A System Dynamics Model of the Development of New Technologies for Ship Systems

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(Abstract)

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System Dynamics has been applied to various fields in the natural and social sciences. There still remain countless problems and issues where understanding is lacking and the dominant theories are event-oriented rather than dynamic in nature. One such research area is the application of the traditional systems engineering process in new technology development. The Navy has been experiencing large cost overruns in projects dealing with the implementation of new technologies on complex ship systems. We believe that there is a lack of understanding of the dynamic nature of the technology development process undertaken by aircraft-carrier builders and planners. Our research effort is to better understand the dynamics prevalent in the new technology development process and we use a dynamic modeling technique, namely, System Dynamics in our study.

We provide a comprehensive knowledge elicitation process in which members from the Newport News Shipbuilding, the Naval Sea Command Cost Estimating Group, and the Virginia Tech System Performance Laboratory take part in a group model building exercise. We build a System Dynamics model based on the information and data obtained from the experts. Our investigation of the dynamics yields two dominant behaviors that characterize the technology development process. These two dynamic behaviors are damped oscillation and goal seeking. Furthermore, we propose and investigate four dynamic hypotheses in the system. For the current structure of the model, we see that an increase in the complexity of new technologies leads to an increase in the total costs, whereas a increase in the technology maturity leads to a decrease in the total costs in the technology development process. Another interesting insight is that an increase in training leads to a decrease in total costs.

Acknowledgements

I think research is a long and enriching walk. The path is sometimes hidden and very difficult to find; at times it is right ahead, well formed and well illuminated. During my research walk, I met a number of intellectuals. They contributed immensely in my research efforts, providing me with most valuable ideas, and helping me find the path every time I used to get lost during my walk.

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Chapter 1. Introduction

1.1 Introduction to the Problem

In today's world, the fact that technology is all-pervasive is well known and realized. Sophisticated and rapidly changing technology is the foundation for a vast majority of products and services we depend on. Nevertheless, although technology is everywhere, its development and real-world applications are still faced with tremendous problems for technology users as well as technology developers and implementers.

The introduction of new technologies leads to increases in costs due to unforeseen system performance degradation, additional downtime, and increased maintenance over a system's life cycle. Within this context, performance refers to the specific measures related to the technical competence or operational capability of the technology. It can be thought of as the degree to which the system reflects (meets or exceeds) operational requirements. Cost overruns form part of one of the important control mechanisms in implementation processes, wherein cost overruns are traded off against technical performance realizations. The traditional systems engineering implementation process can then be thought of as the chief reason for the ineffective development of new technologies. In the traditional implementation of the systems engineering process as far as the management of research and development, emphasis is usually placed on breaking the various activities of the process into discrete and non-dynamic process phases that are isolated in structure and function (Roberts, 1964). This is different from how the process really works, wherein the different stages in the technology development process actually "talk" to each other on a continuous basis. The technology development process consists of upfront research, design, engineering and development, prototype development (or procurement), testing of prototypes (development and non-development), and adaptability studies (impact on interfacing systems and operations) (definition provided by Newport News Shipbuilding and Naval Sea Command Cost Estimating Group experts, and discussed in detail in Chapter 3, Section 3.2.2). These different pieces of the technology development process are closely interrelated with some of the activities occurring later. This provides a control feedback to earlier occurring activities; thus giving a dynamic nature to the whole process.

1.2 Research Objectives

The three main objectives in the research are identified as:

- To build a System Dynamics performance assessment framework model for the technology development process.
- To identify the performance drivers in the technology development process.
- To investigate and understand the dynamic behavior that characterizes the technology development process.

These objectives are pertinent to some of the future challenges in the System Dynamics field. System Dynamics has been applied to various fields in the natural and social sciences. There still remain countless problems and issues where understanding is lacking and the dominant theories are event-oriented rather than dynamic in nature (Sterman, 2000). Within the realm of System Dynamics modeling, understanding the connection between System Dynamics model structure and model behavior in complex model formulations is a big challenge (Richardson, 1996). Profound understanding comes after a prolonged series of model tests of deepening sophistication and insight.

1.2.1 System Dynamics Modeling

The traditional system engineering process addresses the management of technology development by breaking it into discrete parts such as “preliminary design”, “detailed design” and “hardware” (Roberts, 1964). These parts are assumed to be independent and isolated. The parts are still further broken down into subordinate tasks, giving the overall management of technology development a “work breakdown structure” look. There are two primary drawbacks to such an approach. The first is that the dynamic nature of the research and development process is completely ignored. The emphasis is placed upon discrete sets of events, separated in time and lacking any base understanding of the underlying common elements that bind them (Roberts, 1964). The second drawback is that the fundamental systems nature of research and development is ignored. Research and development is essentially an iterative process and is driven by an “action-results-information-new action” methodology. This is disregarded to a large extent in the implementation of the traditional system engineering process. Thus, there is a compelling need to study the dynamics of the process. This research attempts to do that by means of using System Dynamics.

1.2.2 Performance Drivers/ Dynamic Hypotheses

The chief performance metrics (as tracked by Newport News Shipbuilding) in the Technology Development process are cost, risk, schedule, and technical performance.

Newport News Shipbuilding, located and headquartered in Newport News, Virginia, is one of the top ten defense companies in the United States. Newport News Shipbuilding designs, builds, and maintains nuclear powered aircraft carriers and submarines for the U.S. Navy, and also provides maintenance and repair services for a wide variety of military and commercial ships.

Cost is defined as the amount of dollars expended in the various development efforts like project management, design, engineering, and testing and evaluation. Risk is measured as the overall measure of probability of failure of the occurrence of specific desired events. Schedule is defined as the time taken to complete the entire research and development process. Technical performance refers to the specific performance characteristics related to the operational capability of the technology. This research hypothesizes that performance is driven by the dynamic nature of the management of the technology development process. The implementation of the traditional systems engineering approach to the problem fails to "see" the overall integrated picture, making local decisions, which though being good for the specific task at hand, adversely affect overall performance. In contrast, the system dynamics approach takes into account the inherent dynamic nature of the technology development process.

1.2.3 Dynamic Behavior

The fundamental modes of observed behavior in dynamic systems are exponential growth, goal seeking, and oscillation (Sterman, 2000). These modes of behavior are discussed in detail in Chapter 2, Section 2.1.2. **Exponential Growth** arises from self-reinforcing feedback. The greater a quantity is, the greater is its net change (increase or decrease), and this feedback to the process further augments the net change. **Goal Seeking** arises from self-controlling feedback. Within this context, negative feedback loops tend to oppose any changes or deviations in the state of the system; they tend to restore equilibrium and hence are goal seeking. **Oscillation** arises due to negative feedback with significant time delays. Due to time delays in the effects of the actions, corrective action taken to restore the equilibrium state or to achieve the goal of a system continues even after the equilibrium has been reached. Thus the goal is overshot. Corrective action is taken again to correct for the overshot value. One of the objectives of the research is to identify and study the dominant behavior prevailing the dynamics of the technology development process. This behavior could be one of the fundamental modes of dynamic behavior or could conceivably be an interaction of two or more of the dynamic behaviors explained above.

