implementations and upgrade activities.

4.4.5. Case Study Collected Data

ERP project documentation and archival records have been reviewed to collect the data. The collected data will be used to determine the model parameters and input variables. The data are categorized into three main groups:

- Tasks
- Costs
- Findings and recommendations

For the purpose of this dissertation, the tasks and costs categories are reviewed in this section.

Table 16. IAS project timeline [Ref: (Fryling, 2010)]

Major Milestone	**Date**
Prospects, Version 7.6	March 1999
Human Resources, Version 7.6	June 2000
Undergraduate and Graduate Admissions, Version 7.6	November 2000
Orientation and Summer Planning Conference, Version 7.6	March 2001
Upgrade to Version 8.0	September 2002
Student Records, Version 8.0	June 2003
Financial Aid, Version 8.0	January 2004
Student Financials, Version 8.0	May 2005
Upgrade to Version 9.0	August 2008

After the ERP implementation phase, the system goes to the support and maintenance mode where some maintenance tasks are requested and completed. A high percentage of the maintenance tasks generated each month are rework tasks. There rework tasks are defined as "error discovered and reported by the functional offices in a production environment. These rework tasks include both in-house generated errors and vendor generated errors" (Fryling, 2010). For the purpose of our SD model, the rework tasks are counted as corrective maintenance tasks and the new support tasks are counted as preventive maintenance tasks. Figure 48 illustrates the percentage of the rework tasks (corrective maintenance tasks in our model) compare to the total support tasks. On average the 80% of the support tasks requested per month is the rework tasks (corrective maintenance tasks). The vertical dotted line in Figure 48 shows the point of the time where a bundle (or in our case a preventive maintenance) is occurred while the vertical solid line shows the point of the time in which the software is upgraded.

One more point is the generation rate of the errors as a result of software upgrades. The upgrade applied in August 2008 results in some rework tasks that are discovered several months later. There rework tasks are considered in the upgrade sub-model and are not part of the 'maintenance' sub model.

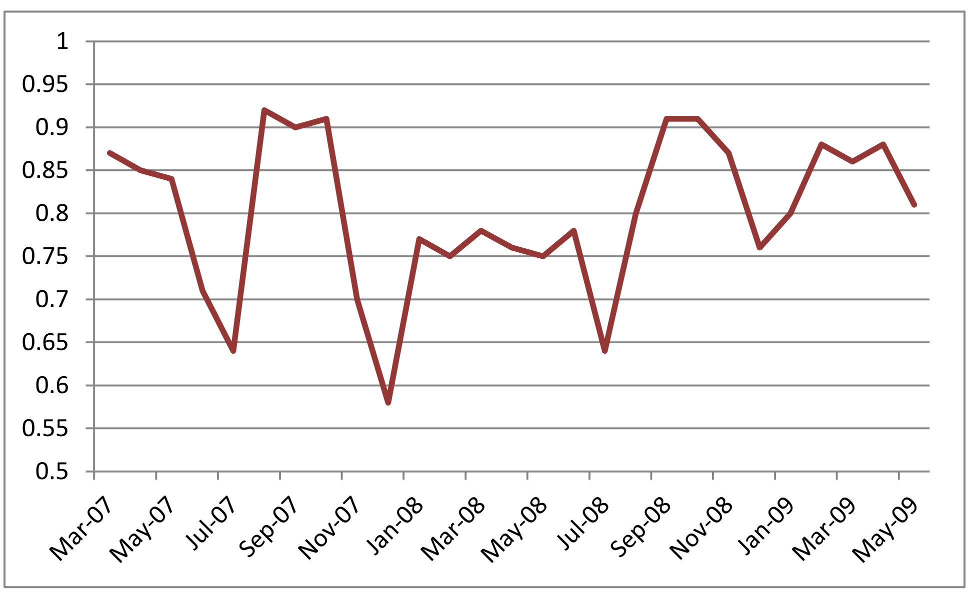


Figure 48. Percentage of rework tasks (Corrective Maintenance) each month [redrawn from (Fryling, 2010)]

Figure 49 shows a better overview of the amount of rework tasks (corrective maintenance) completed per month versus the other support tasks (preventive maintenance tasks). The average number of corrective maintenance task between May 2007 and May 2009 was 192. However, when the upgrade was implemented in August 2008, around 400 rework tasks were requested. To sum up, over the 2-year period from May 2007 to May 2009 there were a total of 5641 helpdesks tasks requested while 5616 of the completed.

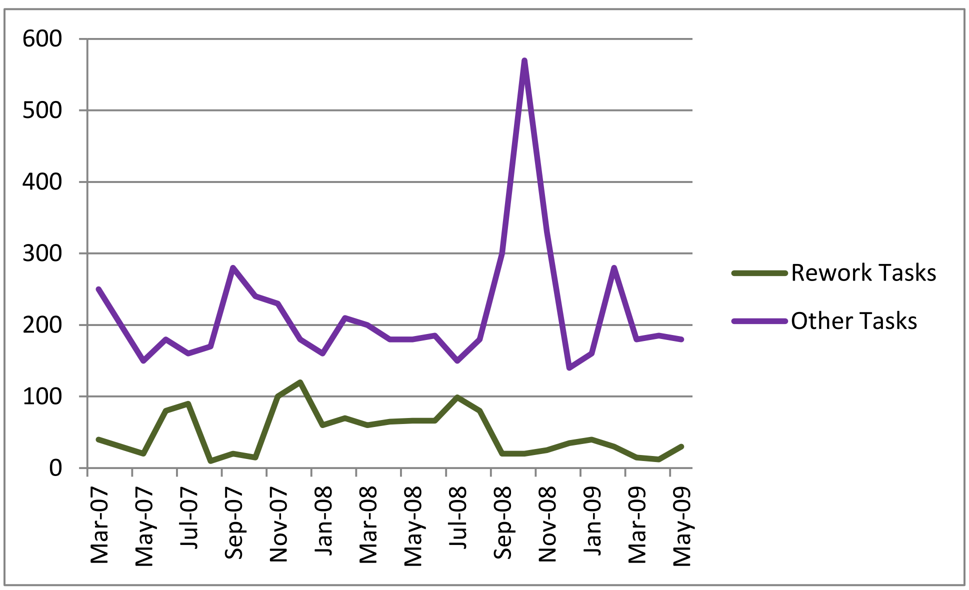


Figure 49. Corrective and preventive maintenance tasks generated per month [redrawn from (Fryling, 2010)]

In addition to the number of tasks, the time required to complete each task is also important in defining the amount of maintenance and upgrade efforts required during technology lifecycle. In the current case study, around 77% of the upgrade tasks require less than a week to complete. There are some assumptions made about the time spent on each maintenance task that are discussed later in this chapter.

The data collected also include the costs of the ERP implementation including the software purchase cost ($2,025,998) and the initial equipment costs ($1,713,665). There are also the software and hardware maintenance costs that need to be included. Figure 50 shows the Pie chart of the costs components over the implementation phase. The costs components over the post-implementation phase fairly remain the same as the implementation phase, the only difference is that there is no software purchase cost in post implementation.

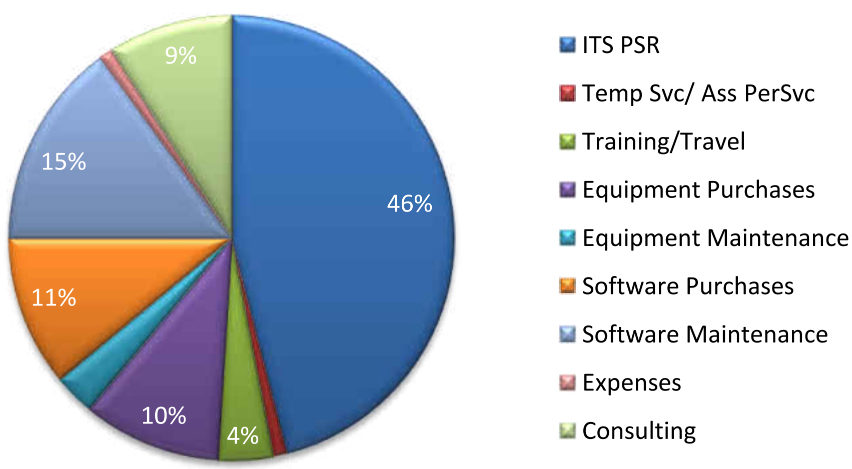


Figure 50. Actual ERP Cost Breakdown From 1998-2006 [redrawn from (Fryling, 2010)]

4.5. Simulation Runs, Results and Analysis

Given the data set discussed in previous section and using some user defined parameters, the model discussed in Chapter 3 was run. Figure 51 shows the control parameters that were set for carrying on various simulation runs. As discussed in previous section, IAS project began in 1999 and lasted till 2008, therefore a 10-year period (120 months) is defined as the time boundaries for the simulation model. Time step of 1 month is chosen.

This section reviews the results of the simulation runs and discusses the analysis of the results. Although the results are presented in form of precise figures, since this is a system dynamics model, the results should be interpreted qualitatively. In the SD models, the trends in the graphs are more important than the exact values (Andersson & Karlsson, 2001).

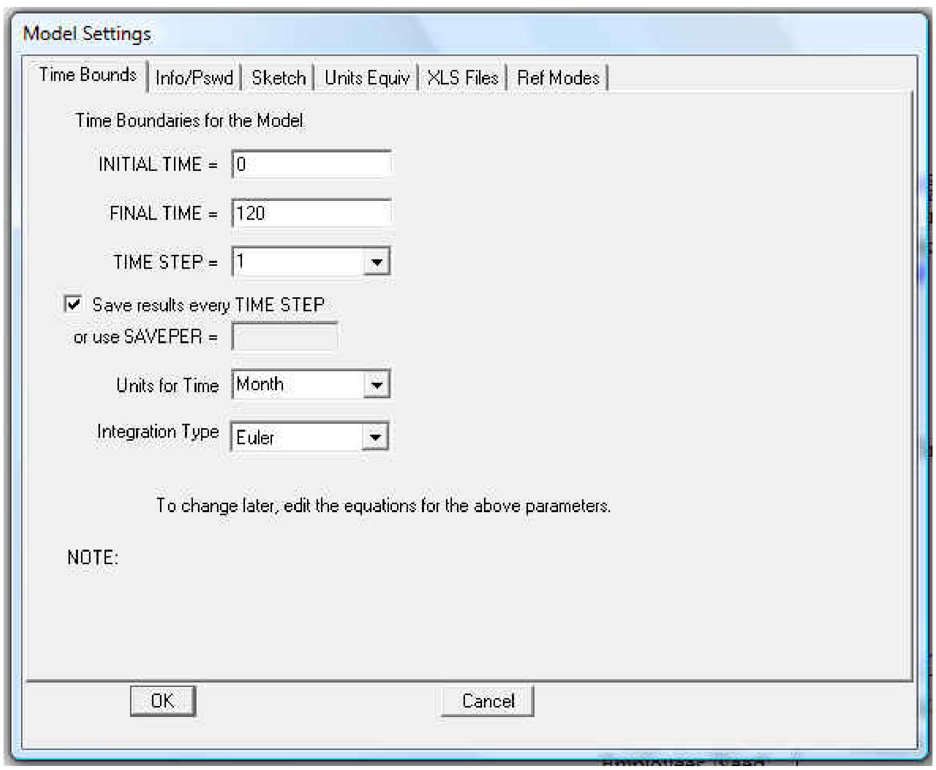


Figure 51. Simulation model setting parameters

4.5.1. Sub model 1: Technology Implementation Activities

The ERP implementation began in March 1999 when the 'Prospect' module was initiated. By 2005, 100% of the ERP implementation was completed. The period between 1999 and 2009 includes implementing 20 bundle applications and two major upgrades. The work generated due to the bundle applications has been used to calculate the amount of 'Estimated Implementation Efforts Backlog' in our model. Initial Bundle work was a function of the initial number of software add-ons and initial required customization (Fryling, 2010). These tasks do not include the upgrade activities. Table 17 summarizes the type and number of implementation tasks completed by June 2008. To find the amount of man-hour work required to implement ERP, we also need to have an estimation of the time per task. The average time to complete a task is set to 1 week (40 hours).

Table 17. Types of Implementation Tasks Completed by June 2008 [gotten from (Fryling, 2010)]

Task Type	**Total Tasks**
Customization	485
Add-ons	1687
Other	142
Total	2314

Not all the parameters used in the model were available from the case study data, therefore some user-defined values have been applied. Table 18 lists the base value and the data source for each parameter in the implementation sub-model. The estimated implementation efforts backlog is set to 11570 man-hour (2314 tasks * 5 hours).

Table 18. The base parameter values of Sub-model 1

Sub Model	Parameters	Default Value	Source
Implementation sub model	Estimated Implementation Efforts Backlog	11570 man hours	Case Study
	Unexpected Rework Rate	3.5%	Case Study
	Standard Implementation Time (for the whole system)	5 years (60 months)	Modeler
	Complexity of Technology	7	Modeler
	Target Implementation Time	3 months	Case study
	Workweek	40 hours	Case study
	Time Required per Task	5 hours	Estimated from case study
	Net Labor	10 person/week	Modeler
	Budget Required per Task	$250 (5 hours * 50 dollars/hour)	Estimated from case study
	Standard Working Error Fraction	3%	Modeler
	Budget Allocated to Technology	$5,000,000	Modeler

The resulting behaviors of some of the main Sub model 1 variables are discussed here. Figure 52 illustrates the ‘Implementation Initiation Rate’. This graph represents how the total 11570 man hours required to implement the ERP are generated over time. As shown, the amount of man-hour work generated over the 120-month period decreases over time, starting from 2200 man-hours per month to almost 0 man-hour at the end of the time horizon. The similar trend can be seen for the ‘Estimated Implementation Efforts Backlog’ (Figure 53).

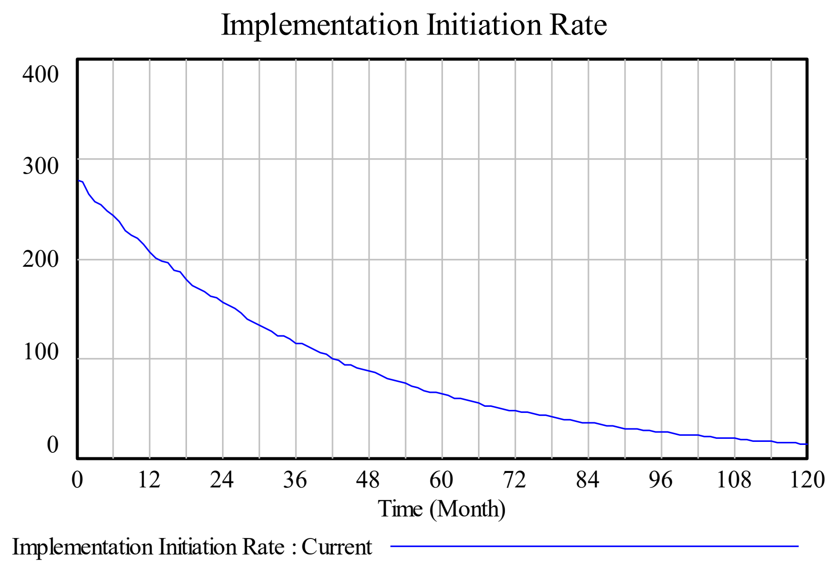


Figure 52. The rate of man-hours work generated per month for ERP implementation

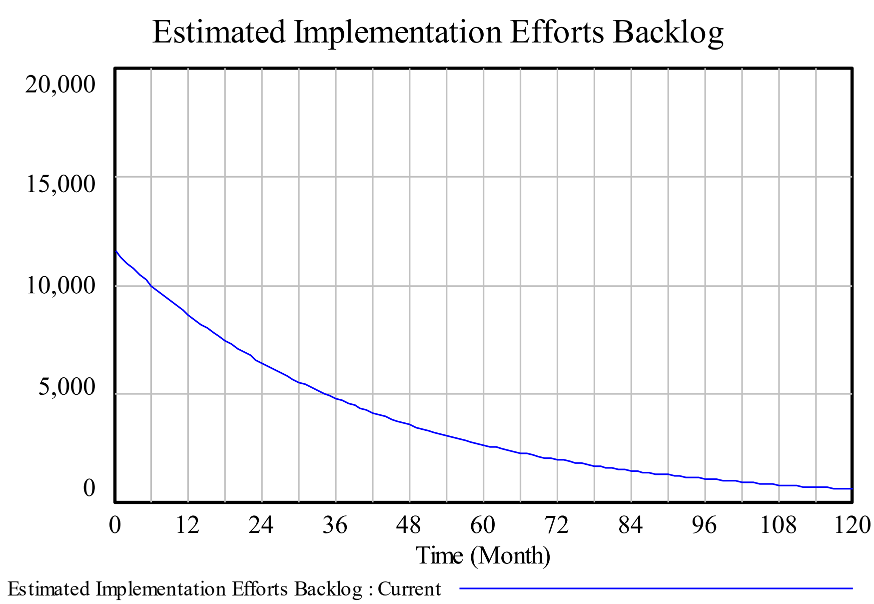


Figure 53. The estimated man-hour implementation work required to be done

It might be interesting to compare the initiation rate of implementation activities versus the implementation completion rate (Figure 54).

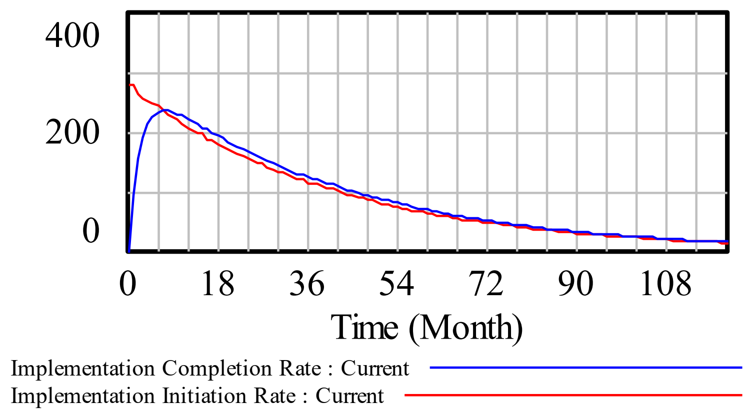


Figure 54. Implementation work initiation rate versus implementation rate

As discussed before, the implementation completion rate is determined based on the implementation plan. It is also restricted by the amount of resource available. The 'Implementation Completion Rate' started increasing at the first 6 months and then the rate was adjusted based on the implementation initiation rate. The completion rate shown in Figure 54 is the same as 'Planned Implementation Rate' meaning that the completion rate was not restricted by the amount of resource available. Suppose that enough resource was not available to conduct the implementation activities as planned. Then, the 'Implementation Completion Rate' was restricted based on the 'Potential Completion Rate' calculated based on the number of workforce available. Figure 55 shows the completion rate for the case in which only 160 man-hours resource are available per month (1 person * 40 hours/week * 4 weeks/month).

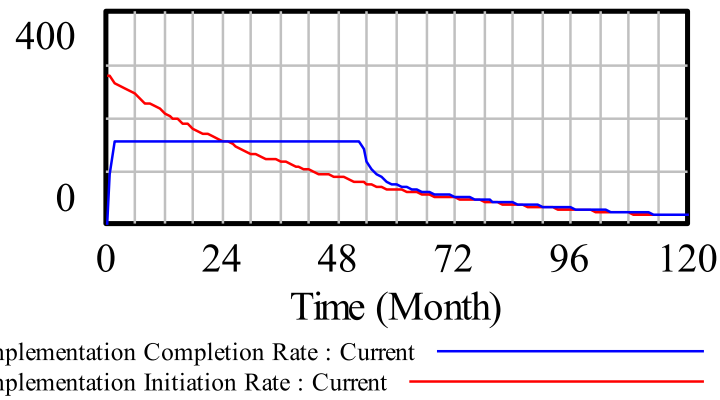


Figure 55. Implementation work initiation rate versus implementation completion rate when only 160 man-hours resource are available per month

It might also be interesting to study the amount of implementation efforts need to be completed at each time step. Figure 56 illustrates the implementation efforts backlog. As cab be seen most of the implementation work was completed during the first 5 years.

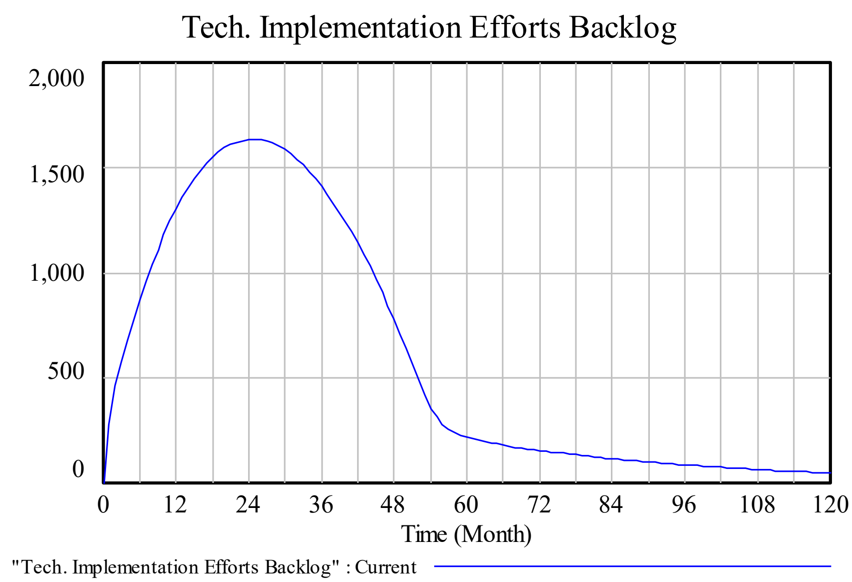


Figure 56. The technology implementation efforts need to be done

The amount of implementation efforts completed over the 10-year horizon is another interesting stock variable to study (Figure 57). The implementation efforts completed over time can be compared to the amount of implementation efforts generated (Figure 58).

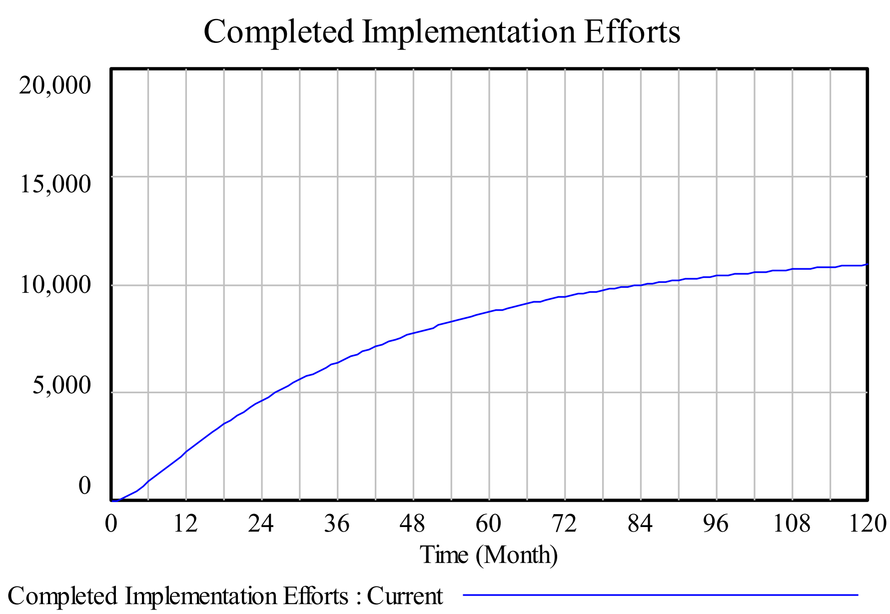


Figure 57. The number of man-hour implementation efforts completed

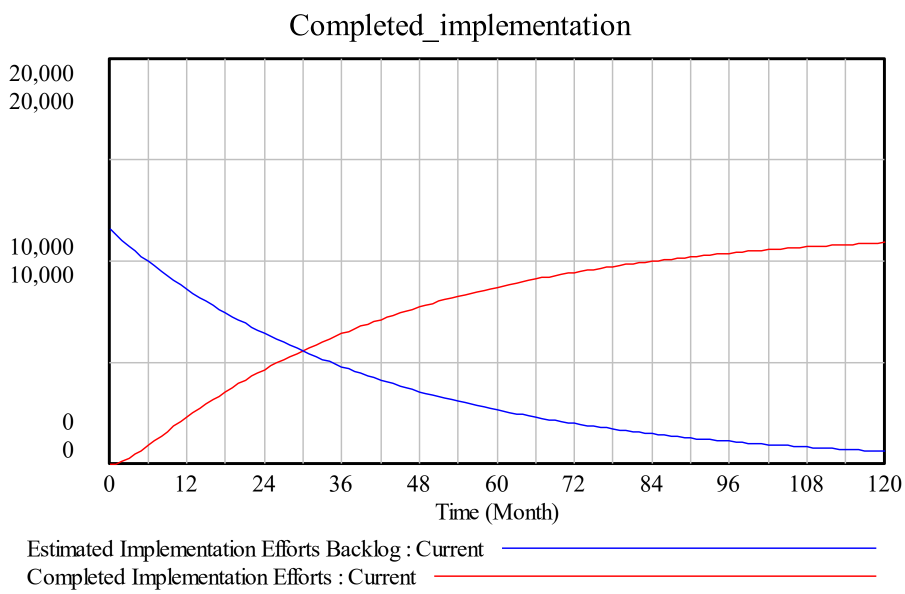


Figure 58. The implementation efforts completed versus the implementation efforts generated

In addition, we can calculate the budget spending rate (Figure 59) based on the amount of budget required per task and the implementation completion rate. The budget required per task can be calculated from the time required per task and the man-hourly or resource-hourly costs (1 week/task * 160 hours/week * 50 dollars/hour). The budget spending rate follows the same trend as the implementation completion rate.

We can also determine the amount of budget spent in implementation phase. The budget spending rate accumulated over time determines the amount of budget spent during implementation phase (Figure 60).

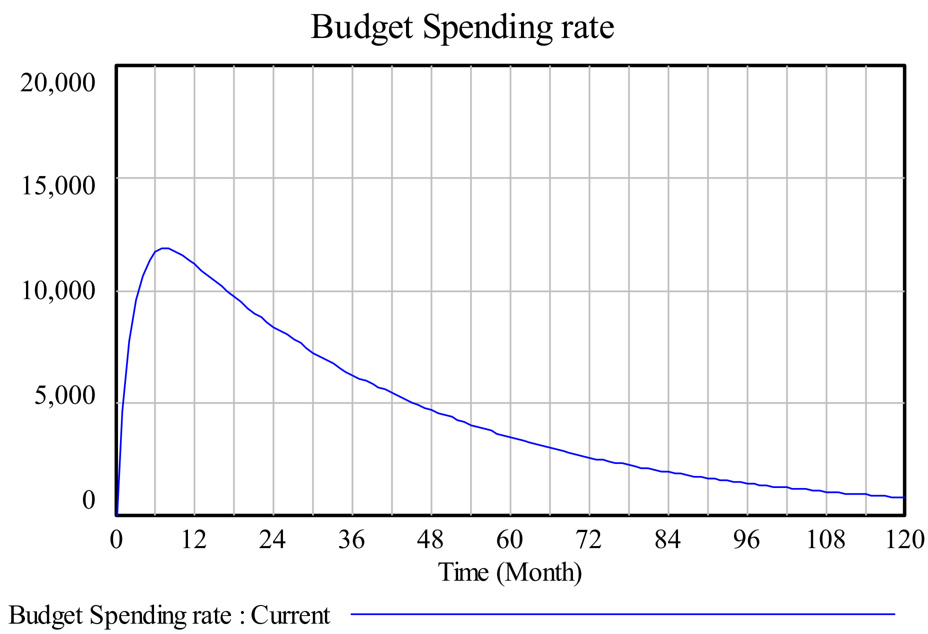


Figure 59. Budget spending rate

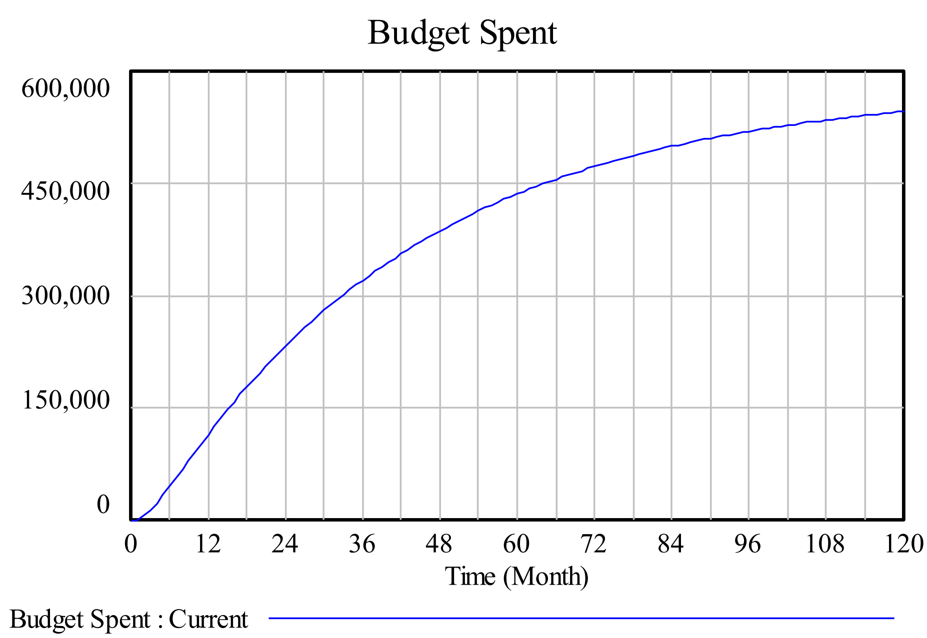


Figure 60. The amount of budget spent for completing implementation efforts

4.5.2. Sub Model 2: Workforce Training Process

Adequate education and user training is among the success factors of ERP implementation. Training increases the chance of users' technology acceptance and reduces the resistance to change. The need for training specifically has been mentioned in the ERP project charter. According to IAS project charter, training should be offered to both functional project team members and the end users (Fryling, 2010).

The number of technical and functional team members need training along with their expertise is listed in Table 19. Moreover, it is assumed that there are 50 employees as end users that need to be trained on how to use ERP system. In addition to these people, those newly hired employees that use ERP system should also be trained properly.

Table 19. The number of support workforce [gotten from (Fryling, 2010)]

Expertise	**Number of Employees**
Number of Business Analyst Employees	5
Number of Database Manager Employees	2
Number of Project Manager Employees	1
Number of System Administrators Employees	4
Number of Trainer/Helpdesk Support Employees	2.5
Total	14.5

The default parameters values used in the workforce training sub model are listed in Table 20. There is one month training cycle, every 8 months working cycle. The average number of people attending each training period is 10 people. To consider the uncertainty in the number of people taking part in each training cycle, a Normal distribution has been applied. In the current base simulation run, the number of trainees attending the training cycle is defined as a normally distributed random variable with mean 10 and variance 1.

Table 20. The base parameter values of Sub-model 2

Sub Model	Parameters	Default Value	Source
Workforce Training	Number of Current Employees Need Training	64.5 (14.5 technical staff+50 end users)	Estimated from case study
	Training Capacity	10 people ~ RANDOM NORMAL(0, 15 , 10 , 1 , 10)	Modeler
	Training Cycle	1 month	Modeler
	Working Cycle time	8 months	Modeler
	Training Length	1 to 2 weeks~ RANDOM UNIFORM(0.25, 0.5 , 0.25)	Case study
	Pre-implementation training/travel cost	$649,116	Case study
	Pre-implementation office and training supplies	$11,059	Case study
	Training provided per employee per week	$100	Case Study

Another parameter to discuss is the training duration. The length of the training period for each person is different based on the level of the expertise and the skill set required for the employee. The typical length of training is one to two weeks during the training cycle. A uniform distribution UNIFORM (0.25, 0.5) has been used to show the uncertainty in the length of the training session for each employee.

Figure 61 illustrates the training schedule variable. The training schedule is defined using a PULSE TRAIN function. The schedule gets the value of 1 during the training cycle and gets 0 otherwise. Figure 61 shows that there is one month training every 8 months working cycle.

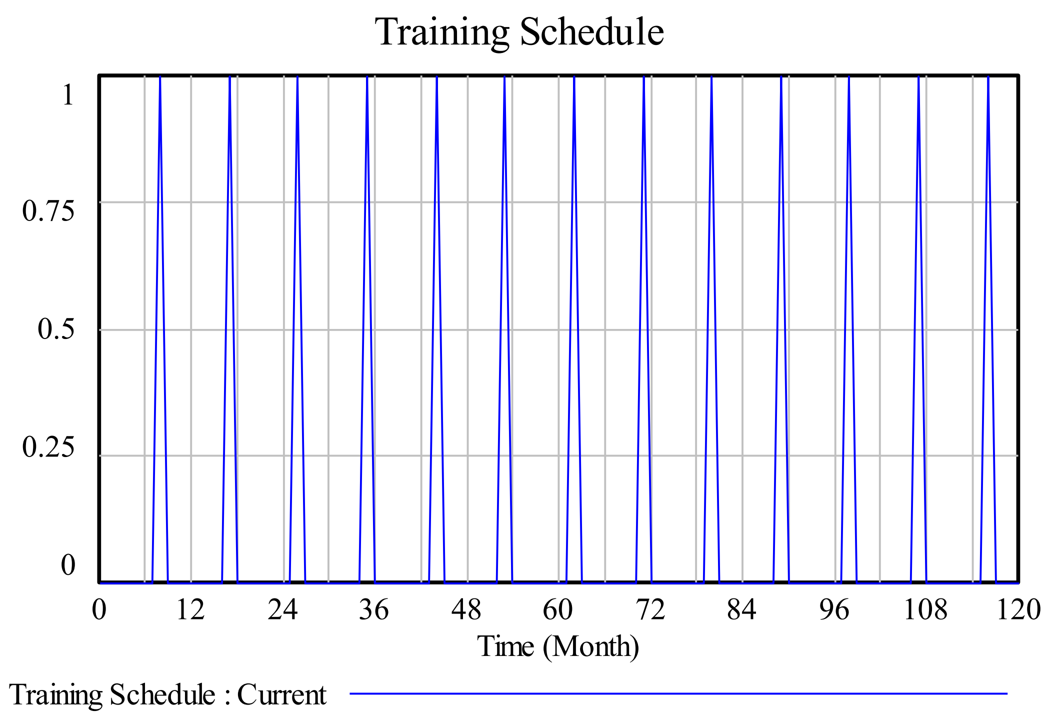


Figure 61. The training schedule

Figure 62 shows the number of employees including technical project team members, end users and newly hired employees that need to be trained. The curve slops upward during working cycle and slops downward during training cycle when the people are trained. Since the number of employees who receive training is not equal in each training cycle, the sizes of the downward slopes are not the same in Figure 62. The number of employees who receive training in each training cycle is determined based on the training rate and the training duration. As discussed before, training rate is determined based on the training capacity defined as a normally distributed variable with mean 10 people and also the binary training schedule variable discussed in Figure 61. Figure 63 and Figure 64 show the training capacity and the training rate respectively.

Figure 62. Number of employees need to be trained

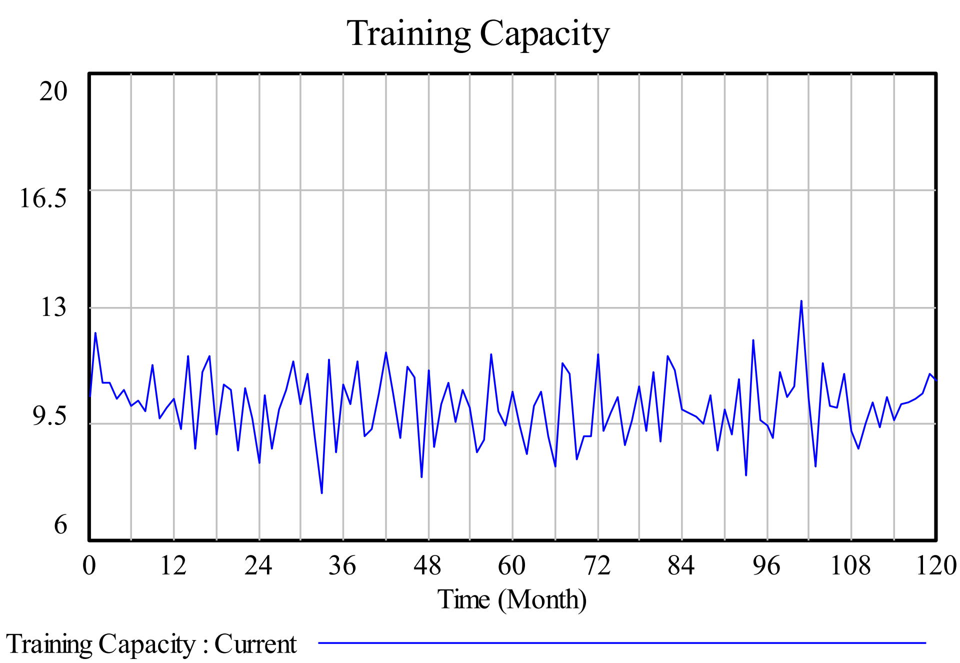


Figure 63. Average number of employees available to participate in training

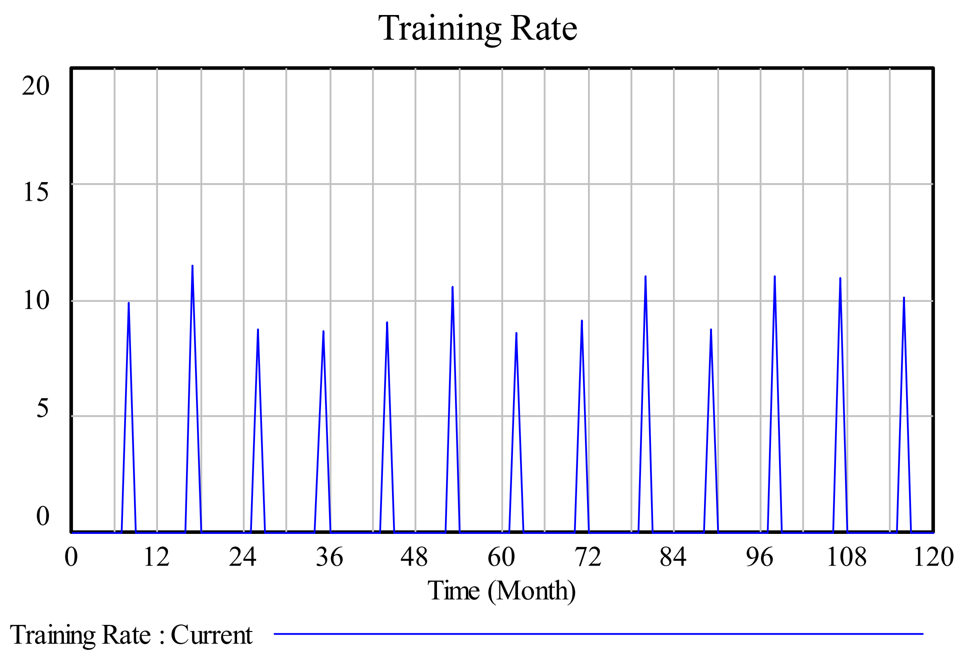


Figure 64. Number of employees entering the training cycle

Trainees require one to two weeks to finish training. It is assumed that all trainees pass the training session, therefore the rate of employees completing the training session is equal to the training rate. We just need to use a delay function and consider the training duration to plot the number of trained employees. Figure 65 plots both the number of employees starting the training (blue color curve) and the number who have completed training (red color curve). The gap between two curves shows the training duration/length.