1.3 Motivation for Research

One of the chief motivations for this research was to better understand the system engineering process as it pertains to the technology development process within the scope of new technology implementation in complex systems or organizations. As mentioned earlier, the implementation of the traditional system engineering process fails to address the dynamic nature of the technology development process. Not much work has been done in the past to study the management of technology development from a "dynamics" perspective.

The second motivating factor for this research was the impact of the System Dynamics model on its end users. The Office of Naval Research funded this research and the Navy is going to be the end user of an overall cost-estimating model, of which the System Dynamics model of the technology development process is a part. According to experts from NAVSEA (Naval Sea Systems Command) Cost Estimating Group, Newport News Shipbuilding, and the Office of Naval Research (all of who have taken part during the current group modeling process described later in this Chapter), the Navy has been repeatedly experiencing cost and schedule overruns in large new technology implementation projects on aircraft carriers. Given the current atmosphere of fast-changing technologies, a highest-level system mission for the Navy is to keep upgrading and/or replacing obsolete technology to maintain the highest levels of Mission Preparedness and Condition Readiness (see Glossary, Appendix A). Thus, an objective for the Navy is to better manage the new technology implementation projects in terms of achieving reduced cost and schedule overruns. A certain degree of buy-in to the concept of System Dynamics exists in the Navy. The System Dynamics modeling methodology has been used earlier by Cooper (1980) to model the management of a large ship design and construction program so as to describe its dynamic structure, and as a result it quantified the causes for cost overruns in that program. Additionally since 1996, the Navy has funded the development of the Operations and Support Cost Analysis Model (OSCAM) for its operations and support activities. This is a system dynamics model as well.

1.4 Methodology Overview

Modeling of any system is fundamentally a creative and intensive process. Assumptions are made at various steps of the modeling process. These assumptions need to be tested from the data that are gathered and analyzed from the field, and the models are then revised based on the results. However, there are no particular strictly defined rules of modeling (Sterman, 2000). The involvement of the decision-makers at all the steps of modeling process is very crucial. Their views and active participation are very important for successful and meaningful modeling.

Overview of the Modeling Process

1.4.1 Problem Articulation

The identification of a clear purpose is a very important step. Models are most effective when designed for a small problem/part of the system rather than the whole system itself. Identification of a clear purpose based on a problem in the system helps in making decisions about the framing of the model: what it should include and what should be left out.

Two powerful processes in the initial characterization of the problem are the framing of the reference modes and the definition of the time horizon.

Reference Modes: These are graphs and other descriptive data showing the development of the problem over time. These graphs help the modelers and the decision-makers break free from the narrow event-oriented outlook to a broader system-wide outlook. The reference modes help characterize the problem dynamically, that is, as a pattern of behavior, unfolding over time, which shows how the problem arose and how it might evolve in the future. To develop reference modes, it is important to first identify a time horizon for the problem and to define the variables and concepts that are considered important for understanding the problem.

Time Horizon: This is a very important feature in any problem characterization, wherein the time to study the problem is chosen.

1.4.2 Formulating Dynamic Hypotheses

The next step in the modeling process is to develop a working theory that explains the problem at hand. Since the theory should account for the dynamics of the behavior of the system based on the underlying feedbacks and interactions between its different components, it is called a dynamic hypothesis. The role of the modeler is to elicit the views of the decision-makers involved with the problem. System Dynamics seeks endogenous explanations for phenomena rather than exogenous ones. Explanations based on exogenous (see Glossary (Appendix A)) entities/variables are not of much use as they articulate dynamics of endogenous (see Glossary (Appendix A)) variables in terms of exogenous variables whose behavior was assumed in the first place and cannot be changed. Therefore, an *Endogenous Explanation* for the system in terms of the interactions and feedback relationships among different components/variables is proposed. *Mapping System Structure* and a *Model Boundary Chart Development* (see Glossary (Appendix A)) are important tools used in Step 2; they communicate the boundary of the system and list the key endogenous and exogenous variables of the system respectively. All main subsystems are represented in a *Subsystem Diagram* and the various inputs, outputs, and constraints on the individual subsystems are also drawn. The links/interactions between the different subsystems are also represented.

1.4.3 Formulating a Simulation Model

This next step in the modeling process involves setting up a formal model complete with equations, parameters and initial conditions that represent the system. Given the complexity of systems, real-world experiments are often impractical and infeasible. Therefore, a simulation model needs to be developed in the virtual realm.

1.4.4 Testing and Validation

This step involves the testing of the model as to whether it replicates the behavior of the real-world system. Another important task of testing is to verify whether the variables and parameters of the model have a meaningful concept in the real world. When models are subjected to extreme conditions, their robustness is determined. A model should not just be a means to mirror field data exactly. In addition, elements of the model should have a sound conceptual basis for being included.

1.4.5 Policy Design and Evaluation

Model-based policy analyses involve the use of the model to help investigate why particular policies have the effects they do and to identify policies that can be changed to improve the problematic behavior of the real system. New policies can be formulated and their impact on system performance under alternative scenarios can be evaluated. This is done once the model has been developed and has gained the modeler's and decision-maker's confidence. Interactions between different policies can be complex in many cases and thus need to be properly taken into account.

1.5 Overview of the Results

The System Dynamics Technology Development model was developed and simulated. Newport News Shipbuilding (NNS) and Naval Sea Command (NAVSEA) Cost Estimating Group experts provided the user-input parameters. The model per se is not technology specific as it is mostly process specific. This means that it is generalizable. The results obtained from running the simulation are discussed in detail in Chapter 4. The simulation was run for two years (104 weeks), the time horizon of the technology development process. The simulation results showed two main modes of dynamic behavior. One dynamic behavior was the damped oscillation observed for these variables: Technology Development (TD) Effort, TD Testing Effort, TD Management Effort, and TD Actual Costs Realization rate. This was attributed to the presence of oscillatory structures (in the overall causal loop and stock and flow structures) that are characterized by a set of negative feedback loops (presented in Figure 4.1). The other dynamic behavior observed was the goal seeking observed for the variable Actual Testing Results. The feedback structure causing this type of dynamic behavior is identified in Figure 4.6. The dynamic hypotheses (discussed in detail in Chapter 3, Section 3.2.1) were tested using the model developed in VENSIM Professional 4.0 by varying parameters and observing the changes in the subsequent results from the simulation. Some sensitivity analysis was also performed on the model. Sensitivity analysis was done using three sets of key parameter combinations, namely, (1) very high technology complexity-very immature technology-no training, (2) medium technology complexity-medium mature technology-average training, and (3) very low technology complexity-very mature technology-high training. These were chosen to represent two extreme condition scenarios and an average condition scenario.

1.6 Organization of the Thesis

The thesis is organized in five chapters, including the first chapter which is an introduction to the research. Chapter 2 is a literature review in the fields of System Dynamics, Knowledge Elicitation and Group Modeling, and New Technology Development and Integration. The System Dynamics model and the modeling process are presented in Chapter 3. The results obtained from the model and the testing, sensitivity analysis, validation and verification completed are presented in Chapter 4. Chapter 5 concludes with an overview of the results, some policy suggestions, and a discussion on the future research areas.

Chapter 2. Literature Review

2.1 System Dynamics

> "The system approach is the modus operandi of dealing with complex systems. It is holistic in scope, creative in manner, and rational in execution. Thus, it is based on looking at a total activity, project, design, or system, rather than considering the efficiency of the component tasks independently. It is innovative, in that rather than seeking modifications of older solutions to similar problems, new problem definitions are sought, new alternative solutions generated, and new measures of evaluation are employed if necessary" (Drew, 1995, pp. 4).

2.1.1 Origins and Fundamental Notions of System Dynamics

System Dynamics (SD) is a policy modeling methodology based on the foundations of (1) decision making, (2) feedback mechanism analysis, and (3) simulation. Decision-making focuses on how actions are to be taken by decision-makers. Feedback deals with the way information generated provides insights into decision-making and effects decision-making in similar cases in the future. Simulation provides decision-makers with a tool to work in a virtual environment where they can view and analyze the effects of their decisions in the future, unlike in a real social system.

Forrester first used the concept of System Dynamics in an article entitled “Industrial Dynamics: A Major Breakthrough for Decision Makers” which appeared in *Harvard Business Review* in 1958. His initial work focused on analyzing and simulating micro-level industrial systems such as production, distribution, order handling, inventory control, and advertising. Forrester expanded his system dynamics techniques in *Principles of Systems* in 1968, where he detailed the basic concepts of system dynamics in a more technical form, outlining the mathematical theory of feedback system dynamics (Forrester, 1968).

A stark feature of modern times is continuous change. Changes in existing elements often encounter resistance from people themselves (for whose betterment the changes were sought in the first place). The problems we face today are often too complex and dynamic in nature, i.e., there are many factors and forces in play that we do not comprehend easily. Also, these factors and forces themselves are very dynamic in nature. *Systems thinking* is advocated by many “thinkers” who advocate holistic thinking and the conceptualization of “systems” wherein “everything is connected to everything else”. Systems Dynamics is an approach whose main purpose is to understand and model complex and dynamic systems. It employs concepts of nonlinear dynamics and feedback control, concepts that will be discussed in detail shortly.

<u>Feedback</u>

Actions taken on an element in a system result in changes in the state of the element. These, in turn, bring about changes in other linked elements, and the effects may trail back to the “first” element. This is called feedback. Feedbacks are of two types: 1) Positive or self-reinforcing, which amplify the current change in the system; and 2) Negative or self-correcting, which seek balance and provide equilibrium by opposing the change taking place in the system. Complex systems are “complex” because of the multiple feedbacks/interactions among the various components of the system.

2.1.2 SD Behaviors

The feedback structure of a system generates its behavior. Most dynamics observed in systems fall under three fundamental modes of behavior: exponential growth, goal seeking, and oscillation (Sterman, 2000). These modes of behavior are shown in Figure 2.1. *Exponential Growth* arises from positive or self-reinforcing feedback. The greater a quantity is, the greater is its net change (increase/decrease), and this is the feedback to the process that further augments the net change. Thus this is a self-reinforcing feedback and there is an exponential growth/decline. *Goal seeking behavior* arises from negative or self-controlling feedback. Negative feedback loops tend to oppose any changes or deviations in the state of the system; they tend to restore equilibrium and hence are goal seeking. The rate of change diminishes as the goal is approached, such that there is a smooth attainment of the goal/equilibrium state of the system. *Oscillation* arises due to negative feedback with significant time delays. Corrective action to restore an equilibrium state or to achieve the goal of the system continues even after the equilibrium has been reached due to time delays in identifying the effects of the actions on the system. Thus the goal is overshot. Corrective action taken again (negative feedback loop) leads to undershooting and hence oscillation. The principle that behavior is a result