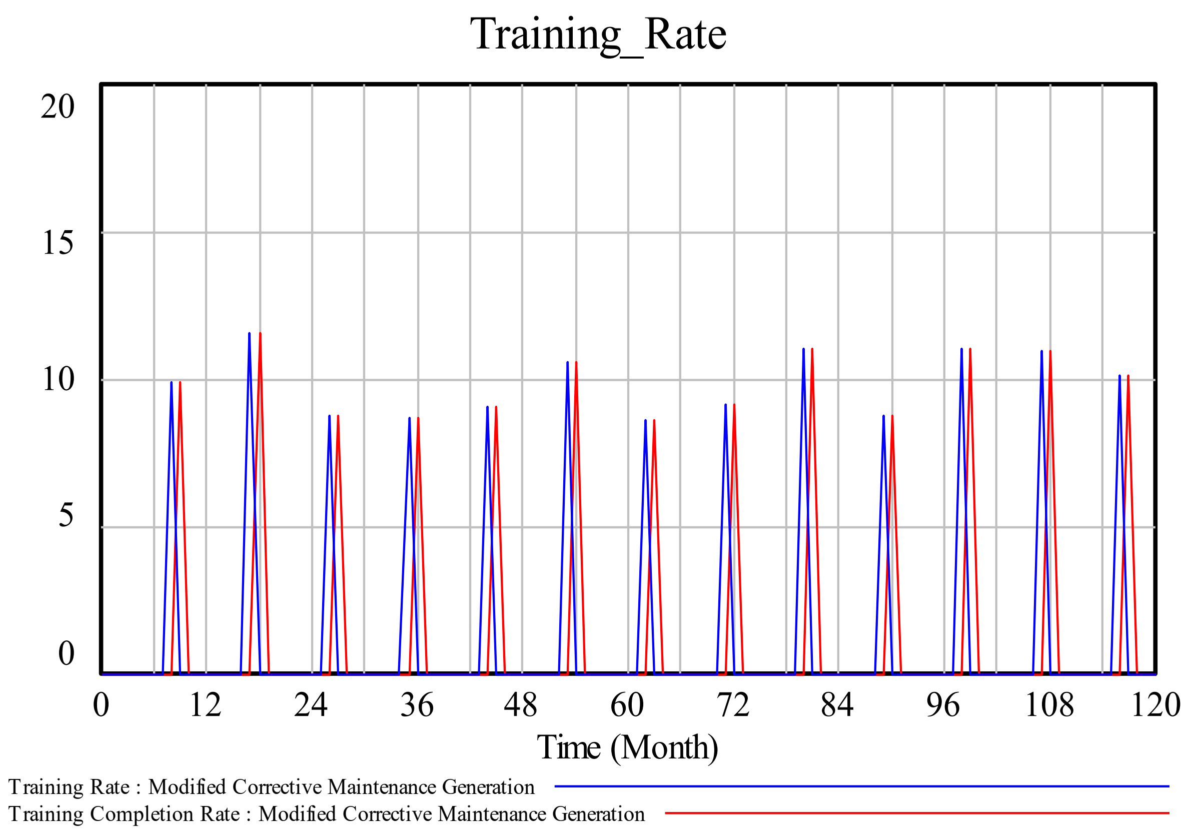


Figure 65. The number of trainees versus the number of employees who completed training

In order to calculate the total training cost, it is important to know the total number of employees who receive training during the project life horizon. Figure 66 illustrates the trained employees stock over the 10-year project horizon. As can be seen, every 8 months the number of trained employees increases based on the number of employees who receive training during the one-month training cycle.

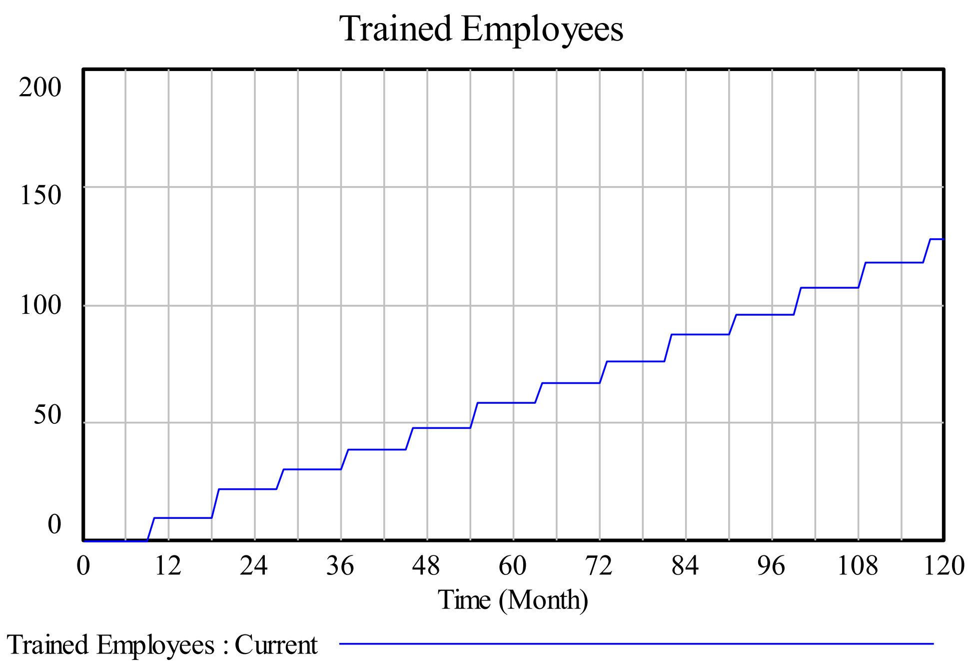


Figure 66. The number of trained employees over time

4.5.3. Sub-Model 3: Workforce Hiring Process

New workforce hiring is requested in the case existing workforce is less that the required workforce. 'Total Workforce' variable shows the existing number of employees required to work with the technology and the 'Target Workforce' represents the number of required workforce. We assume that the 'Target Workforce' is determined based on both the number of employees required and the budget available to hire new employees. If there are less employees that needed, then the employees are hired based on the 'Workforce Gap' and the 'Time to Hire Required Workforce'.

As the hiring process takes place, employees move to the '1-3 Year Experienced Employees' stock. After an average employment time of 3 years, some of the employees promoted to the next experience level and moves to the '3-5 Year Experienced Employees' stock and some quit the company. The employees with 3-5 years experience repeat the same story. After an average employment time of three years, some are promoted and some leave the university. The promotion fraction varies depend on the experience level. It was assumed that 80% of the employees with 1-3 years experience are promoted to the next level and 20% leave the university. The promotion fraction is the same for employees with 3-5 years experience and employees with 5-7 years experience. However, the promotion fraction of employees with 5-7 years experience is set to be 90%. Table 21 lists the default values used in sub model 3.

Table 21. The base parameter values of Sub-model 3

Sub Model	**Parameters**	**Default Value**	**Source**
Workforce Hiring	Time to Hire Required Workforce	5 years (60 months)	Estimated from case study
	Average Employment Times 1, 2, 3	3 years (36 months)	Modeler
	Promotion Fraction 1 and 2	80%	Modeler
	Promotion Fraction 3	90%	Modeler
	Target Workforce	100 employees	Estimated from case study
	Average Salary	$1062/week	Case study

The project plan was to have 100 employees involved and educated in the ERP system. This number is considered as the target workforce. Initially the project started with 50 employees and the plan was to hire new employees to fill the workforce gap within the five years from the project start date. Figure 67 shows the workforce gap. As seen, the gap is higher at the project start time and as time goes by it decreases. The workforce gap is at its lowest value around the fifth year of the 10-year project horizon.

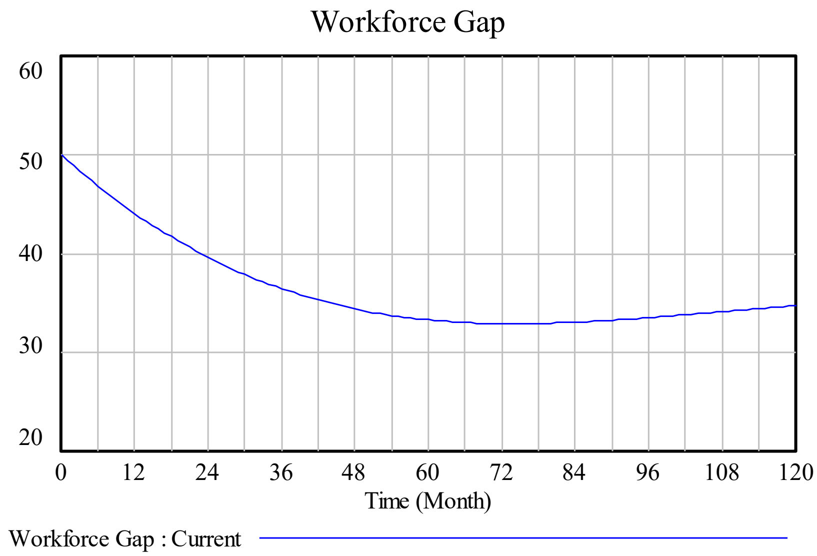


Figure 67. The workforce gap

The hiring rate of new employees is calculated based on the workforce gap and the target time to hire the required workforce (Figure 68). The hiring rate follows the same trend as the workforce gap.

Figure 68. The new employees hire rate

Figure 69 compares the number of employees in 4 different experience levels over time. As it is expected, the number of employees with 1-3 years experience over time decreases and the number of employees in other experience categories increases.

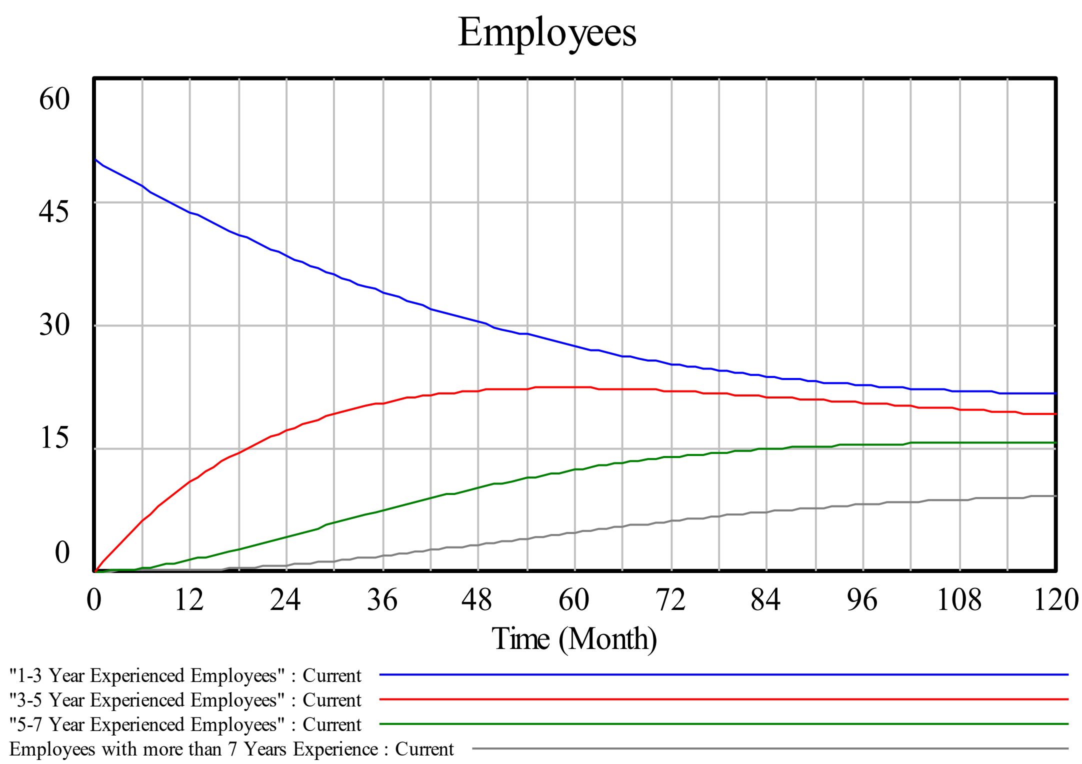


Figure 69. The number of employees in different experience categories

4.5.4. Sub-Model 4: Service, Maintenance and Support Process

Often the software packages as offered by vendors do not fully satisfy the companies requirement and a significant amount of customization and frequent maintenance are required. Companies can request a custom-built software from vendors, but this brings additional costs and risks and often results into implementation delay. What makes ERP systems different from other traditional software packages is that they are neither custom-built nor off-the-shelf software. They are developed based on industry best practices or better say vendor's perception about best practices. There are two options for companies to fill the gap between the best practices offered by ERP and the existing business processes. One alternative is to accept the functionality gap and do nothing. The other alternative is to modify the business processes to meet the ERP functionality. Most companies are not willing to conduct the second alternative since it is an enormous challenge to change the business processes because they are rooted in the organizational culture and requires a significant paradigm shift (Fryling, 2010). Therefore, "Because of the way ERP packages are designed, some tailoring is always required to get them up and running. But the extent of the tailoring can vary from one organization to the next" (Brehm, Heinzl, & Markus, 2001).

Since any small customization may affect other parts of the system, the ERP vendors discourage customization and do not support customization for free. While the ERP vendor takes the responsibility of correcting bugs in the source code, it is the responsibility of the companies to implement changes in the program code to fix urgent problems and moreover they are responsible for correcting configuration bugs resulted from customization or wrong parameter setting in the system (Brehm et al., 2001).

Table 22 summarizes the common way that ERP maintenance and support activities are distributed among vendor and the adopter company. As discussed before, Oracle, the ERP vendor, offers software support four times a year. This support includes fixing bugs and bundling issues, making governmental mandated requirements and offer some customer requested changes. These support efforts are considered as planned preventive maintenance in the SD model.

According to case study data, the bundle frequency is 12 weeks. Moreover, during the 10-year horizon the vendor has released two new versions of the software in order to solve major software issues and offer new functionality. These efforts are categorized as upgrade activities and will be discussed in Sub Model 5 (upgrade and technology maturity). The upgrade frequency is set to 156 weeks. In order to remain on the supported version of the software, the vendors want their clients to upgrade their systems regularly.

Table 22. The ERP system maintenance activities and participants [gotten from (Brehm et al., 2001)]

Maintenance activities	**Vendor**	**Adopter company**
Corrective	×	⋆
Adaptive	×	
Perfective		
Non functional	×	⋆
Functional	×	×
Preventive	×	

Legend: ×: main task ∗: secondary task

The fix bundles that are offered several times a year and the upgrade that are provided every couple years often break other software components and cause some rework tasks. Moreover, they may even generate new tasks that have not already been considered. These rework tasks along with new tasks are counted as corrective maintenance activities in our model. Table 23 summarizes the way that maintenance and upgrade activities are distributed across the ERP vendor and the adopter and the way that they are considered in our SD model.

Table 23. The ERP system maintenance activities and participants in our SD model

Support activities	**Maintenance category**	**Participant (who pay?)**	**Occurrence time**
Fix bundles	Preventive Maintenance	Vendor	Every 12 weeks
Rework tasks	Corrective Maintenance	Adopter (University of Albany)	Anytime
Unexpected new tasks generated as a result of bundle or upgrade	Corrective Maintenance	Adopter (University of Albany)	Anytime
Upgrade	Upgrade	Vendor	Every 156 weeks

The following is an overview of the case study data related to the 'Maintenance and Support" sub model (Fryling, 2010):

- The average number of rework tasks (corrective maintenance) reported in non-upgrade months between May 2007 and May 2009 was 192.
- On average rework tasks make 80% of the tasks received each month. The remaining 20% is called new tasks including customization and add-ons.
- Fix bundles (preventive maintenance) are offered four times a year (every 12 weeks). The project includes 20 bundle applications.
- The rework tasks increases by 12.5% in a month when a bundle was applied.
- There was a 217.5% increase in rework tasks when the software upgrade implemented in August 2008 (107 tickets was added to the helpdesk ticket).

The above information provides a good estimation about the amount of the corrective and preventive maintenance that we need to include in the SD model. It is worth noting that although the fix bundles (preventive maintenance) reduce the amount of errors in the system (in this case the rework tasks) in the long run, the data show an increase in the rework tasks in each month when the bundles or upgrade have taken place.

The next step is to calculate the base value of the 'maintenance' sub-model parameters based on the information provided above. As discussed before, fix bundles or preventive maintenance are every 12 weeks, therefore the preventive maintenance schedule is defined to have an operational cycle of length 12 weeks (3 months) followed by a preventive maintenance cycle of 1 week (0.25 month). A PULSE TRAIN function is used to show the maintenance schedule using a binary variable. Another parameter of the model is the amount of 'Planned preventive maintenance per month'. As explained before, the vendor offers four bundles per year, given the assumption that it takes 40 man-hours (1 week) to implement a bundle, therefore the planned preventive maintenance per month is almost 14 hours (4 bundles/year * 40 hours /bundle * (1/12) year/month).

We also need to estimate the amount of corrective maintenance generated per month. As discussed before, the average number of rework tasks per month is 192. This number makes only 80% of the total corrective maintenance generated, the other 20% is the new tasks including customization and add-ons, therefore the average total number of corrective maintenance tasks is 240 ($\frac{192}{0.8}$). Since 240 is the average, it has been assumed that the number of rework tasks generated per month is a normally distributed random variable with mean 240 and variance 10.

Moreover it has been assumed that it took 8 hours to complete each rework task. Therefore the 'Corrective Maintenance Generation Rate' is set as:

*RANDOM NORMAL (min, max, mean, variance, seed)*8 hours*

*RANDOM NORMAL (0, 300, 240, 10, 240)*8 hours*

Table 24 shows the base parameter values of 'Maintenance' sub model calculated based on the information discussed above.

Table 24. The base parameter values of Sub-model 4

Sub Model	Parameters	Default Value	Source
Maintenance and Support	Operational Cycle	12 weeks (3 months)	Case study
	Preventive Maintenance Cycle	1 week (0.25 month)	Case study
	Preventive Maintenance average completion (delay) time	2 weeks (0.5 month)	Modeler
	Planned Preventive Maintenance per month	14 hours	Estimated from case study
	Maximum Support service per week	160 hours (4 work labor *40 hours/labor/week)	Modeler
	Corrective Maintenance Generation Rate	RANDOM NORMAL(0, 300, 240, 10 , 240)*8 240 rework and new tasks per month and 8 hours per task	Estimated from case study

The values listed in Table 24 were used to simulate the model and Figures 70-73 show the results of the model for preventive maintenance activities. Specifically, Figure 70 shows the preventive maintenance schedule time. Figure 71 shows the completion rate of preventive maintenance over time. As discussed before, the vendor mainly offers fix bundles every 12 weeks and the average delay time in completing preventive maintenance is 1 month. Figure 72 shows the level of the 'required preventive maintenance' stock over time. As can be seen, the stock level decreases over the maintenance cycle and increases during the operational cycles. The stock value at each point of the time represents the remaining amount of man-hours preventive maintenance need to be completed. Finally Figure 73 shows the amount of preventive maintenance completed and accumulated over time.