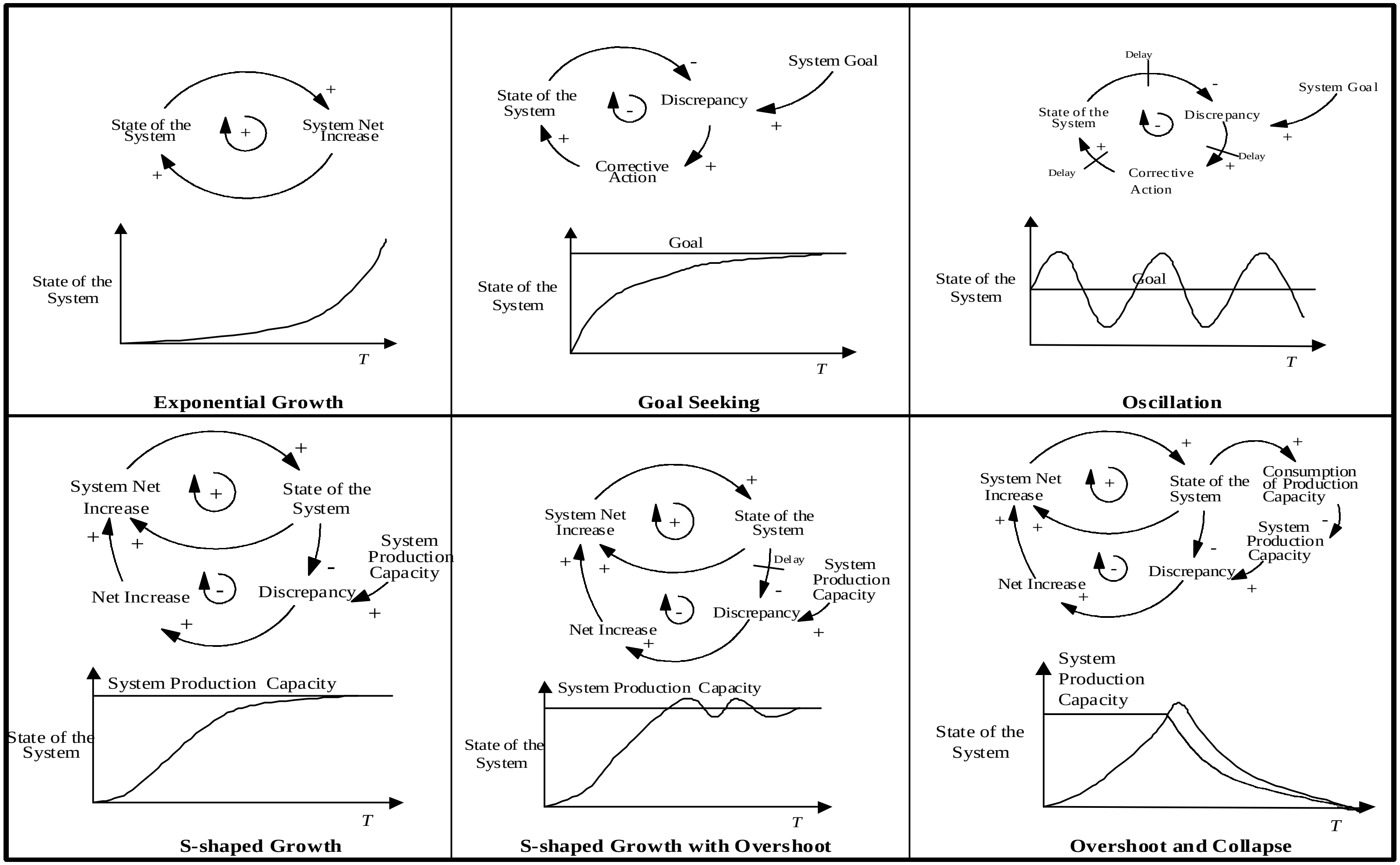

Figure 2.1 System Dynamics Structures and their Behavior (Sterman, 2000)

of the structure of the system enables a discovery of the system structure (its feedback loops, non-linear interactions) by observing the behavior of the system. Therefore, when the pattern of behavior is observed, conclusions can be drawn about the dominant feedback mechanisms acting in the system.

Nonlinear interactions among the three major feedback structures give rise to other complex patterns of behavior of the systems (Sterman, 2000). *S-shaped growth* arises when there is a positive feedback initially, and later negative feedback dominates, leading to attainment of equilibrium by the system. *S-shaped growth with overshoot* occurs when, after an initial exponential growth phase, negative feedback with time delays kicks in. In this case, the system oscillates around the equilibrium state. *Overshoot and collapse* occurs as a result of the equilibrium state itself declining after the exponential growth phase has commenced, and negative feedback is triggered. Since the equilibrium declines, a second negative feedback gets activated, wherein the system approaches the new equilibrium state.

2.1.3 Causal Loop Diagrams

The feedback structure of complex systems is qualitatively mapped using causal diagrams. A Causal Loop Diagram (CLD) consists of variables connected by causal links, shown by arrows. Each link has a polarity. A positive (denoted by "+" on the arrow) link implies that if the cause increases (decreases), the effect increases (decreases) *above (below) what it would otherwise have been*. A negative (denoted by "-" on the arrow) link implies that if the cause increases (decreases), the effect decreases (increases) *below (above) what it would otherwise have been* (Sterman, 2000).

For example,

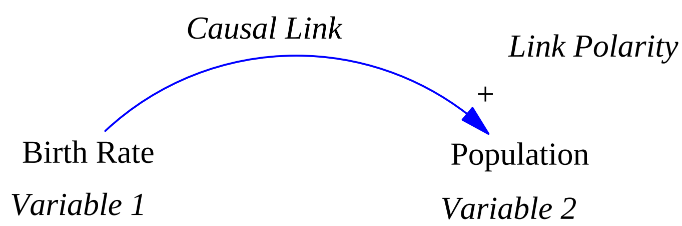

Figure 2.2 Example of a Causal Link

Causal loops are immensely helpful in eliciting and capturing the mental models of the decision-makers in a qualitative fashion. Interviews and conversations with people who are a part of the system are important sources of quantitative as well as qualitative data required in modeling. Views and information from people involved at different levels of the system are elicited, and from these, the modeler is able to form a causal structure of the system.

2.1.4 Stocks and Flows

Causal loops are used effectively at the start of a modeling project to capture mental models. However, one of the most important limitations of the causal diagrams is their inability to capture the stock and flow structure of systems. Stocks and flows, along with feedback, are the two central concepts of dynamic systems theory. Stocks are accumulations as a result of a difference in input and output flow rates to a process/component in a system. Stocks give the systems inertia and memory, based on which decisions and actions are taken. Stocks also create delays in a system and generate disequilibria (Sterman, 2000).

<u>Notation</u>:

All stock and flow structures are composed of stocks (represented by rectangles), inflows (represented by arrows pointing into the stock), outflows (represented by arrows pointing out from the stock), valves, and sources and sinks for flows (represented by clouds).

General Structure

Figure 2.3 General Structure of a Stock and Flow

<u>Mathematical Representation of Stocks and Flows</u>

$$\text{Stock}(t) = \text{Stock}(t_0) + \int [\text{Inflow}(t) - \text{Outflow}(t)]\, dt$$

Stocks are the state variables or integrals in the system. They accumulate (integrate) their inflows less their outflows. Flows are all those which are rates or derivatives. If a snapshot of a system was taken at any instant of time, what would be seen is the state of different processes or components of the system. These are the stocks in the systems. The inflows and outflows are what have been frozen and so cannot be identified. Stock and flow networks undoubtedly follow the laws of conservation of material. The contents of the stock and flow networks are conserved in the sense that items entering a stock remain there until they flow out. When an item flows from one stock to another, the first stock loses exactly as much as the second one gains.

Auxiliary variables

Auxiliary variables are often introduced in stock and flow structures to provide a better understanding. Auxiliary variables are neither stocks nor flows; they are functions of stocks and exogenous inputs (see Glossary (Appendix A)). They are variables used for computational convenience.

The contribution of Stocks to Dynamics is multifold: (1) Stocks denote the state of a particular element in the system, and based on this information, decisions can be made or actions can be taken. (2) They provide the system with inertia and memory. For example, intangible stocks like beliefs and memories characterize our mental states. (3) They induce delays in the system. A stock or accumulation occurs when the output lags the input to a process, and whenever this happens, delays occur. (4) Stocks decouple inflow from outflow. Inflows and outflows are controlled or decided upon by different people/resources in the system. A difference in inflow and outflow rates creates disequilibria.

2.2 Knowledge Elicitation and Group Modeling

The topic of group discussion and decision-making is of significant interest vis-à-vis SD model building as system dynamics modelers have done intensively interactive modeling with decision-makers for a long time. SD modelers typically rely on multiple, diverse streams of information to create and calibrate model structure. According to Vennix et al. (1992), the most productive source of information in these streams is the information contained within the mental models of the key actors in a system, and accessing the minds of these experts and actors in a system is largely an art. The academic preparation of SD modelers rarely includes formal training to help build formal skills in eliciting information for model building.