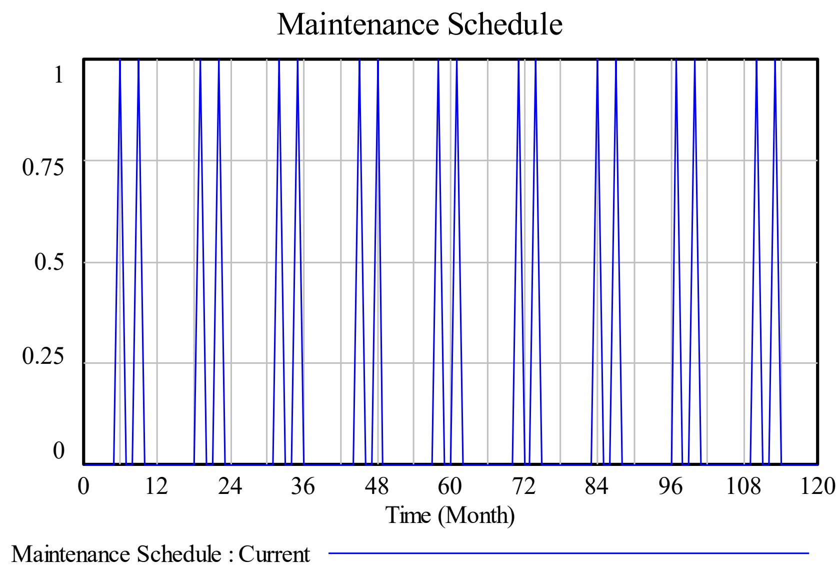


Figure 70. The preventive Maintenance Schedule

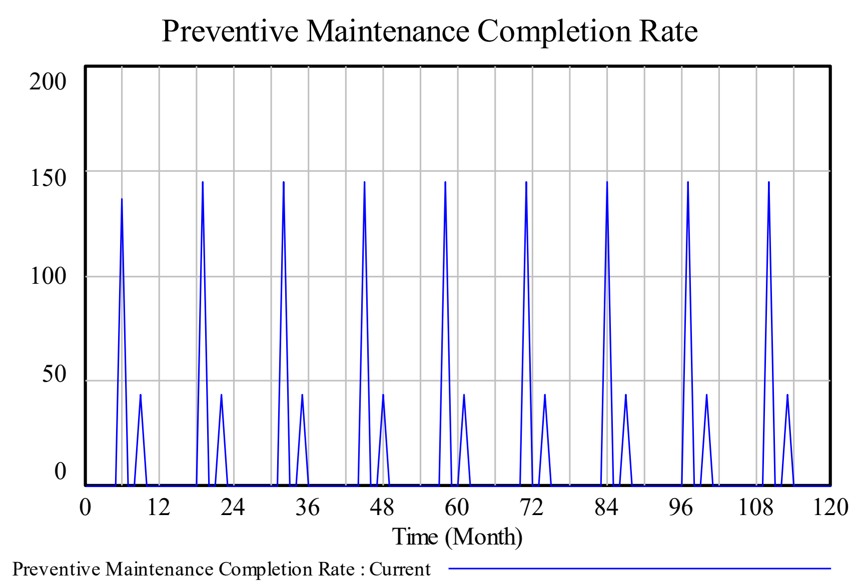


Figure 71. The preventive maintenance man-hours completion rate

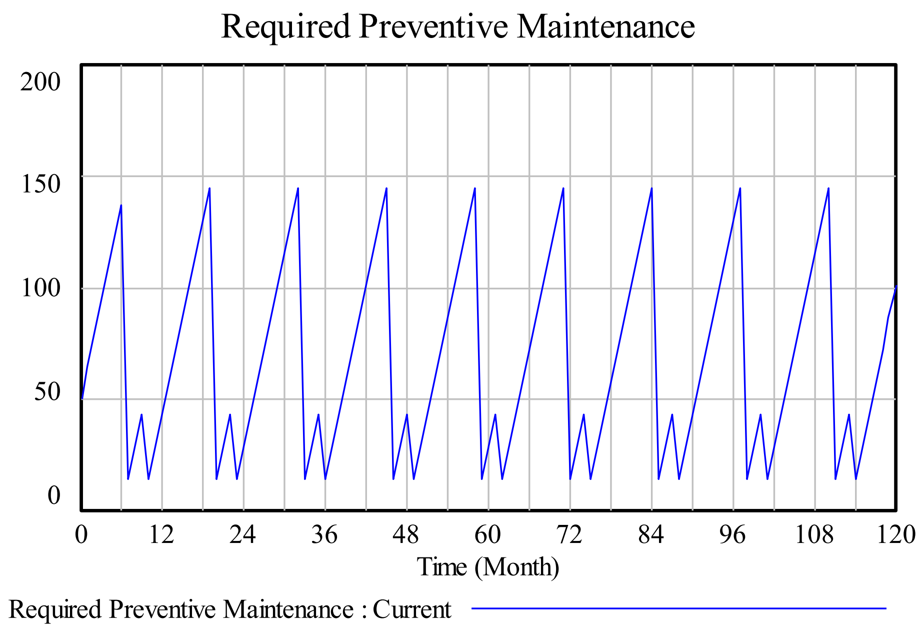


Figure 72. The amount of preventive maintenance need to be completed

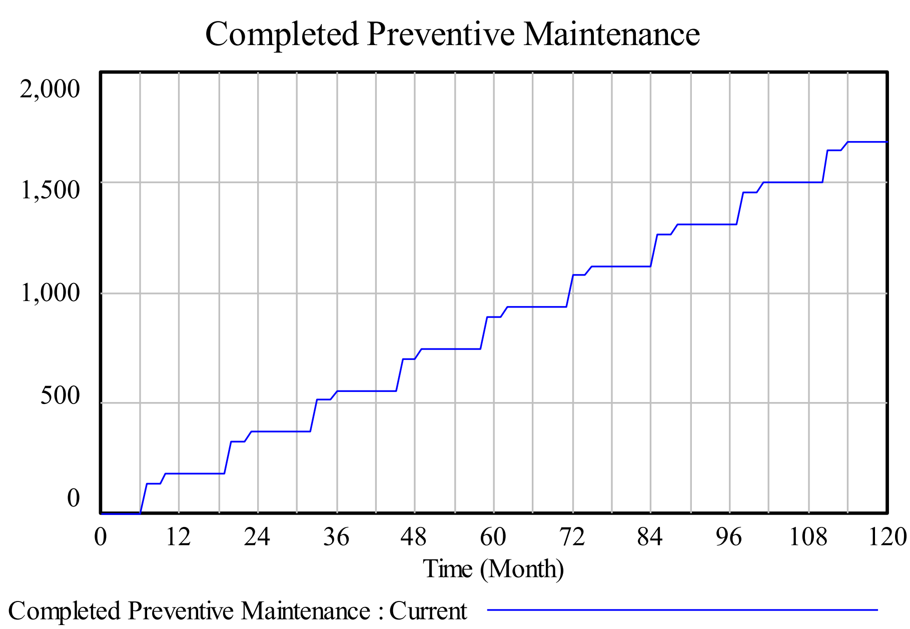


Figure 73. The amount of preventive maintenance man-hours completed

The second part of the 'maintenance' sub model is the corrective maintenance activities. As discussed before, the average 'corrective maintenance generation rate' is 240 rework tasks per month. If we assume that it takes 8 hours to complete a rework task, the generation rate of corrective maintenance can be calculated as shown in Figure 74. The randomness in the amount of corrective maintenance man-hours generated per month is modeled using a normally distributed random variable with mean 240 and considering 8 hours to complete each task.

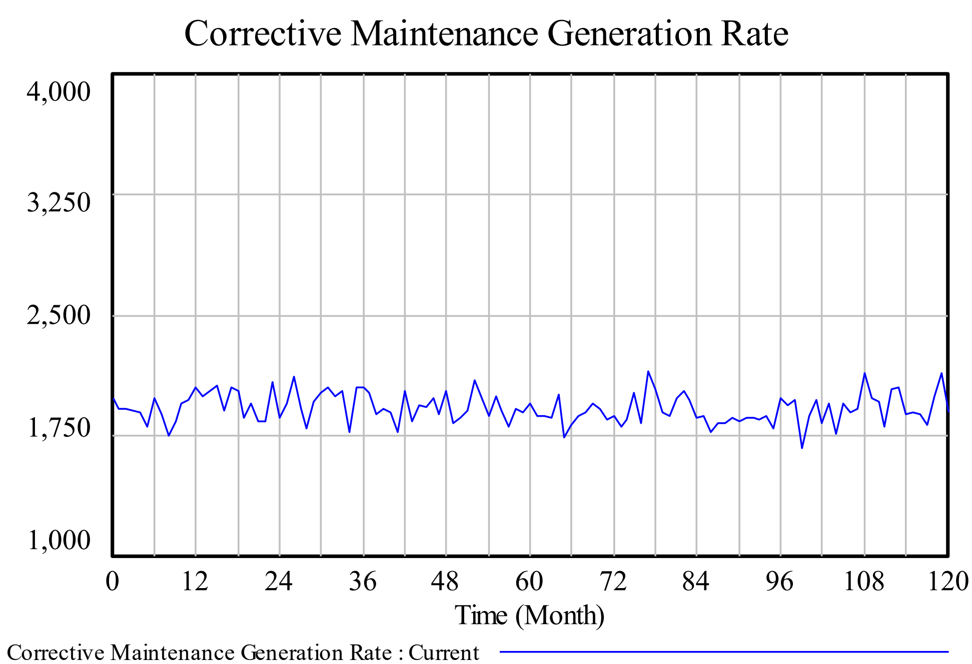


Figure 74. The random amount of corrective maintenance man-hours generated per month

The corrective maintenance generation rate shown in Figure 74 does not include the impact of fix bundles applied every 12 weeks. One average in months when bundles are applied, there are some extra rework tasks added to the corrective maintenance. As discussed before, unlike what we expect when conducting preventive maintenance for hardware, bundles (preventive maintenance) applied for software may increase the rate of rework tasks generated in short term. In general, the preventive maintenance activities are applied to reduce the corrective maintenance occurrence, but in the ERP case study discussed here, when bundles took place, there was an increase in the amount of rework tasks generated during the month in which the bundle took place. It has been assumed that on average there was a 10% increase rework tasks in a month when a bundle is applied. To apply this point, a new variable called 'Preventive Maintenance Impact' has been added to the Maintenance Stock and Flow diagram (Figure 75). The 'Preventive Maintenance Impact' variable is defined as follow:

IF THEN ELSE (Maintenance Schedule=1, 1.1, 1)

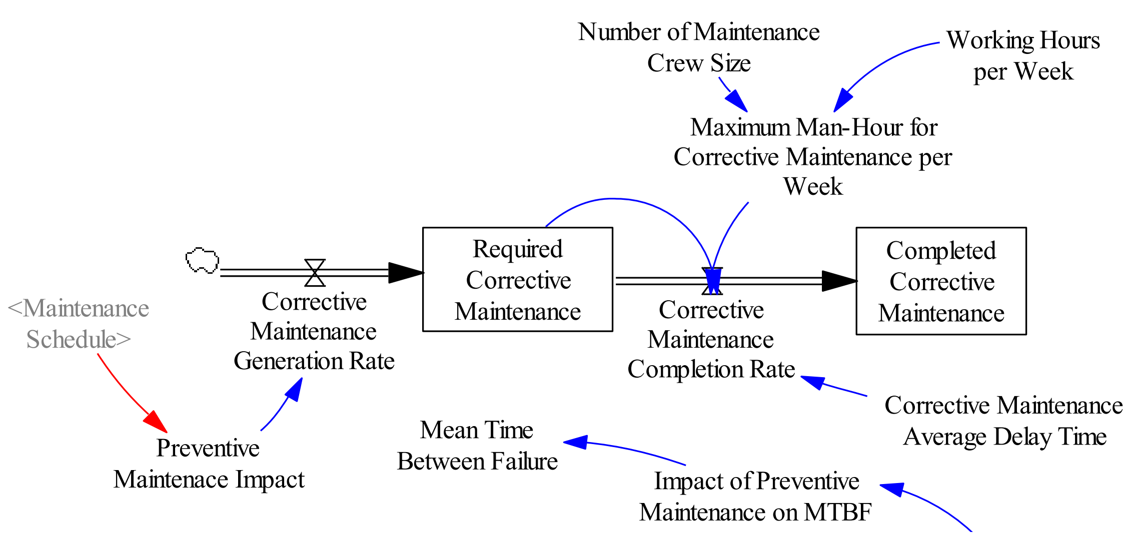


Figure 75. Corrective maintenance sub-model modified to include the 'preventive maintenance impact'

This variable is multiplied with the previous 'Corrective Maintenance Generation Rate' to give the modified corrective maintenance generation rate:

*[RANDOM NORMAL (0, 300, 240, 10, 240)*8 hours]*[IF THEN ELSE (Maintenance Schedule=1, 1.1, 1)]*

According to the above equation, if the maintenance schedule is 1 meaning that we are in a preventive maintenance cycle, then the corrective maintenance generation rate is multiplied by 1.1 (10% increase rate), otherwise it remains as before (a random variable with mean 240).

It should be noted that in the current case study since we have the corrective maintenance data, we have simply estimated the corrective maintenance generation rate. In general case, the corrective maintenance rate is calculated using 'technology life span', 'mean time between failure' and 'mean time to repair' variables. The adjusted corrective maintenance generation rate based on the impact of preventive maintenance is shown in Figure 76.

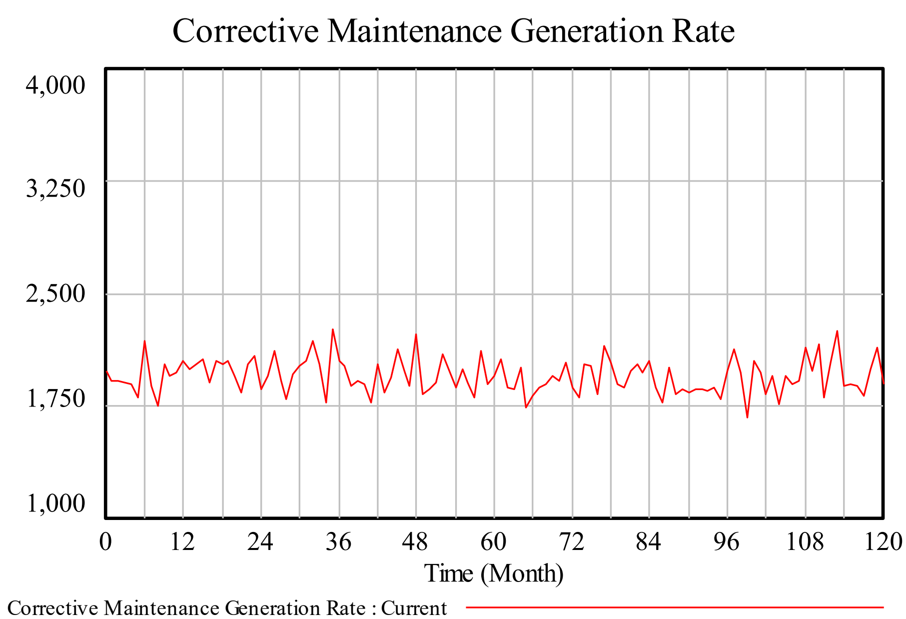


Figure 76. The adjusted corrective maintenance generation rate

Figure 77 compares the initial generation rate of corrective maintenance with the case that bundles are applied. The amount of 'corrective maintenance' man-hours need to be completed, the 'completion rate' and the ' are shown in Figure 78 and 79 respectively.

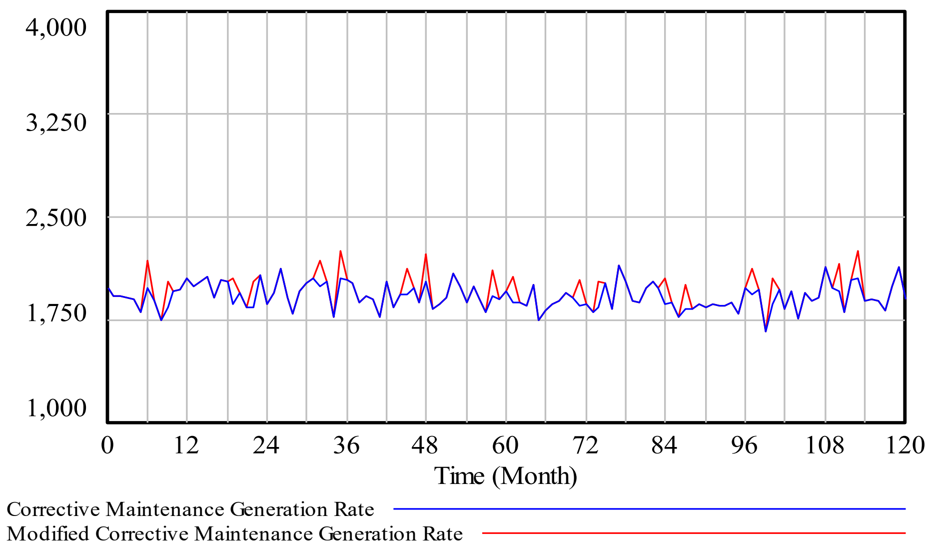


Figure 77. The impact of bundles implementation on the corrective maintenance generation rate

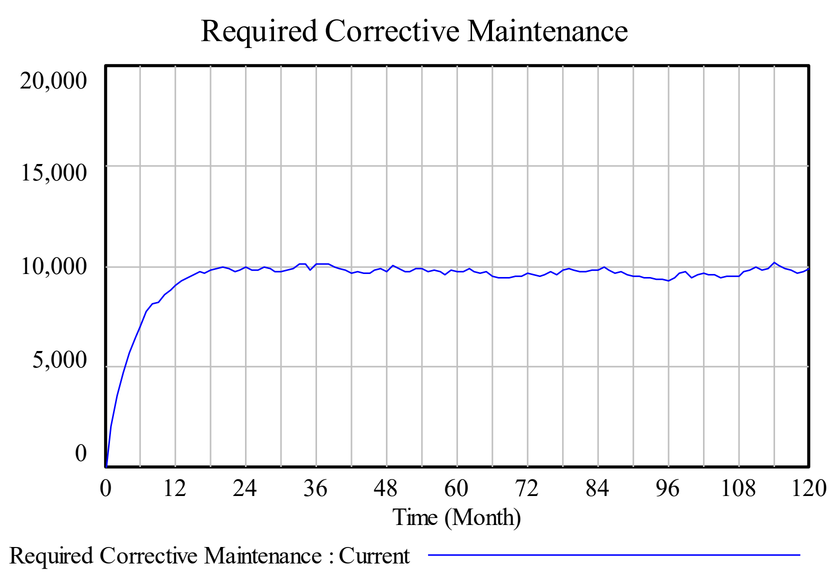


Figure 78. The corrective maintenance man hours need to be completed

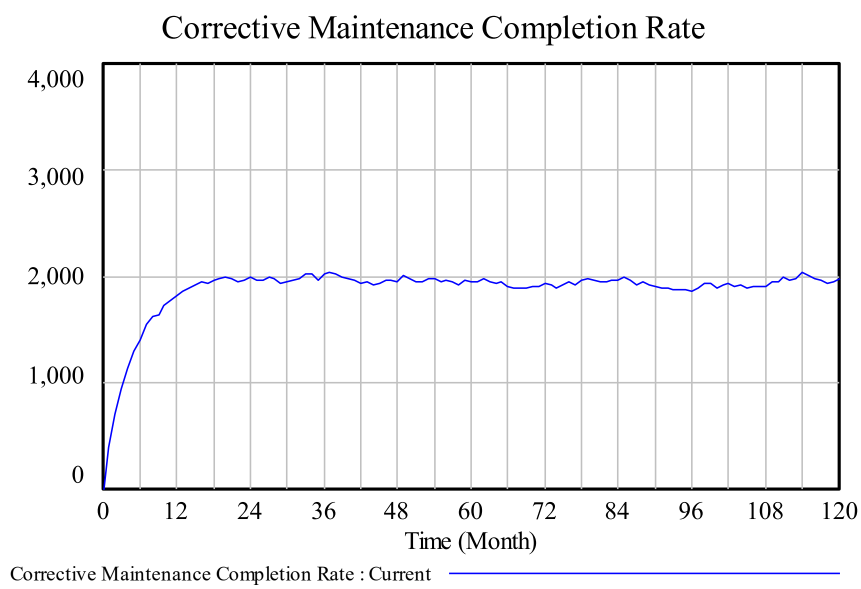


Figure 79. Corrective Maintenance Completion Rate

Figure 80 illustrates the total amount of corrective maintenance man-hours completed during the 10-year horizon.