Some formal work in the field of model building process and types of tasks to be carried out with decision-making groups has been done. Richardson and Pugh (1981) defined seven stages in building a SD model: problem identification and definition, system conceptualization, model formulation, analysis of model behavior, model evaluation, policy analysis, and model use or implementation. Roberts et al. (1983) proposed an almost identical set of six steps to organize their model-building approach. Problem identification and definitions includes going through the steps of formally defining the problem, identifying a time horizon, defining the level of abstraction and aggregation, and defining the system boundaries. It also includes what should be included within the purview of the system and what should not. System conceptualization consists of establishing the relevant variables in the system, mapping relationships between the variables, determining important causal loop feedback structures, and generating dynamic hypotheses as proposed explanations of the problem. Model formulation entails developing mathematical equations and quantifying the model parameters. In the analysis or evaluation stage, the model is checked for logical values and sensitivity analyses are conducted. Policy analysis includes conducting experiments on the model by changing key policies and observing and analyzing the resulting changes in the model outputs.

Eliciting information residing in the mental models of the decision-makers of the system is facilitated by two important techniques: divergent thinking and convergent thinking (Vennix et al., 1992). Divergent thinking implies different key persons of the system coming up with their opinions or thoughts on issues, as an individual exercise. It is most helpful and meaningful in the problem definition and model conceptualization phases where an individual or a group is attempting to determine what factors or variables to include or exclude from a system's boundary. One of the approaches to facilitate divergent thinking in the modeling process is called the "Nominal Group Technique" approach, developed by Andre P. Delbecq and Andrew H. Van de Ven in 1968, and first tested in 1969. It began as a technique to enhance the effectiveness and efficiency of program planning in health services. It is now used extensively in areas of productivity measurement systems development, strategic planning, and strategy implementation.

Sink (1983) delineated a five-staged structured process through which the Nominal Group Technique helps groups generate ideas and reach consensus: (1) Individual silent generation of ideas, (2) Individual round-robin feedback from group members of their ideas, which are recorded on a flip chart, (3) Group clarification of each recorded idea, (4) Individual voting and ranking on priority ideas, and (5) Discussion on group consensus results and focus on potential next steps. The last of the above stages essentially is the "convergent thinking" exercise, wherein the group works together on the ideas it has come up with, to build a consensus on approach and various issues.

Although much experience has been gained in the area of modeling as learning, it seems that building models with decision-making groups is still more art than science. In recent years, significant interest and efforts have been concentrated on coming up with a more formal approach to the craft of group model building. Andersen, Richardson, and Vennix (1997) talk about "adding more science" to the craft of model building in SD. One of the important elements they discuss are the various goals of group model building: (1) Mental model alignment of the various key people involved in the system, (2) Creating agreement (consensus) about a policy or decision, and (3) Generating commitment with a particular decision.

In their efforts to formalize the modeling process, Andersen and Richardson (1997) proposed a set of scripts for group model building. They use the term "scripts" to represent small behavioral descriptions of facilitated group exercises that move a group forward in a systems thinking process or activity. The expected results at the end of a modeling group activity are: (1) A precise description of the problem to be solved; (2) A stakeholder analysis in which the key players (both the top management personnel and the modeling team who will execute the model) of the target organization are identified;

and (3) A sketch of the model structure. In order to obtain these results, they delineate a series of “scripts”.

PLANNING FOR THE GROUP MODELING MEETING

The planning phase for the group modeling sessions involves making a detailed and careful script of the entire process. The main issues in building the scripts are:

1) Goal Setting:

Interviews with key managers or “gatekeepers” are conducted to gain an initial understanding of the problem. A gatekeeper is a contact person within the target organization who helps select the appropriate people within the organization, helps plan the modeling sessions, and works closely with the modeling group. The audience role and purpose needs to be clarified by identifying the key stakeholders (preferably from top management/decision makers), the experts in the technology, and the internal modeling team. The session products or the expected deliverables at the end of the session need to be clarified.

2) Logistics:

An appropriate room layout for the modeling session needs to be planned, where every member can see everyone else. Richardson and Andersen (1995) advise assigning two to five roles in the session to individuals, such as facilitator, modeler, process coach, recorder, and gatekeeper. A facilitator conducts and manages the group session, with an aim of facilitating the expression of views of all the key players involved in the modeling exercise. A modeler’s role is to be a keen observer in the modeling exercise by listening and capturing the ideas and views of different session members and to provide inputs on the technical modeling aspects as and when required. A process coach ensures that the modeling group does not deviate substantially from the modeling agenda, and provides feedback to the facilitator in terms of the effectiveness of the modeling process being followed. A recorder takes detailed notes on the various session activities and developments. A gatekeeper is a contact person within the target organization who helps select the appropriate people within the organization, helps plan the modeling sessions, and works closely with the modeling group.

3) Types of Group Task Structures:

During the modeling session, tasks can vary from divergent (brainstorming) tasks to ranking and evaluating tasks, to integrative or design-oriented tasks. Divergent tasks are ones in which different key personnel of the target organization come up with their opinions or thoughts on issues about the system and the problem as an individual exercise. In convergent tasks, the group works on the ideas it has come up with to build a consensus on an approach and on various issues. The group also ranks and evaluates different emerging ideas by voting.

Ford and Sterman (1998) additionally provide a structured method for knowledge elicitation from the decision-makers. The first step involves the creating of an environment in which elicitation will occur. This is achieved by a brief description of the model purpose, the major subsystems, the roles of each subsystem and the relationships to be characterized. The next step is to focus on one relationship at a time. The facilitator describes the relationship operationally by identifying the input and output variables (with units of measure) which the relationship describes. The next step is a visual description whereby the experts visualize and imagine the flow of inputs and outputs in the relationship. The purpose of this step is to activate, bound, and clarify the experts' mental images of the relationship (Ford and Sterman, 1998). The next step in the elicitation process is to obtain a graphical description of the relationship by means of graphical plots of the output variables versus the input variables in the relationship. The next step is to have a group discussion on the relationships as characterized by different experts. The aim of such a discussion is to better understand the relationship and not so much as to resolve the differences in the different characterizations of the relationship by different experts.

2.3 Real World versus Virtual World

Throughout this research, the relationship between the real and virtual world has been constantly kept in mind. A modeling and simulation effort should have the primary goal of establishing policies or procedures that can be implemented in the real world. However, many modelers and performance measurement teams often lose sight of the real world implementation. It was important for everyone involved with this research to understand the relationship between the real and virtual worlds and the strengths and weaknesses of each. Figure 2.4 shows the interactions between the virtual and the real world.

In the virtual world the system structure is known and controllable. Information is complete, accurate and the feedback is almost instantaneous from actions within the system. Decisions and policy implementations are usually perfect. The goal of the virtual world is learning (Sterman, 1994).

The goal of real world systems is performance. In the real world, systems often have unknown structures, long time delays, and experiments are uncontrollable. Given these factors, often policies that are implemented into the real world system do not realize their full impact until long after the policy is implemented. Information from real world systems is often incomplete due to long delays, and data is often biased or contains errors (Sterman, 1994).