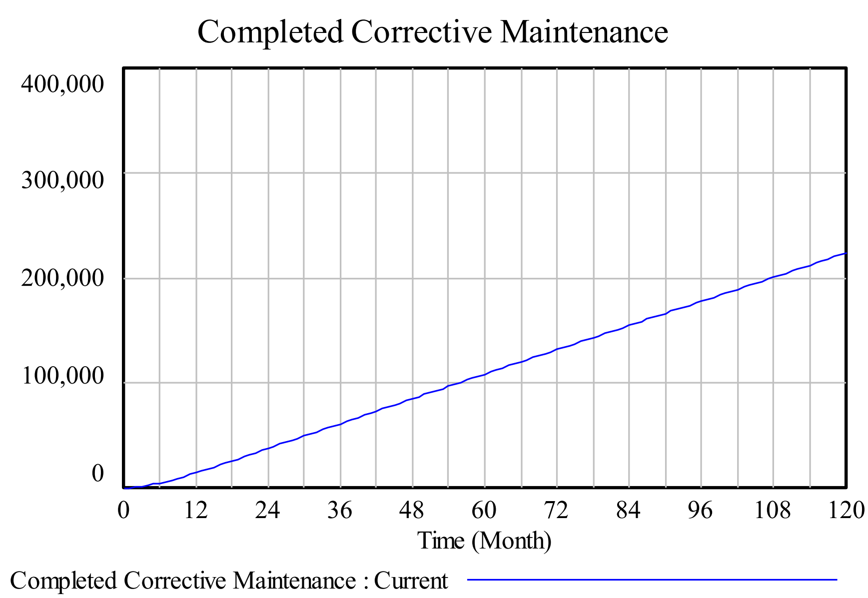


Figure 80. The completed corrective maintenance man-hours

4.5.5. Sub-Model 5: Upgrade and Technology Maturity

While fix bundles are offered four times a year, upgrades take place every couple years. The intention of ERP upgrades is to add new functionalities and solve the issues with the software previous versions. ERP vendors offer the upgrades and want their clients to upgrade their systems regularly and within a specific timeframe. Although the client can choose not to upgrade their system, they will be responsible for all the bugs and problems arisen from remaining on an unsupported version of the software. University of Albany has decided to continue with the vendor support and upgrade the software as it is offered by vendor. The IAS project history shows two upgrades taken place. In September 2002 the software was upgrade to Version 8.0 and in August 2008, the software was upgrade to Version 9.0. The following is a brief overview of the upgrade-related case study data (Fryling, 2010):

- The upgrade frequency was 156 weeks.
- The normal time available to complete upgrade Work was 52 weeks
- As a result of the upgrade taken place in August 2008, there was a 217.5% increase in the rework tasks.
- The types and the number of upgrade tasks are listed in Table 25.

Table 25. The type and number of upgrade tasks [summarized from (Fryling, 2010)]

	Upgrade Work	**Upgrade Rework**	**Total**
Add-ons	299	301	600
Customizations	104	104	208
Other	168	174	342
Total	571	579	1150

To apply all the information provided in the case study such as the frequency of the upgrades and the rework tasks generated as a result of upgrade, the ‘Upgrade’ sub model has been modified. The new stock and flow diagram for the ‘Upgrade and Technology Maturity’ sub model is shown in Figure 81. The new variable ‘Upgrade Frequency’ has been added to the stock and flow diagram to reflect the upgrade timeframe. A PULSE TRAIN function has been used to define the upgrade frequency:

PULSE TRAIN (39, 0.5, 39, 100)

Figure 82 shows when the upgrade is taking place over the 10-year project horizon.

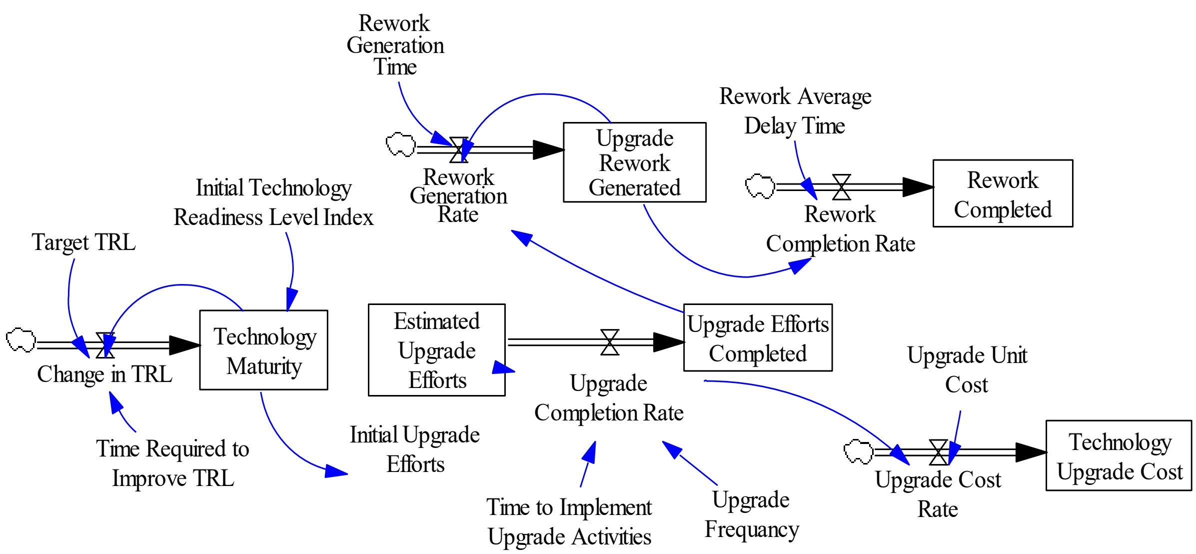


Figure 81. The modified ‘Upgrade and Technology Maturity’ sub model

Table 26 lists some of the main parameter values used in Sub Model 5. The results of the model are illustrated in Figures 83-88.

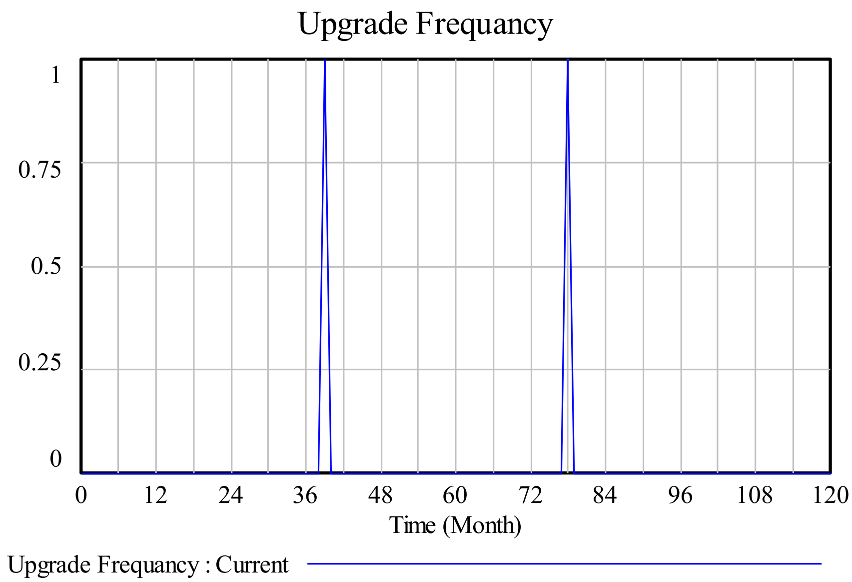


Figure 82. The upgrade schedule/frequency

Table 26. The base parameter values of Sub-model 5

Sub Model	Parameters	Default Value	Source
Upgrade and Technology Maturity	Initial Technology Readiness Index	7	Modeler
	Target TRL	9	Modeler
	Initial Upgrade Efforts	571 upgrade work * 40 hours/upgrade	Case Study
	Upgrade Frequency	Every 39 months	Case Study
	Maximum Support service per week	160 hours (4 work labor *40 hours/labor/week)	Modeler
	Time to Implement Upgrade Activities	2 months	Estimated from case study
	Rework Generation Time	8 Months	Modeler
	Upgrade Rework	579*40 hours/upgrade	Case Study

Figure 83 shows the level of upgrade efforts man-hours over time. As can be seen, the level of the upgrade efforts that need to be implemented decreased in a step-wise manner at two time points over the project horizon. The upgrade durations are two months and have occurred based on the upgrade schedule illustrated in Figure 82. The completion rate of the upgrade man-hours over the upgrade period is shown in Figure 84.

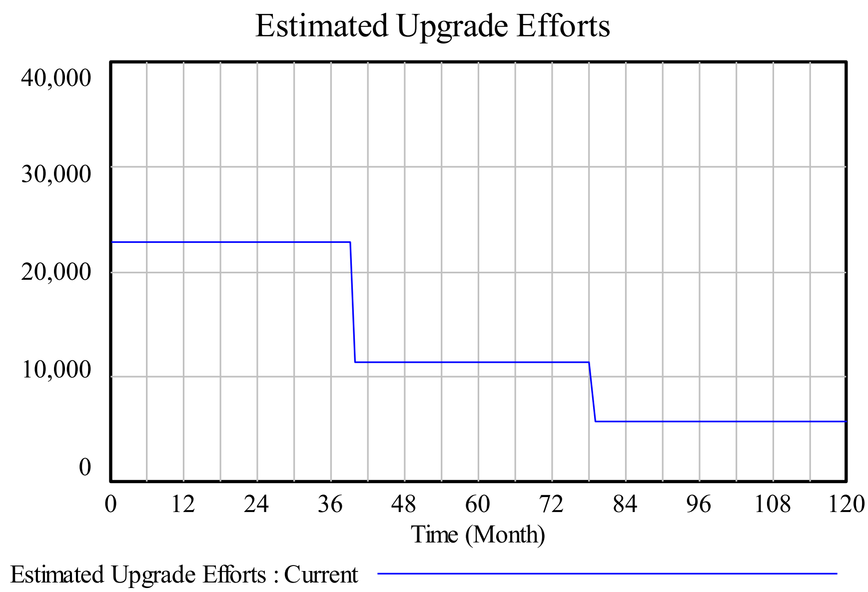


Figure 83. The upgrade man hours need to be completed

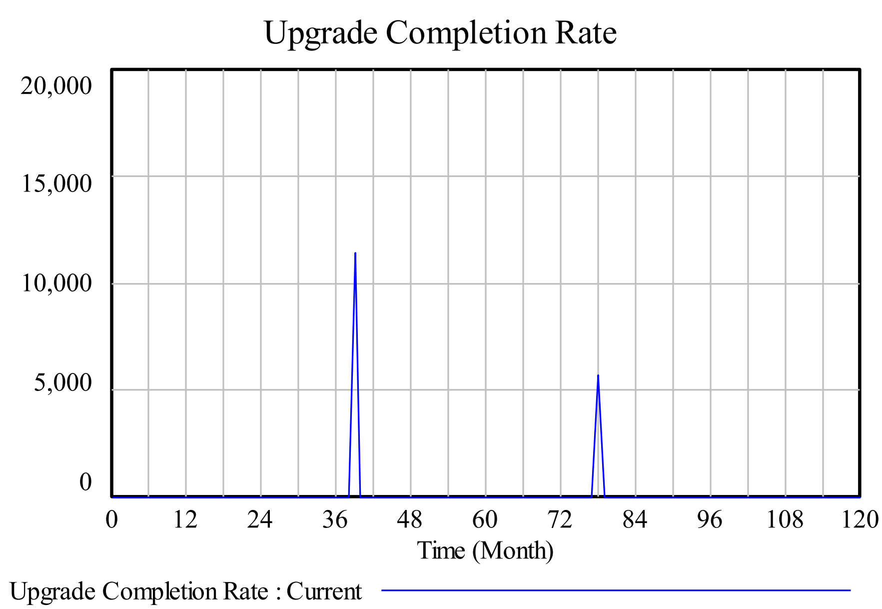


Figure 84. The upgrade completion Rate during upgrade periods

Figure 85 depicts the total upgrade man-hours completed over time and Figure 86 illustrates the generation rate of the rework tasks. The area under the curve in Figure 86 shows the total amount of rework generated. Figure 87 shows the total amount of rework generated over time. Moreover, the amount of the rework efforts completed over time is shown in Figure 88.

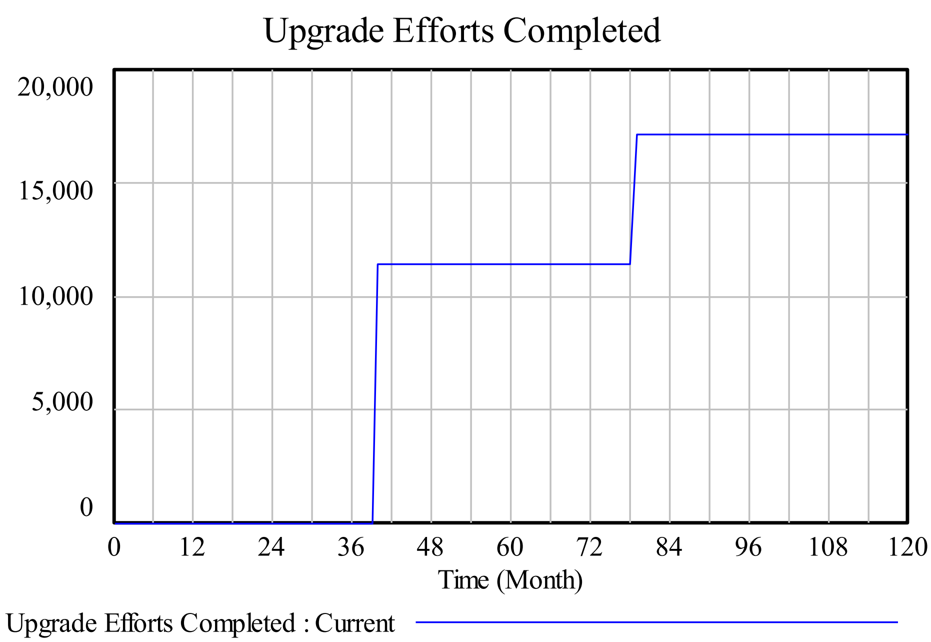


Figure 85. The upgrade man-hours completed over time

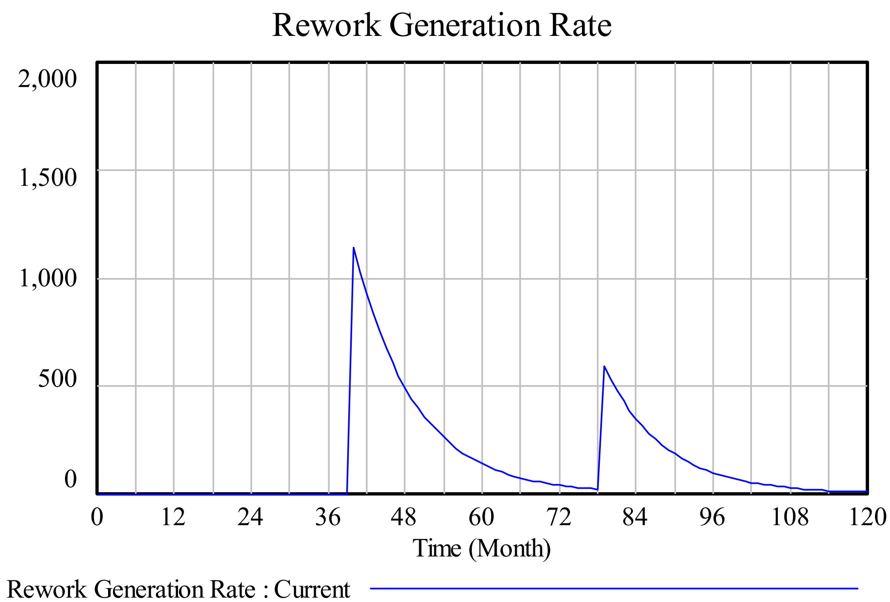


Figure 86. The generation rate of rework efforts as a result of software upgrades

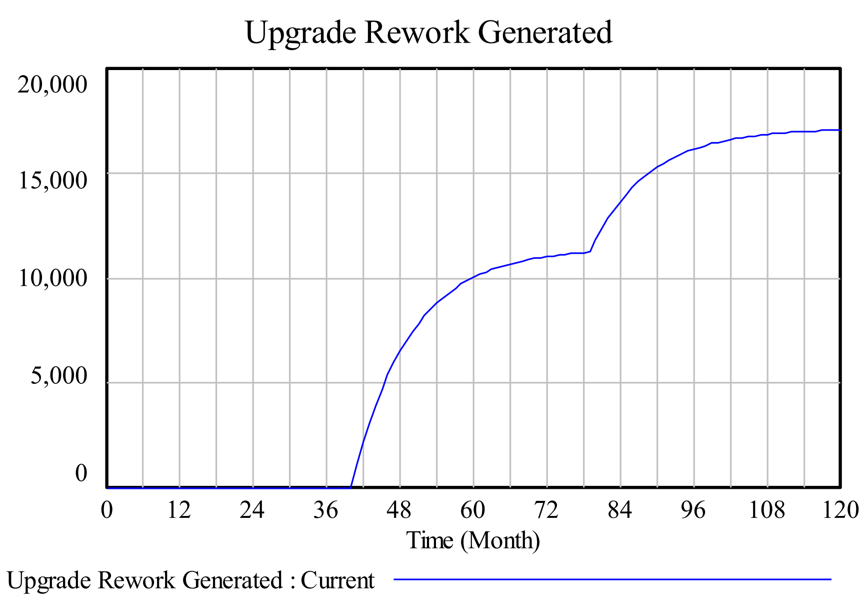


Figure 87. The total amount of rework efforts generated over time

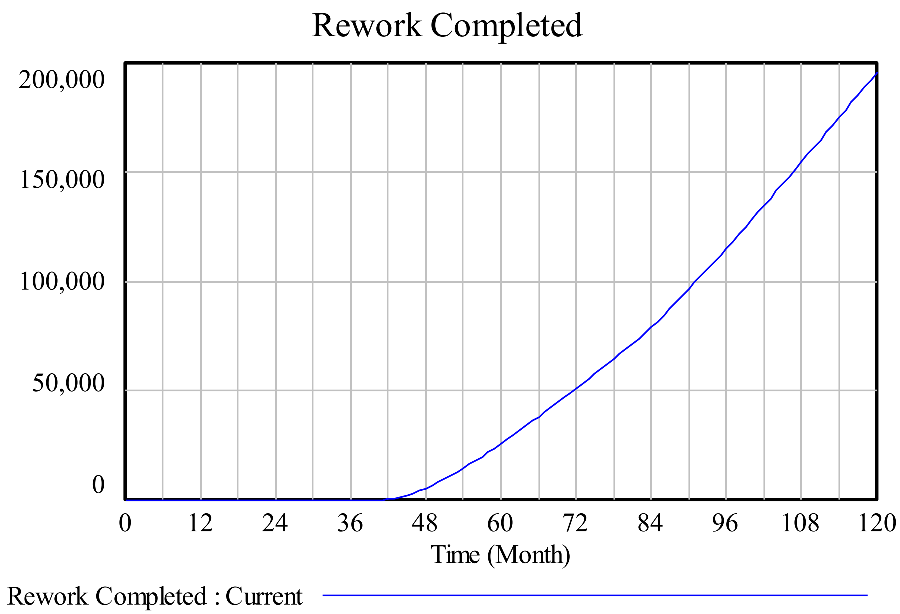


Figure 88. The amount of rework efforts completed over time

4.5.6. Sub-Model 6: System Performance

There are not any specific data available in the current case study about the impact of the ERP implementation on the system performance. However, the result of the model will be shown for some hypothetical parameter values. As discussed before, the performance measure under study in this work is the number of the work errors generated in the system. It has been assumed that the ERP technology helps the university decrease the amount of the work errors in the system. Figure 89 shows the generation rate of work errors over time. As can be seen, the work error generation rate decreases over time as the ERP is implemented and used. Figure 90 depicts the total number of work errors over time.