The erroneous or incomplete data often leads to inaccurate mental models. Mental models serve as the basis for one's beliefs of how a system works. Receiving inaccurate or incomplete data about the system often leads to erroneous beliefs of how the system performs (Sterman, 1994). This condition leads to the establishments of rules, system structure, or strategies that govern the system in a sub-optimal manner. When strategies, policies, structure, or decision rules are inaccurate, decisions made within the system are also incorrect. This creates negative consequences for the system processes and leads to a vicious circle for declining system performance. However, modeling offers the decision-maker with the opportunity to learn about system behavior, ask pertinent questions, collect accurate information and define more effective policies. The constant and effective interface between the virtual and real world allows for better decision-making over the long run.

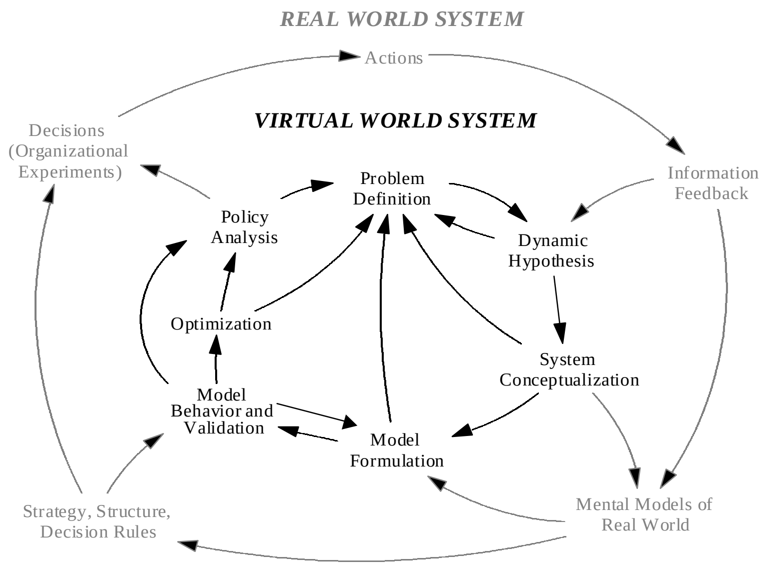

Figure 2.4 The Interaction of the Virtual and Real World (Triantis and Vaneman, 2000)

Today, given the complex systems within which new technologies are implemented, effective incorporation and implementation of a new technology poses a formidable challenge in almost all industries and organizations. There exists a vast body of literature on the research efforts in new technology implementation processes and issues.

2.4 New Technology Implementation: Development and Integration

> " 'They did not anticipate that the steel axe would lead to more sleep, prostitution, and a breakdown of social relationships and customs.

> Change agents frequently do not sense or understand the social
> meaning of the innovations that they introduce.'
> Rogers (1995), speaking from Sharp (1952: 69-92)

The preceding quotation illustrates the possible consequences when implementers do not anticipate long-term and side effects of a change. The implementers of the steel axe did not foresee the consequences of their introduction of a relatively simple technology. These missionaries believed that the aboriginals would use steel axes as they had their stone ones (Rogers, 1995). The missionaries did not anticipate that this new technology would evoke new understandings of the technology. Today, given the complex systems within which new technologies are implemented, it is even more difficult for implementers of modern technologies (e.g., flexible manufacturing systems, customizable voice and electronic mail systems, biotechnology) to anticipate users' understanding of the technology and the side-effects of the technology (e.g., Weick, 1990). "
-- quoted in part from Griffith (1999, pp. 473).

Effective incorporation and implementation of a new technology poses a formidable challenge in almost all industries and organizations. Often new technologies hold tremendous promise for enhancing operational efficiency and effectiveness in organizations. Much of this potential, however, is never realized, much more often due to poor technology management rather than technical shortcomings. According to Griffith et al. (1999), a major cause of failure of technology innovations is the inability of organizations to develop effective implementation processes. Thus, project managers have the responsibility to create a concept of how implementation funding, technology integration, and support are interrelated.

Most of the work in literature on new technology implementation is focused on implementation issues in manufacturing processes. Most of the research is oriented on human-issues, which essentially means that it seeks to explore how humans react at a social level to the implementation of new technology in their work environment. Most of the literature focuses on whether certain variables such as participation of the topmost level managers makes a difference, and does not focus on the nature of the underlying process of technology implementation. Goodman and Griffith (1991) explored new technology implementation with a process approach view. However, their study focuses on manufacturing organizations. They identify five critical processes in technology implementation, namely, socialization, commitment, reward allocation, feedback/redesign, and diffusion. Socialization refers to the processes by which individuals acquire skills about the new technology. Commitment refers to the binding of the individual in the organization to certain behavioral acts relevant to the technology. This may be in the form of educating the workers about the long-term benefits of the technology and inculcating in them a sense of loyalty for need for the implementation of the new technology. Reward allocation refers to the allocation of different types of benefits and incentives to workers who are associated with the new technology implementation. Data are collected once the technology is in place and in the transient operating phase. The transient operating phase of a new technology is the operating phase after the technology has been introduced in the organization and before it has achieved its full working potential. Based on feedback, redesign activities are undertaken to enhance the operation of the new technology. Most new technologies follow the path of evolution in structure, process, and outcomes. This means that as the technology spreads throughout the organization, one would expect the creation of a social environment for the emergence of value consensus on the new technology. The technology spread, or so-called "diffusion," also signals its legitimacy and acceptance into the overall structural fabric of the organization.

All literature cited to this point looks at technology as Commercial-Off-The-Shelf products that are implemented in complex organizations. Almost no literature exists that explores the development process of a technology and then its integration into a complex system. The development process of a technology consists of various research and development (R&D) activities. The process includes project management, research, requirements definition, specification development, engineering, modeling and simulation, drawing development, hardware and software development, system architecture development, and testing (Iansiti, 1997). There is a lack of a system level understanding of the dynamics of the technology development process, both from management and process perspectives.

There are some references in the literature on work done in the area of the SD approach applied to project management issues. The SD approach to project management is based on a holistic view of the project management process and focuses on the feedback processes that take place within the project system. Cooper (1980) developed a SD model at Pugh-Roberts Associates that was the first major practical application of System Dynamics to project management. It was used to quantify the causes of cost overruns in a large military shipbuilding project. Further versions of the model were developed and used to support a strategic analysis of prospective shipbuilding programs. One of the major novelties of this work was the concept of the *rework cycle*, a structure at the core of the model that explicitly incorporates the concepts of undiscovered rework, time to discover rework, work quality, and varying staff productivity.

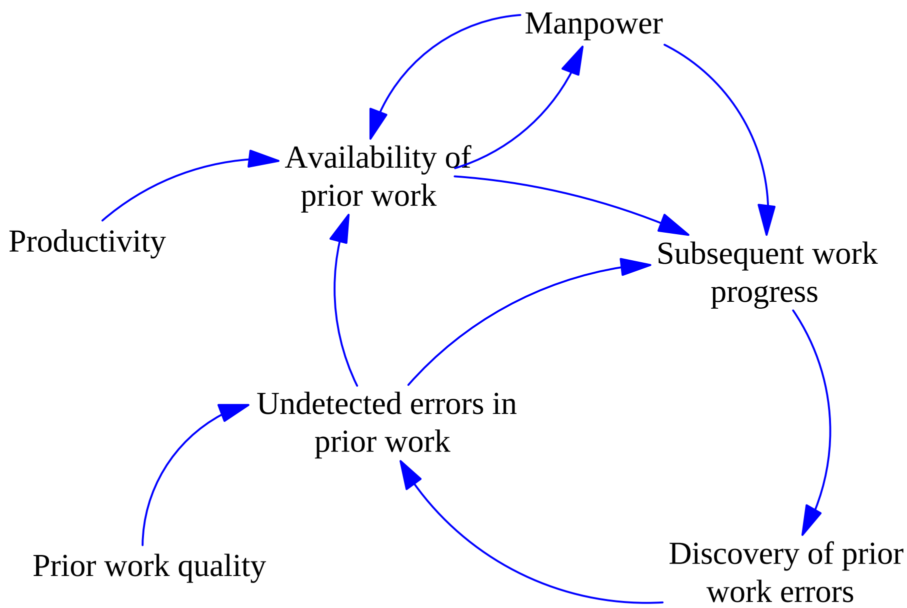

Figure 2.5 Conceptual Structure of Cooper's (1980) model

One of the key relationship structures of Cooper's model is shown in Figure 2.5. The structure centers around the quality of work performed. Cooper contended that out-of-sequence, incomplete, and/or incorrect work has serious impacts on the performance of subsequent work. The need for rework (because work is discovered to be incomplete or incorrect) may delay or impair dependent work in subsequent phases. The need for rework may remain undiscovered until progress in a subsequent phase becomes directly dependent on the required work.

Cooper contended that cost overruns in large Navy ship construction projects could be broken into two majors segments: 1) Overruns as a result of the direct impact of a design change, or the “hard-core” costs, and 2) Overruns due to “delay and disruption” costs – the second and third order “ripple effects” of dealing with the direct changes. These snowballing effects are the most difficult to quantify and justify. Cooper’s model was successful in describing the dynamic behavior of such rippling effects and capturing the dynamic structure of the shipbuilding process that leads to the cost overruns attributed to the indirect effects resulting from direct design changes.

Some studies have examined the dynamics of specific types of projects. Abdel-Hamid and Madnick (1991) developed a SD model for the evaluation of a software development project. Figure 2.6 below shows the structure of the software production process proposed by them.

According to Abdel-Hamid and Madnick, the software development lifecycle includes designing, coding and testing phases. They contend that as the software is developed, it is also reviewed to detect any errors, e.g., using quality assurance activities such as structured walkthroughs of the software code. Errors detected through such activities are reworked. They further propose that not all software errors are detected during development; some “escape” detection until the testing phase.

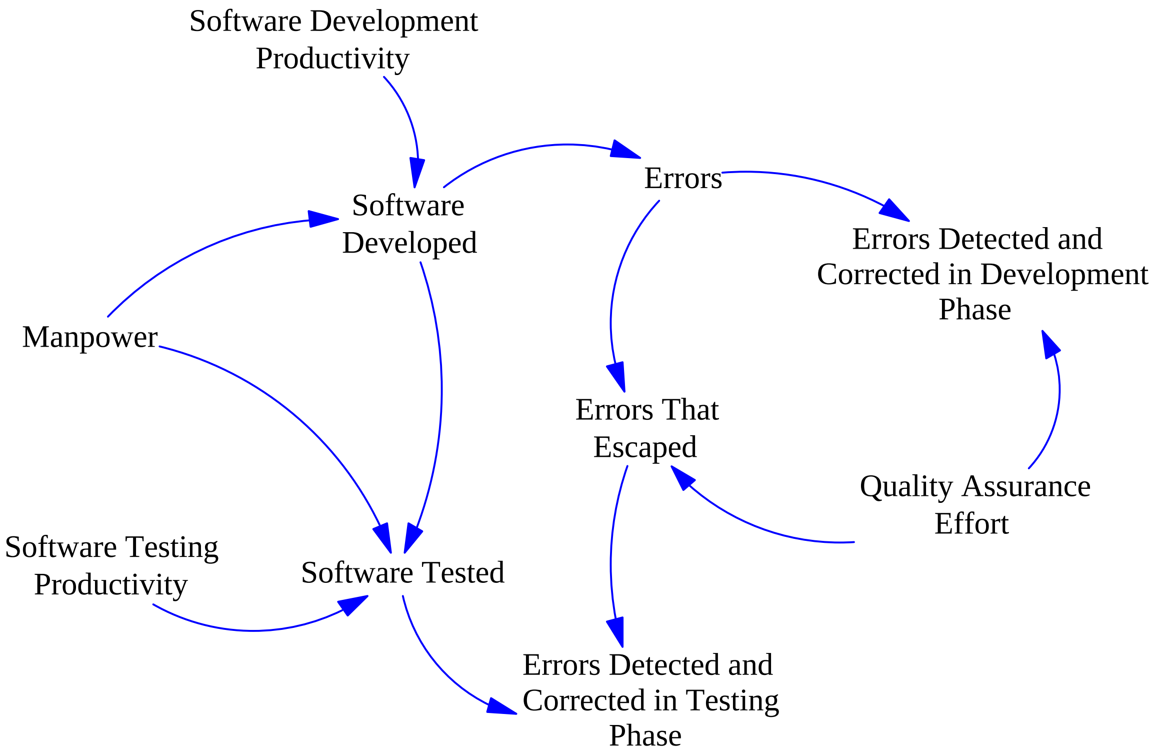

Figure 2.6 Conceptual Structure of Abdel-Hamid and Madnick's (1991) Model

The decision-makers in a technology development process evaluate the process based on certain performance measures that are tracked during the entire life cycle. The chief performance metrics are discussed in the next section.

2.5 <u>Performance Metrics</u>

The key performance metrics of interest are cost, schedule, technical performance, and risk.

Cost: Cost is viewed as the total life cycle costs (LCC) of the technology implementation. It would include costs starting from the R&D phase going all the way up to the disposal of the technology.

Cost is the amount paid or payable for the acquisition of materials, property, or services (NNS and NAVSEA experts). It is also used with descriptive adjectives such as "acquisition cost", or "product cost," etc. Although dollars normally are used as the unit of measure, the broad definition of cost equates to economic resources, i.e., manpower, equipment, real facilities, supplies, and all other resources necessary for weapon, project, program, or agency support systems and activities. (Source: Defense Acquisition Desk Book, Parametric Cost Estimating Handbook)

Schedule: Schedule refers to the time elapsed for a particular task. The time elapsed is both actual versus the planned time. Schedule includes program events/activities, their inter-relationships defined by program phase and activity/event time durations. The events may represent management objectives and provide for management and control of such effort (NNS and NAVSEA experts).