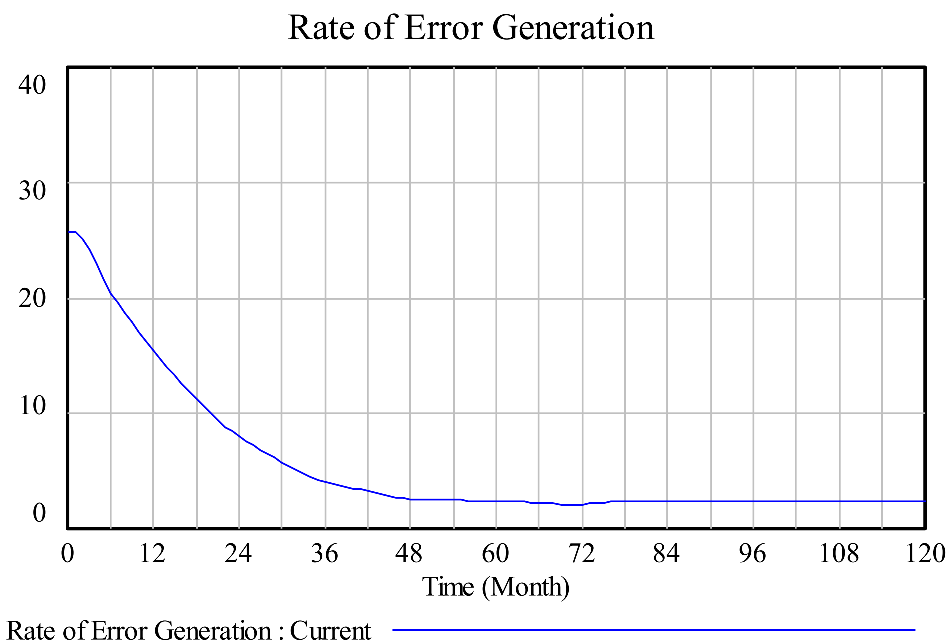


Figure 89. The work errors generation rate over time

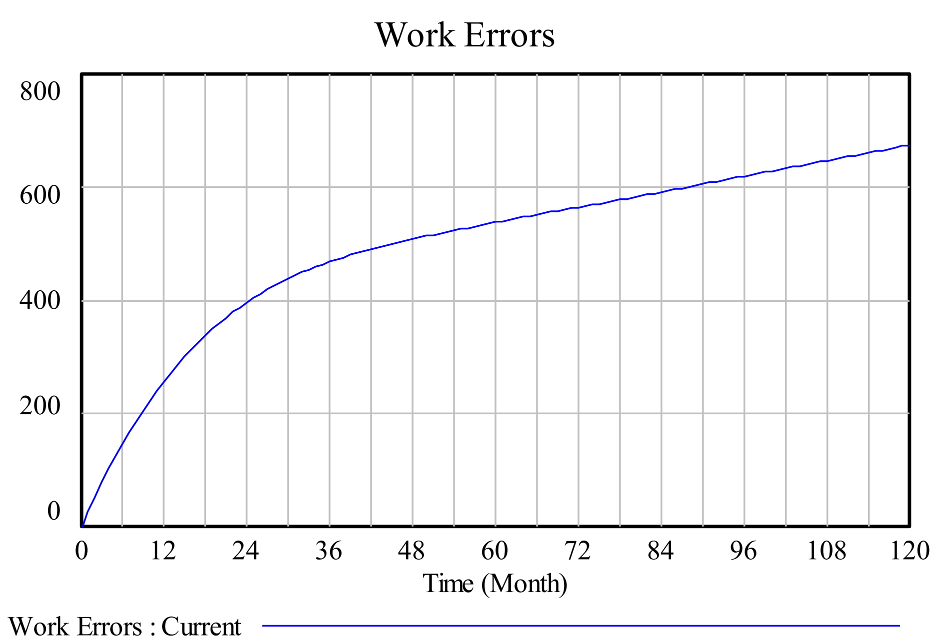


Figure 90. The total number of work errors generated over time

4.5.7. Sub-Model 7: Total Ownership Cost

One of the main objectives of the model is to estimate the total ownership cost of technology in the long-term. The total ownership cost is defined as the "long term accumulation of costs to maintain the ERP" (Fryling, 2010).

In this case, we want to find the total cost of the technology over a 10-year horizon (120 months simulation run). Figure 91 illustrates different components that make up the TOC. Figure 91 is called TOC causes tree.

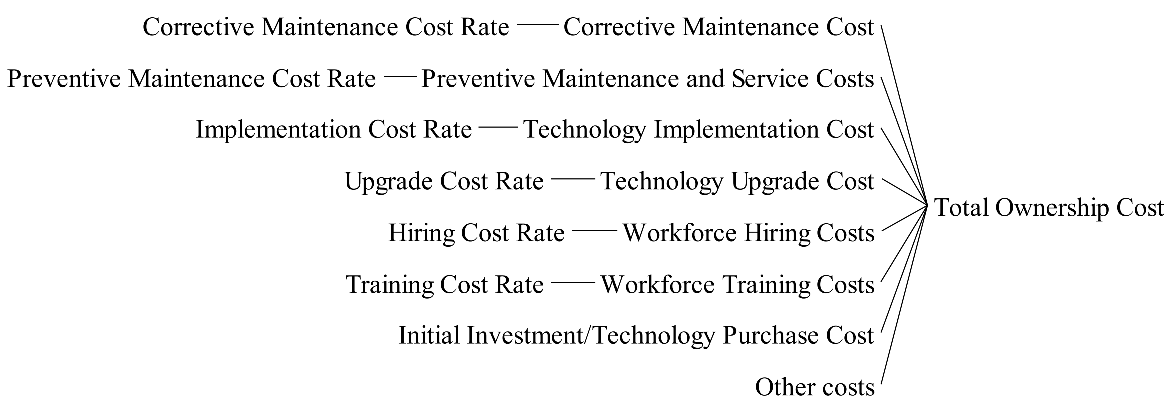


Figure 91. Different components of TOC

As can be seen in Figure 91, the total cost is estimated based on the implementation cost rate, preventive and corrective maintenance cost rates, upgrade cost rate, workforce cost rate including hiring and training costs, initial investment and also other costs. Figure 92 gives more details on the third level of the TOC causes tree and lists the variables that are directly and indirectly connected to estimate each element of TOC.

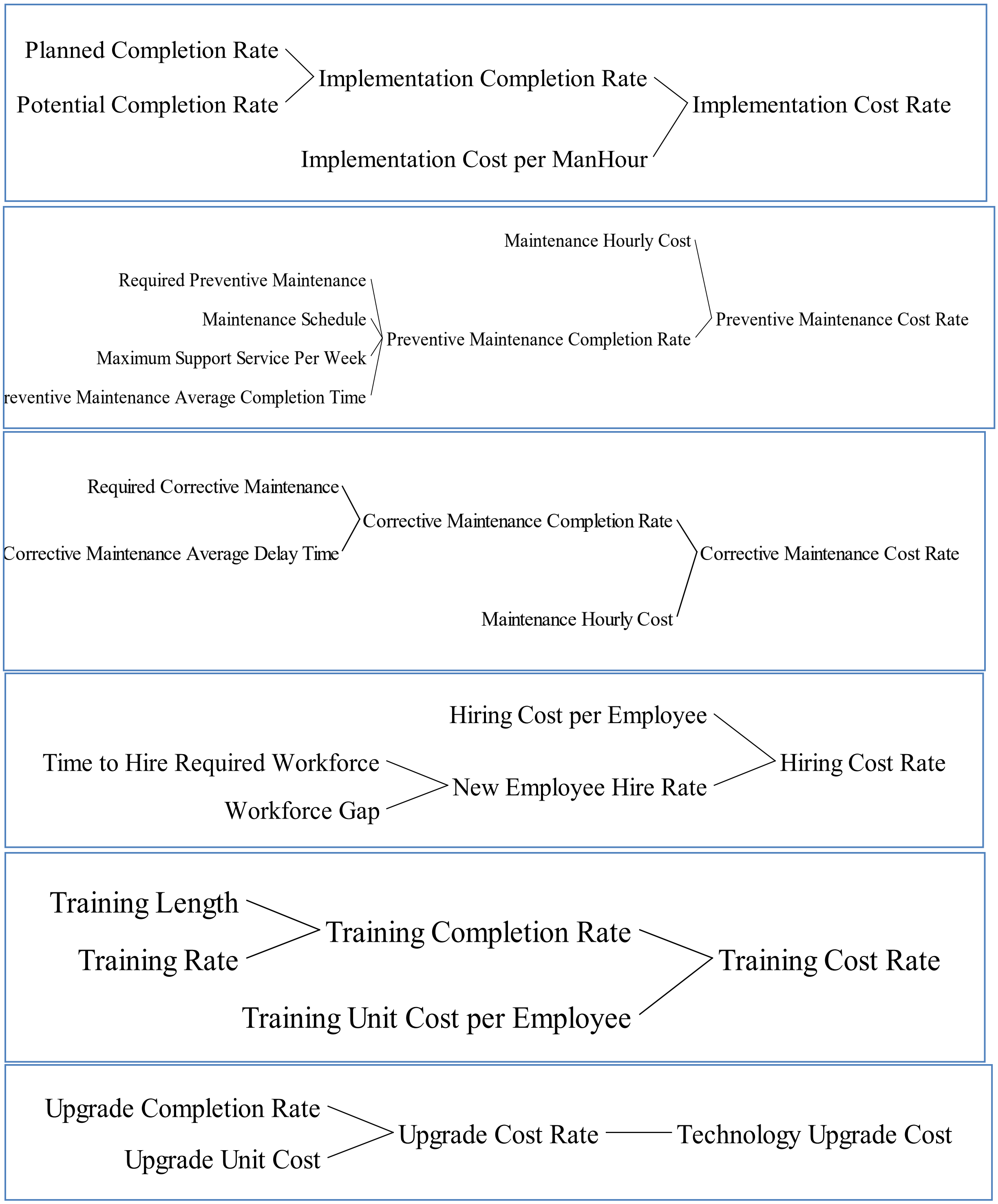


Figure 92. Variables that are used in TOC calculation

The parameters and the initial values of the variables that are used in calculating TOC are listed in Table 27. The case study cost data listed in this table are considered as inputs to the TOC sub-model.

Table 27. The base parameter values/inputs to TOC Sub-model

Cost components based on Case study data (Fryling, 2010)	**Value**	**Corresponding variable in the current SD Model**	**Source**
"Actual training provided per employee per week= Units: Money/person/Week	$100	Training Unit Cost per Employee 4*$100=$400/employee/month	Case study
"Pre-implementation general expenses (furniture, vendor meetings, ads for P/A positions, misc.)"	$56295	Initial value of 'Technology Implementation Cost' stock variable= $56295	Case study
"Pre-implementation hardware maintenance costs"	$341726	Initial value of 'Preventive Maintenance and Service Cost' stock variable= $341726	Case study
"Pre-implementation office & training supplies"	$11059	Initial Value of 'Workforce Training Cost' stock variable ($11059+$649116=$660175)	Case study
"Pre-Implementation Training/Travel Costs"	$649116		
"Pre-Implementation Personal Service Costs"	$43328	Initial Value of 'Workforce Hiring Cost' stock variable= ($43328+$5.2032e+006)	Case study
"Pre-implementation workforce salary costs"	$5.2032e+006		
"Average other costs per week"	$133.45/week	Other cost rate =4*$133.45/month=$533.8/month	Case study
"Initial software purchase price"	$2,009,820	Initial investment/technology purchase price= ($2,009,820+$1,713,665)	Case study
"Initial equipment costs"	$1,713,665		
Average Salary	$1062/week	Hiring Cost per employee (4*$1062/month)=$4248/month	
	$60/hour*	Implementation cost per man-hour $50/hour	Modeler
	$30/hour**	Maintenance hourly cost $30/hour	Modeler
	$70/hour***	Upgrade cost per man-hour	Modeler

*,**, *** Note: The man-hour costs are assumed to be different for implementation, maintenance and upgrade since the required expertise level is different for each type of activities.

The inputs and the initial values of Sub-model 7 variables have been set based on the case study data listed in Table 27. The model outputs will be discussed as follow.

The rate of implementation cost is shown in Figure 93. As can be seen, the occurrence rate of implementation cost has a similar trend to the implementation efforts taken place over time. The implementation cost rate is getting higher at the start of the project and getting lower while reaching the end of the project. Just a quick reminder, that the implementation time plan was 5 years (60 months). As you can see, most of the implementation efforts and accordingly the implementation cost have been occurred during the first 5 years of the 10-year horizon. The total implementation cost and the total workforce training cost occurred over time are illustrated in Figures 94 and 95 respectively.

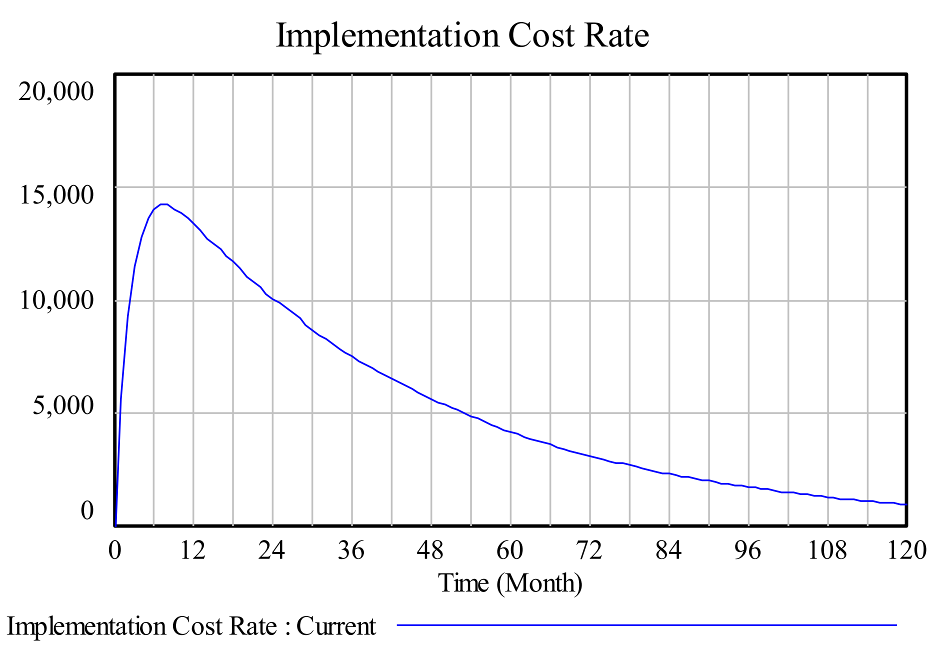


Figure 93. The implementation cost occurrence rate

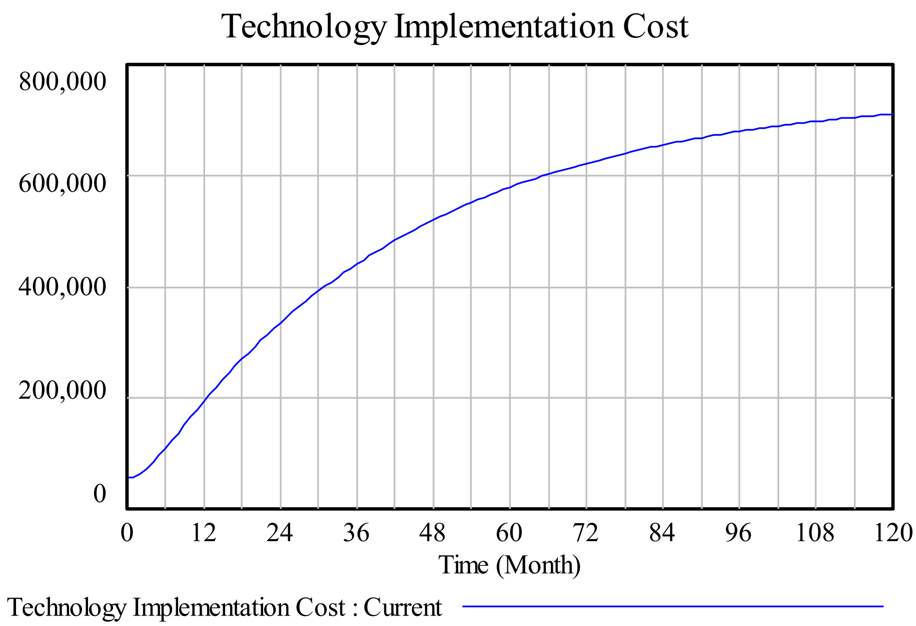


Figure 94. The total implementation cost occurred over time

The step function of the workforce training cost resembles the training schedule. There is one month training every 8 months working cycle. The occurrence rate of hiring cost is shown in Figure 96 and Figure 97 represents the total workforce hiring costs over time. The hiring cost rate has a similar trend as the workforce hiring rate. The hiring rate decreases over time and therefore the hiring cost rate decreases.

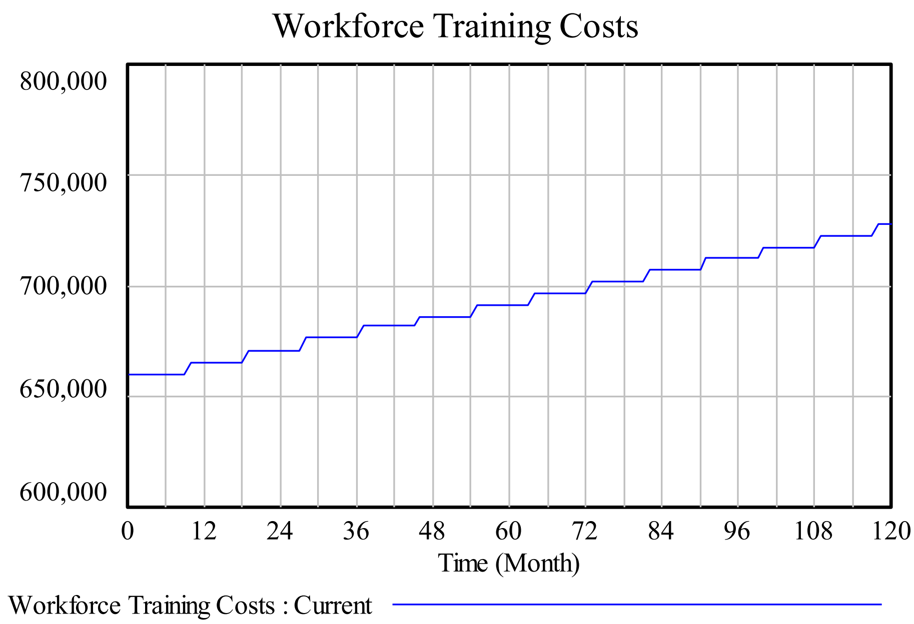


Figure 95. The total workforce training cost occurred over time

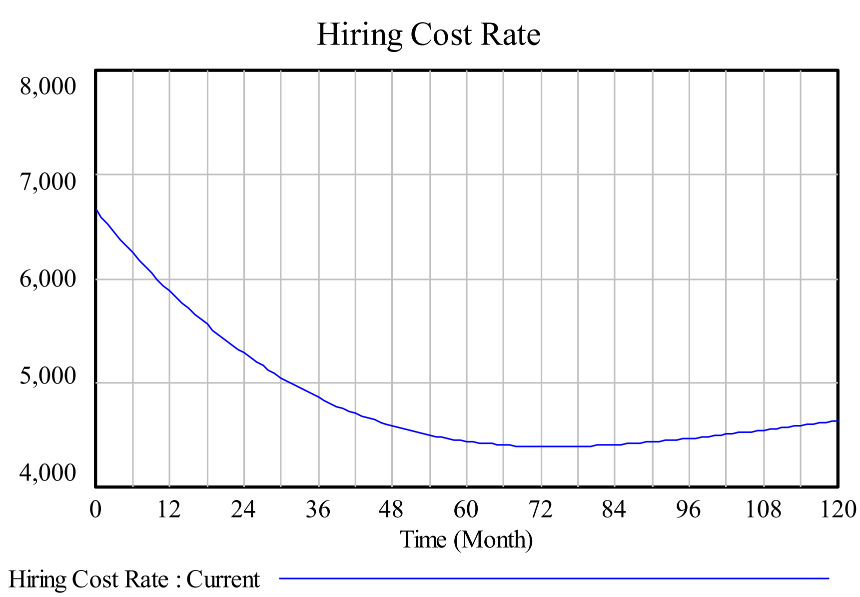


Figure 96. The workforce hiring cost rate

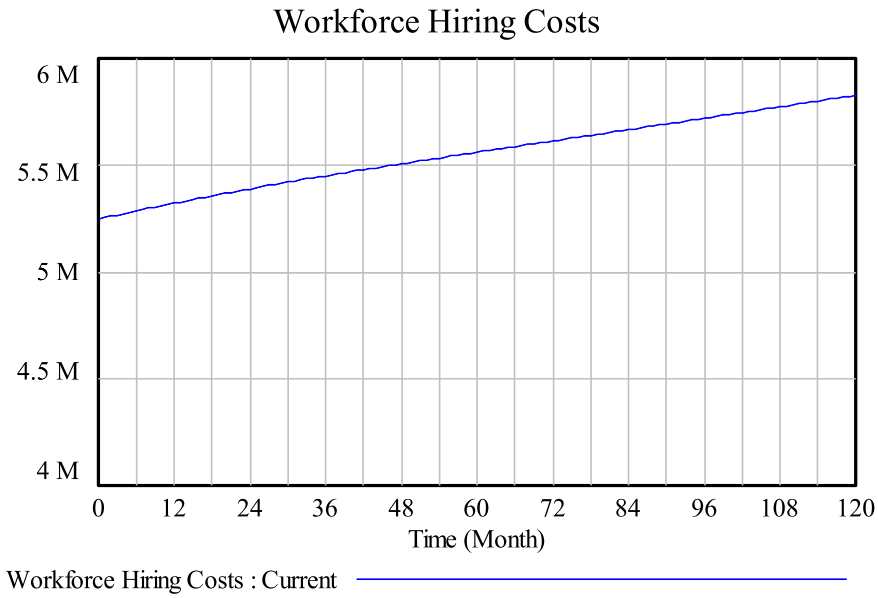


Figure 97. The total workforce hiring cost over time

The total preventive maintenance cost, the occurrence rate of corrective maintenance, the total corrective maintenance cost, and technology upgrade cost are represented in Figures 98-101 respectively. The preventive maintenance cost step function shown in Figure 98 represents the preventive maintenance schedule. There is one preventive maintenance cycle every 12 weeks (3 months) working cycle.

Figure 99 depicts the occurrence rate of corrective maintenance cost. The rate of corrective maintenance increases during the initial technology implementation phase and then it gets stable over the rest of the 10-year horizon. The random patterns shown on the curve is due to the unexpected number of corrective maintenance occurred after implementation phase. The corrective maintenance cost accumulated over time is shown in Figure 100.

The step function shown in Figure 101 depicts the two upgrades implemented over the project life cycle and their corresponding expenses.

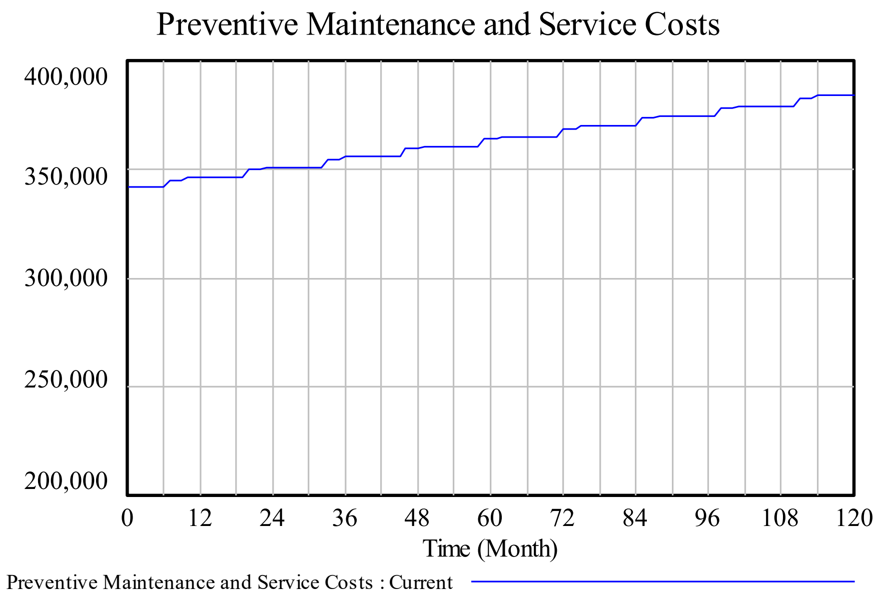


Figure 98. Total preventive maintenance cost over time

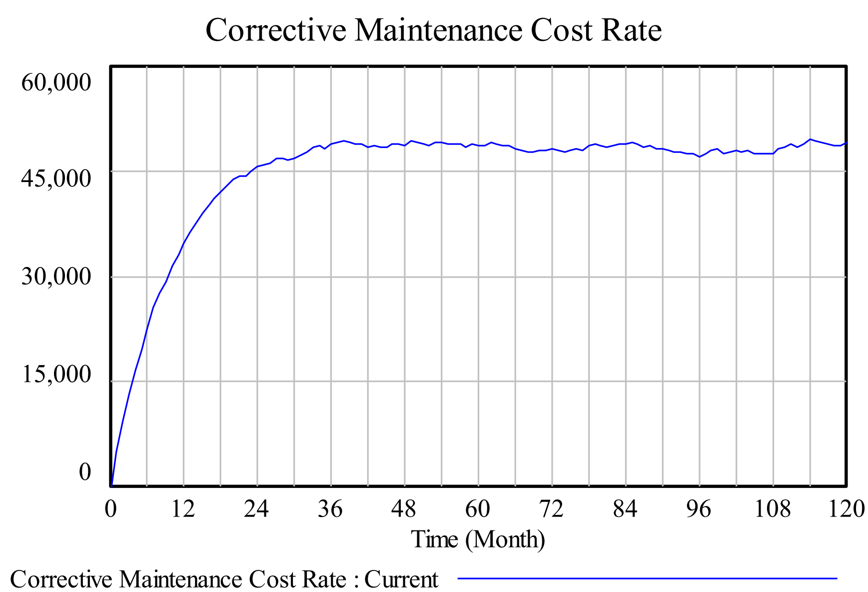


Figure 99. The occurrence rate of corrective maintenance cost

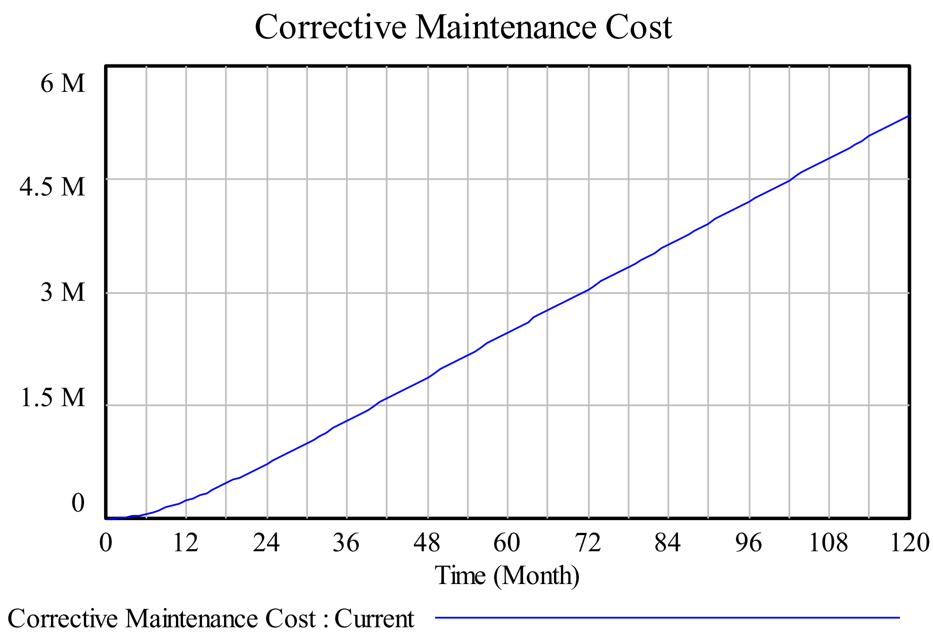


Figure 100. Total corrective maintenance cost over time

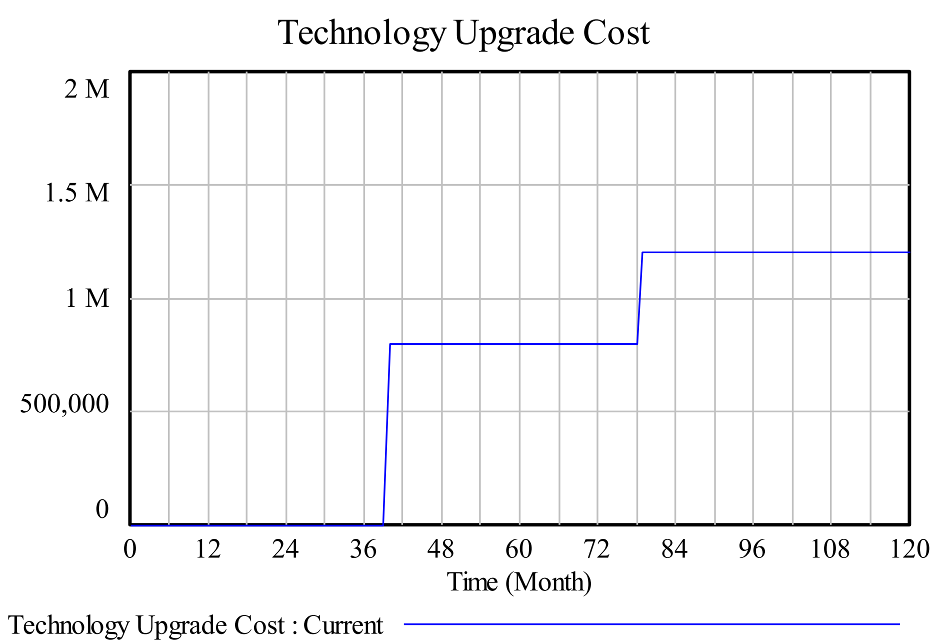


Figure 101. The total technology upgrade cost over time

To provide a better understating of different components of the TOC, all cost elements that have been already discussed are plotted into one graph (Figure 102). Figure 103 shows the summation of the cost elements depicted in Figure 102 along with the software investment and purchase price as total ownership cost of ERP system over 10 year horizon.

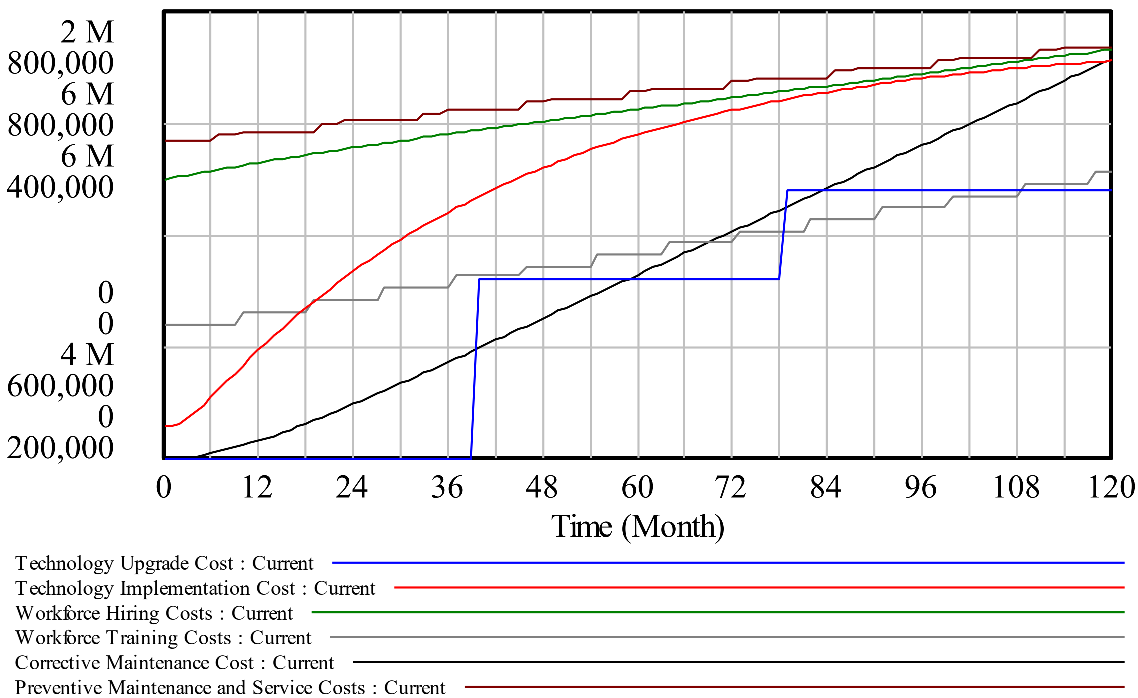


Figure 102. Different components of TOC

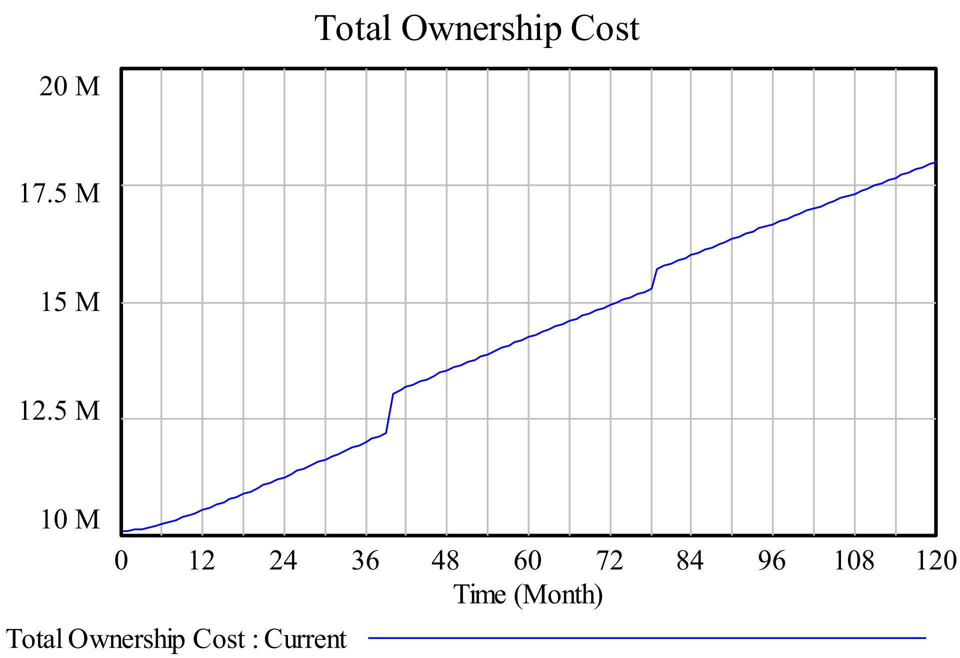


Figure 103. Total Ownership Cost of ERP project

The two jumps in TOC curve show the beginning of the two upgrade cycles occurred in Months 39th and 78th . Figure 104 shows each cost component as percentage of total ownership cost. Only 20% of the total cost is the initial investment/software purchase price. The remaining 80% are costs that occur over the technology life cycle. This clarifies the importance of considering the total ownership cost rather than just the acquisition cost when adopting a new technology.

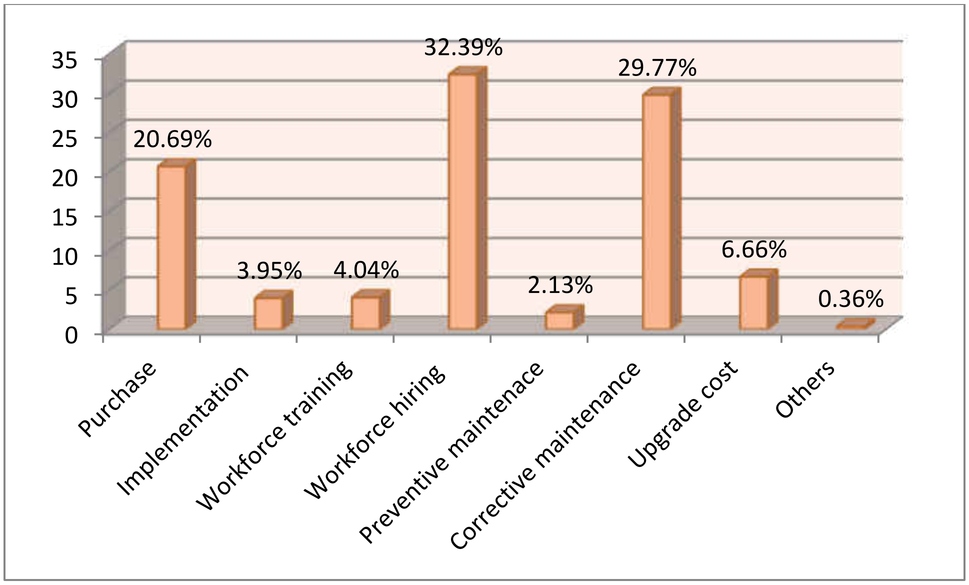


Figure 104. Cost components as percentage of Total Ownership Cost

The results of the model can further be compared with the case study data. Figure 105 shows the actual cost breakdown of ERP project.

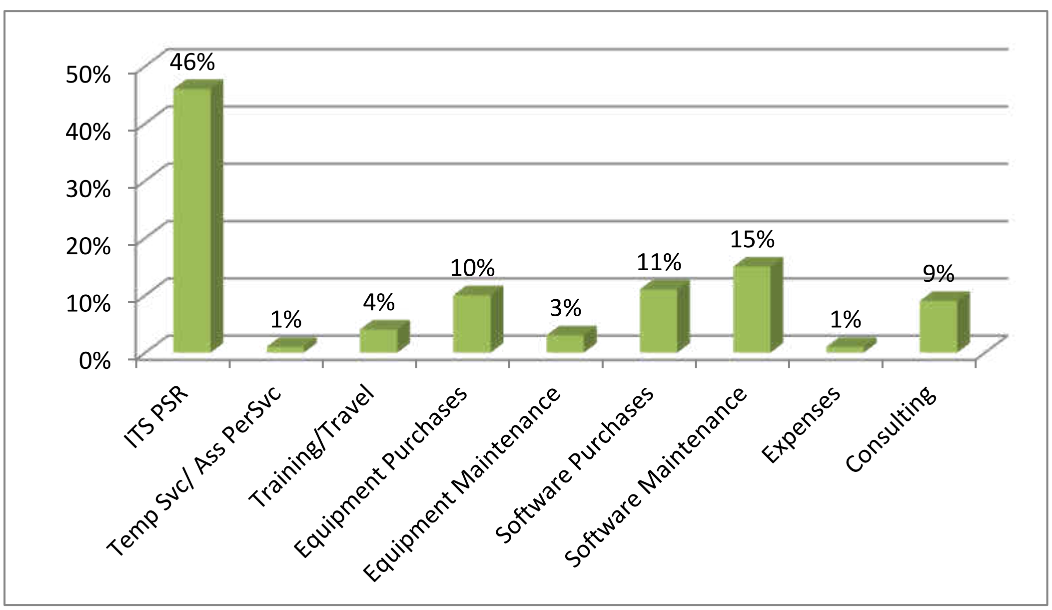


Figure 105. Actual Cost Breakdown of ERP project [redraw from (Fryling, 2010)]

The percentage listed in Figure 104 as model outputs can be compared with the percentage given in Figure 105 as real case study data. Table 28 compares the cost components resulted from the SD model with the cost elements shown in Figure 105.

Table 28. Comparing the results of the SD model with case study data

<table>
<tr><td colspan="3">Case study data (Fryling, 2010)</td><td colspan="4">Current research SD Model</td></tr>
<tr><td>Cost elements</td><td colspan="2">Percentage</td><td>Cost elements</td><td colspan="2">Percentage</td><td>Costs (10-year horizon)</td></tr>
<tr><td>Software Purchases</td><td>11%</td><td rowspan="2">20%</td><td rowspan="2">Purchase and Initial Investment</td><td colspan="2" rowspan="2">20.69%</td><td rowspan="2">$3,723,490</td></tr>
<tr><td>Consulting</td><td>9%</td></tr>
<tr><td>Training/Trave l</td><td colspan="2">4%</td><td>Workforce Training</td><td colspan="2">4.04%</td><td>$727,903</td></tr>
<tr><td>Equipment Maintenance</td><td>3%</td><td rowspan="3">28%</td><td rowspan="3">Corrective Maintenance</td><td colspan="2" rowspan="3">29.77%</td><td rowspan="3">$5,357,510</td></tr>
<tr><td>Software Maintenance</td><td>15%</td></tr>
<tr><td>Equipment Purchases for service and support</td><td>10%</td></tr>
<tr><td>Temporary Service(Temp Svc)</td><td colspan="2">1%</td><td>Preventive Maintenance</td><td colspan="2">2.13%</td><td>$383,889</td></tr>
<tr><td>Expenses</td><td colspan="2">1%</td><td>Other costs</td><td colspan="2"><1%</td><td>$64,056</td></tr>
<tr><td rowspan="3">ITS PSR</td><td colspan="2" rowspan="3">46%</td><td>Implementation cost</td><td>3.95%</td><td rowspan="3">43%</td><td>$711,312</td></tr>
<tr><td>Workforce Hiring</td><td>32.39%</td><td>$5,828,650</td></tr>
<tr><td>Upgrade</td><td>6.66%</td><td>$1,199,100</td></tr>
</table>

4.6. Scenario Analysis

We could conduct some scenario analyses to determine how the decision maker's policies could lead to increases in cost. Three different examples are discussed here.

Example 1: 'Target Workforce'= 100 vs. 200 employees

In the first example, the workforce hiring rates are compared for two cases of setting 'target number of workforce' 100 or 200 employees (Figure 106). Figure 107 shows the pattern by which cost increases over time as a result of targeting 200 employees as the total number of workforce working with the technology.

Example 2: 'Standard Implementation time' 60 months versus 20 months

The second example compares the implementation cost for the case in which the company's plan is to implement the technology in 60 months versus 20 months (Figure 108). The TOC of two cases are compared in Figure 109.

Example 3: 'Technology maturity/Technology Readiness Level' 5 versus 7

The decision maker also could see how the TOC changes as a result of adopting a less mature technology. The change in the TOC is attributed to the upgrade cost. The lower the TRL, the higher the amount of required upgrade efforts and therefore the higher the cost of upgrade (Figure 110).

Figure 106. Comparing new employees hiring rate when target workforce is 100 vs. 200

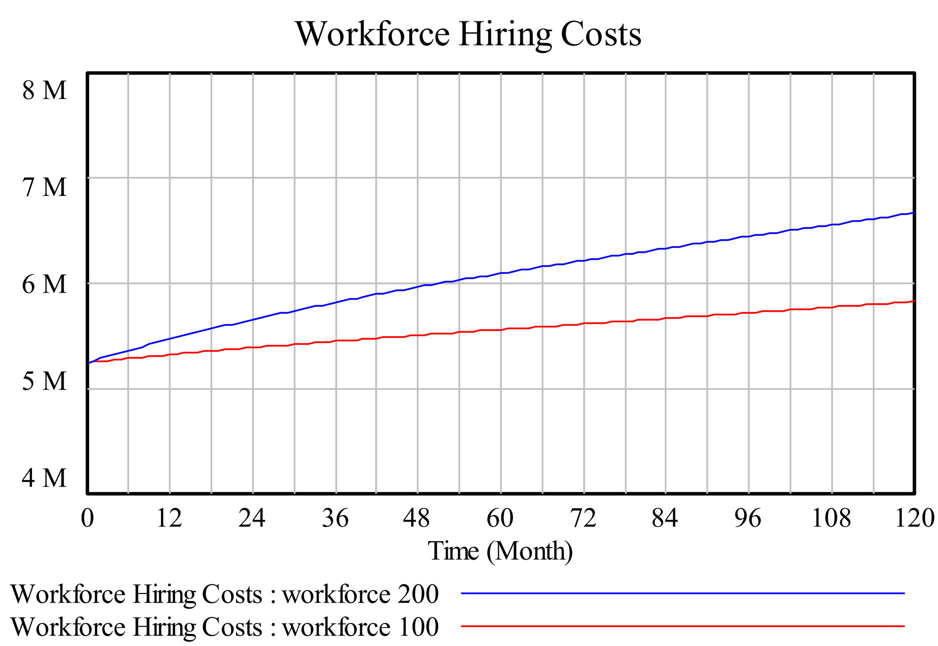


Figure 107. Comparing workforce hiring cost when ‘target workforce’ is 100 vs. 200

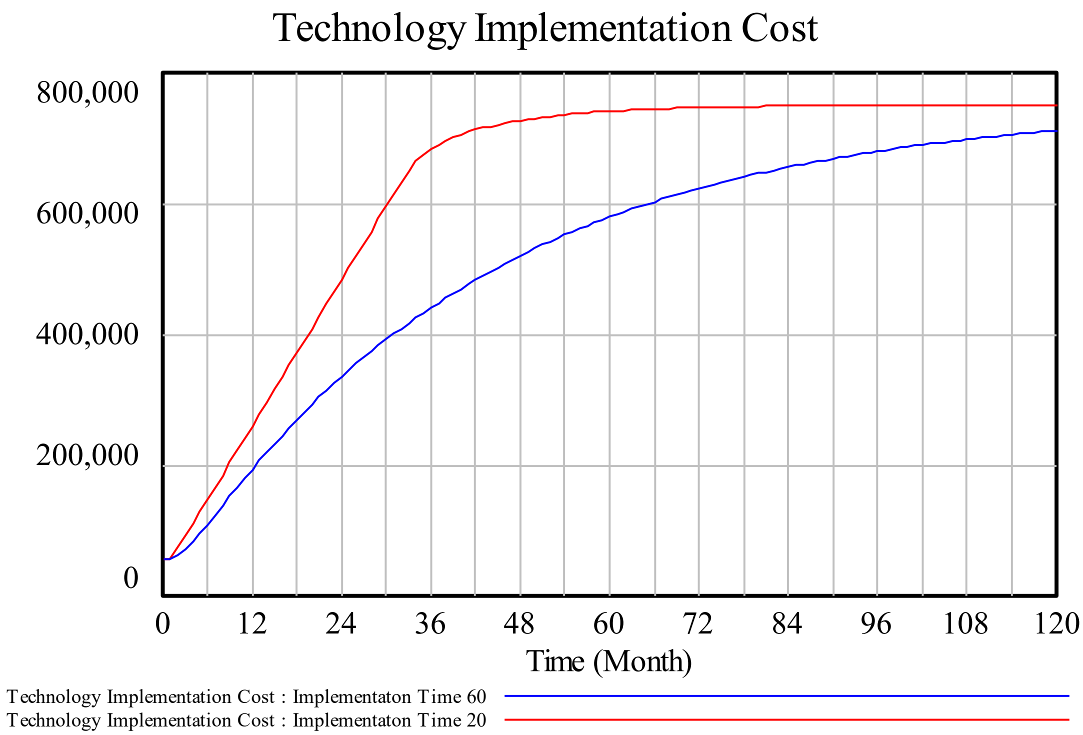


Figure 108. Implementation cost when ‘standard implementation time’ is 60 months versus 20 months

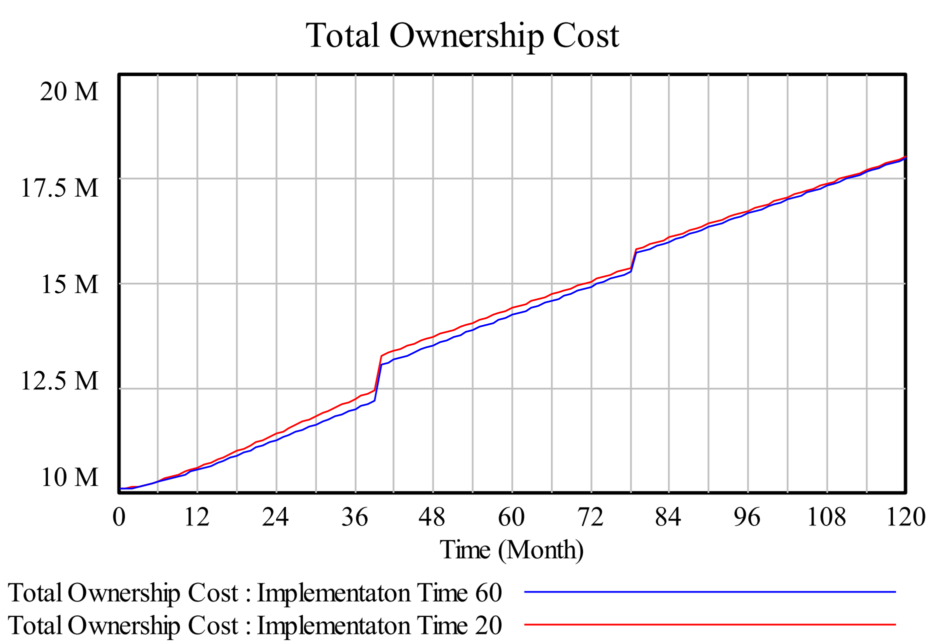
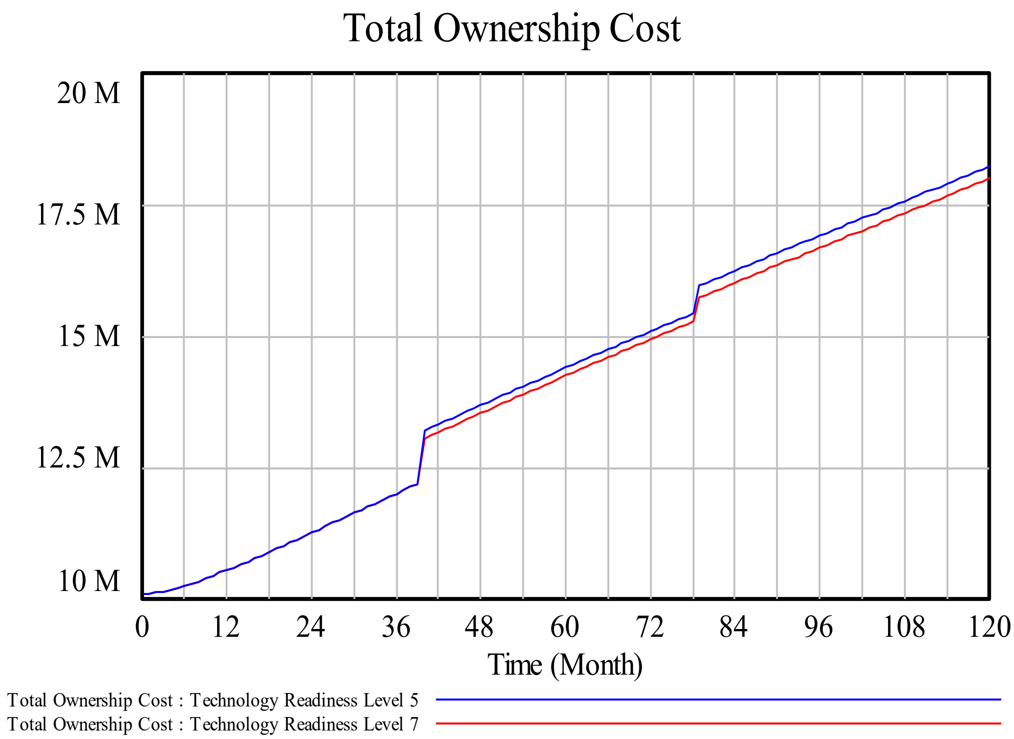


Figure 109. TOC of ‘standard implementation time’ i 60 months versus 20 months



Figure

110. TOC of TRL=7 versus TRL=5

CHAPTER 5
CONCLUSIONS

5.1. Summary of the Results

A systems dynamics model is developed to help decision makers estimate the total ownership cost of adopting a new technology. The model covers three main sub-systems including: (1) technology implementation, (2) system aspect, and (3) human-resource aspect. The 'technology implementation' sub-system models the required efforts during the implementation phase. The 'system aspect' models the service, maintenance and support activities as well as the upgrade efforts conducted during the technology usage and service stage. Moreover, the system aspect analyzes the impact of the technology on the system performance. The 'human-resource' sub-system models the workforce hiring rate related to the new technology and the workforce training process. These three sub-systems have been covered under one SD model consisting of 7 sub-models. Figure 111 show the overall structure of the SD model developed in this dissertation.

Before developing the stock and flow diagram, a Casual Loop Diagram model has been created in Chapter 3. The reinforcing and balancing loops in the CLD model increases the chance of better understanding the major factors that influence the TOC. The CLD provides a basis for creating the SD model.

Chapter 4 discusses the application of the SD for a case of implementing an ERP system. ERP implementation projects are becoming popular. In fact, ERP is one of the fastest growing industries in the software market (Bingi et al., 1999). The point is that a high percentage of ERP projects encounter some sort of failure due to cost or schedule overruns

(Bansal & Negi, 2008). Chapter 4 shows how the SD model developed in this dissertation can be applied to estimate the total ownership cost of the ERP system over a long-term horizon.

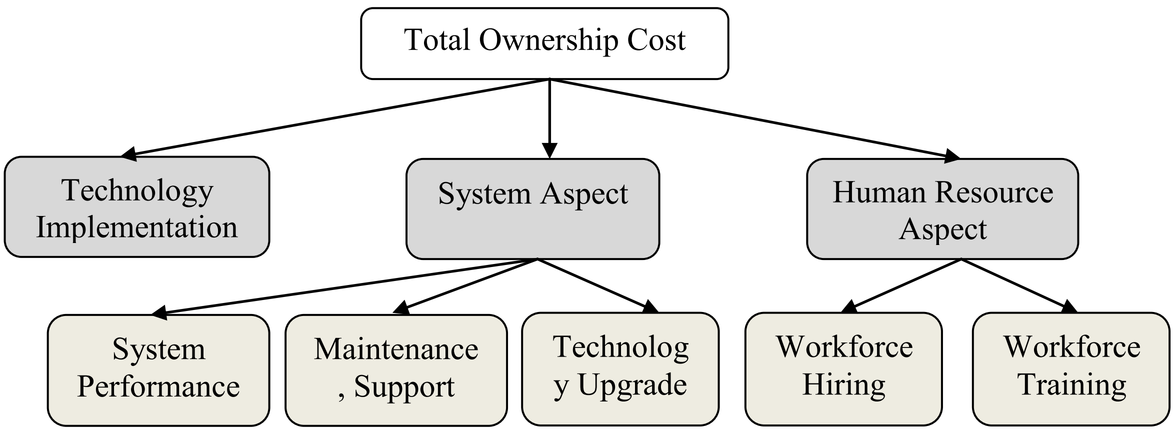


Figure 111. The overall structure of the areas included in the SD model

The model developed in this dissertation provides managers and decision makers an appropriate tool for technology evaluation and trade-off analysis.

5.2. Model Assumptions

The model assumptions are summarized as follow:

- New technology implementation increases the system performance
- The higher the number of technology implementation man-hours, the higher will be the automation level.
- The lower is the Technology Readiness Level (technology maturity), the higher is the amount of required upgrade.

- All newly hired personnel need training
- Training is completed periodically within equal intervals and all trainees pass the training period
- The corrective maintenance operations should be done as soon as they occur as long as we have enough resource to perform the activities
- The work errors are randomly generated in the system based on a user defined statistical distribution adopted based on historical data. The ‘Rate of Error Generation’ is also affected by the technology implementation efforts. The higher the amount of technology implementation efforts, the lower is the work error generation.
- The default values for some model parameters in Chapter 4 are assumed by modeler.

5.3. Model Limitations

The focus of the current dissertation was only on the cost modeling. In the real word, the companies consider both cost and revenue of technology implementation. A technology may bring more cost to the system. On the other hand the benefits may be high enough to convince the amount of budget spending to implement the technology.

Another limitation is that the system dynamics model can never be comprehensive and final. The SD models are based on the modeler assumptions and as the knowledge of the modelers about system increases the SD model can be improved.

The scope of the current SD model has been explained in Chapter 1, there are several other aspects that have not been included in the current model and can be extended in future work.

5.4. Future Research Directions

The model discussed in this dissertation can be extended to include the impact of the market image of the company who sell the technology in selecting a technology scenario. Moreover, the impact of adopting technology on the market image of the company who adopt the technology can also be studied. There are many other factors such as the environmental effect of adopting a technology, the energy consumption, the impact on the surrounding community, and the employees' satisfaction that can be added into the current model. In addition, the companies often need to consider the governmental laws and regulations while adopting a new technology to make sure that the new technology meets the regulation requirements.

In the current research we have assumed that the companies are adopting an already developed technology. There are cases in which the companies are investigating in developing a technology and then go forward to the implementation phase.

The current work can be extended to include the end-of-life phase of the technology. The amount of cost to dispose or recycle a technology should also be considered while adopting a technology.

In addition, sometimes adopting a new technology can also influence the suppliers and customers of a company more than just the quality of the service or goods offered by the company. For example a CRM technology impacts the way a company communicate with its customers and suppliers. Therefore the SD model can be extended to include this aspect as well.

APPENDIX: EXAMPLES OF THE CLD LOOPS

Table 29. The loops that include 'Technology Implementation Time' variable

Variable Name: Technology Implementation Time
Number of Loops in which 'Technology Implementation Time' variable is involved: 4
Loop Number 1 of length 1: Technology Implementation Time →amount of work required to implement Technology **Loop Number 2 of length 4:** Technology Implementation Time → Cost of Implementation → pressure to increase budget →budgeting→technology implementation timeline/goal **Loop Number 3 of length 4:** Technology Implementation Time → Technology efforts implemented → system performance → gap in system performance → technology implementation timeline/goal **Loop Number 4 of length 9:** Technology Implementation Time → Technology efforts implemented →upgrade required upgrade implemented → TRL of technology → technology acceptance by employees →employees satisfaction→system performance →gap in system performance →technology implementation timeline/goal

Table 30. The loops that include 'system performance' variable

Variable Name: system performance
Number of Loops in which 'system performance' variable is involved: 4
Loop Number 1 of length 2: system performance →technology acceptance by employees→employees satisfaction **Loop Number 2 of length 4:** system performance → Pressure to Train → Number of Required Experts → Required Training Hours→Training Frequency **Loop Number 3 of length 4:** system performance → gap in system performance → technology implementation timeline/goal→Technology Implementation Time→Technology efforts implemented **Loop Number 4 of length 9:** system performance → gap in system performance → technology implementation timeline/goal → Technology Implementation Time → Technology efforts implemented→upgrade required→upgrade implemented→TRL of technology→technology acceptance by employees→employees satisfaction

Table 31. The loops that include 'Technology efforts implemented' variable

Variable Name: Technology efforts implemented
Number of Loops in which 'Technology efforts implemented' variable is involved: 3
Loop Number 1 of length 2 Technology efforts implemented →current operational costs→discrepancy of operational costs **Loop Number 2 of length 4** Technology efforts implemented → system performance → gap in system performance → technology implementation timeline/goal → Technology Implementation Time **Loop Number 3 of length 9** Technology efforts implemented→upgrade required→upgrade implemented→TRL of technology → technology acceptance by employees → employees satisfaction → system performance → gap in system performance → technology implementation timeline/goal→Technology Implementation Time

Table 32. The loops that include 'upgrade required' variable

Variable Name: upgrade required
Number of Loops in which 'upgrade required' variable is involved: 2
Loop Number 1 of length 3 upgrade required→upgrade implemented→TRL of technology→ gap in TRL **Loop Number 2 of length 9** upgrade required→upgrade implemented→TRL of technology→technology acceptance by employees → employees satisfaction → system performance → gap in system performance → technology implementation timeline/goal → Technology Implementation Time→Technology efforts implemented

Table 33. The loops that include 'technology acceptance by employees' variable

Variable Name: technology acceptance by employees
Number of Loops in which 'upgrade required' variable is involved: 2
Loop Number 1 of length 2 technology acceptance by employees→employees satisfaction→system performance **Loop Number 2 of length 9** technology acceptance by employees→employees satisfaction→system performance→gap in system performance → technology implementation timeline/goal → Technology Implementation Time→Technology efforts implemented→upgrade required→upgrade implemented→TRL of technology

Table 34. The loops that include ‘technology implementation timeline/goal’ variable

Variable Name: technology implementation timeline/goal
Number of Loops in which ‘technology implementation timeline/goal’ variable is involved: 3
Loop Number 1 of length 4 technology implementation timeline/goal → Technology Implementation Time → Technology efforts implemented → system performance → gap in system performance **Loop Number 2 of length 4** technology implementation timeline/goal→Technology Implementation Time→Cost of Implementation→pressure to increase budget→budgeting **Loop Number 3 of length 9** technology implementation timeline/goal → Technology Implementation Time→Technology efforts implemented→upgrade required→upgrade implemented→TRL of technology→ technology acceptance by employees→employees satisfaction→system performance→gap in system performance

Table 35. The loops that include ‘TRL of technology’ variable

Variable Name: TRL of technology
Number of Loops in which ‘TRL of technology’ variable is involved: 2
Loop Number 1 of length 3 TRL of technology→gap in TRL→upgrade required→upgrade implemented **Loop Number 2 of length 9** TRL of technology → technology acceptance by employees → employees satisfaction → system performance → gap in system performance → technology implementation timeline/goal→Technology Implementation Time→Technology efforts implemented→upgrade required→upgrade implemented

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