Risk: Risk is the probability of failure of a new technology. Risk addresses the problems or issues associated with technical, cost, and scheduling aspects of designing, testing, manufacturing, operating and supporting, and disposing of processes, systems and equipment. Risks affect the ability to successfully achieve cost, schedule, and technical performance objectives. Potential sources of risk include new processes like new designs, new operational requirements, immature or emerging technologies, new performance requirements, and political or organizational changes (NNS and NAVSEA experts).

Technical Performance: It is the degree to which the system reflects (meets or exceeds) the expected operational characteristics.

Performance is a statement of requirements in terms of required results with criteria for verifying compliance, without stating methods for achieving the required results. A performance specification defines the functional requirements for the item, the environment in which it must operate, and the interface and interchangeability requirements (NNS and NAVSEA experts).

Chapter 3. The Model

The modeling process used for the development of the model followed the steps and guidelines presented by Sterman in "Business Dynamics: Systems Thinking and Modeling for a Complex World" (2000). This process is summarized subsequently.

3.1 Problem Articulation

The most important step in modeling is the problem articulation (Sterman, 2000). The identification of a clear purpose is very critical. Models are effective when designed for a small problem or part of the system rather than the whole system itself. Identification of a clear purpose based on a problem in the system helps in making decisions about the framing of the model, i.e., what it should include and what should be left out.

3.1.1 The Problem

Costs and schedule overruns are commonplace in large research and development projects. Cost overruns are exhibited usually when there is a need to hire and train additional personnel midway through the project. Schedule overruns are experienced when allotted time is not met. A point to be noted is that not all research and development projects have these problems. However, we proceeded with the assumption that they have persisted in our client's (Newport News Shipbuilding) experiences in spite of reasonable attempts to avoid them. We considered here a large technology development project, involving a large number of people, a considerable number of detailed tasks, and a long time frame (104 weeks).

3.1.2 Two Powerful Tools in the Initial Characterization of the Problem

Reference Modes: These are a set of graphs and other descriptive data showing the development of the problem over time (Sterman, 2000). These graphs assist the decision-makers and the modelers to break free from the narrow event-oriented perspective to a broader wholistic perspective and to events that are removed in time and space.

The behavior pattern of certain key variables was elicited from the decision-makers. Those variables were:

Risk: It is defined as the probability of failure of the new technology. Risk addresses the problems or issues associated with technical, cost, and scheduling aspects of designing, testing, manufacturing, operating and supporting, and disposing of processes, systems and equipment. Risks affect the ability to successfully achieve cost schedule and technical performance objectives (Group Modeling exercise, as theorized by Richardson and Pugh (1981), Roberts et al. (1983), Vennix et al. (1992), and Andersen et al. (1997), and discussed in Chapter 2, Section 2.2).

Cost: It is viewed as the total life cycle costs (LCC) of the technology implementation. It would include costs starting from the R&D technology development phase going all the way through the disposal of the technology. Cost is the dollar amount paid for the acquisition of materials, property, and services. In contract and proposal document language, it denotes dollars and amounts exclusive of fee or profit (Group Modeling exercise, as theorized by Richardson and Pugh (1981), Roberts et al. (1983), Vennix et al. (1992), and Andersen et al. (1997), and discussed in Chapter 2, Section 2.2).

Performance: It is the degree to which the system reflects (meets or exceeds) the expected operational characteristics. Performance is a statement of requirements in terms of required results with criteria for verifying compliance, without stating methods for achieving the required results. A performance specification defines the functional requirements for the item, the environment in which it must operate, and the interface and interchangeability requirements (Group Modeling exercise, as theorized by Richardson and Pugh (1981), Roberts et al. (1983), Vennix et al. (1992), and Andersen et al. (1997), and discussed in Chapter 2, Section 2.2).

Examples of reference modes for these variables are depicted in Figure 3.1 below.

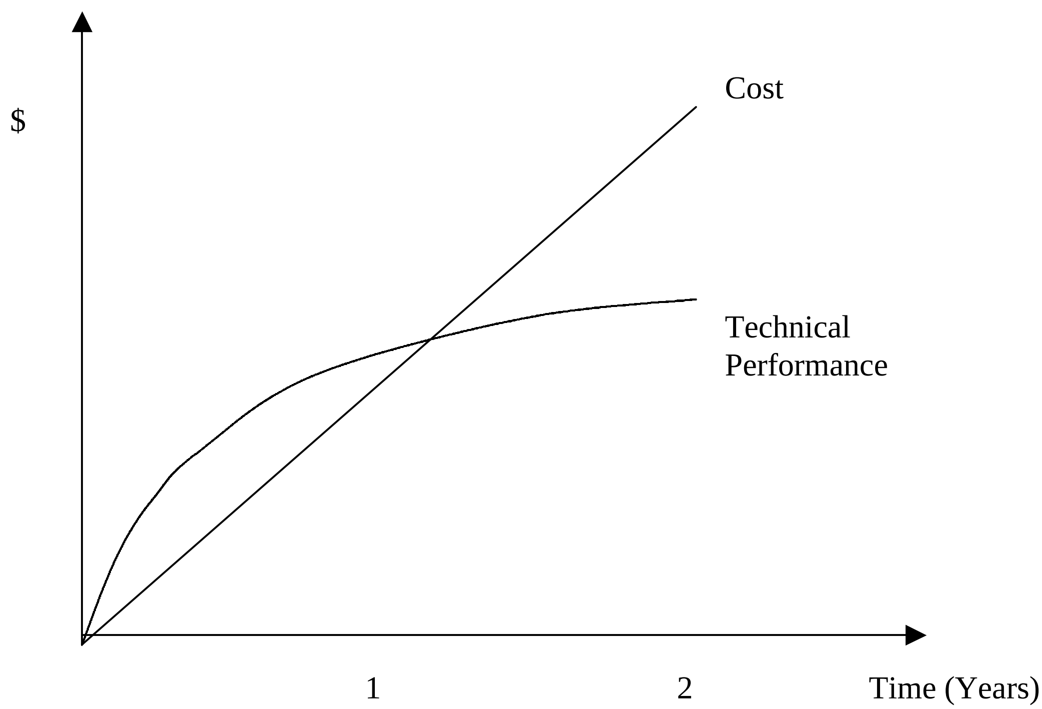

Figure 3.1 Reference modes for Key Variables

Time Horizon: This is a very important feature in any problem characterization. Most conventional approaches focus on studying the problem and the system over a short time horizon. This is mainly due to our event-oriented outlook. We need to realize that the problem might have originated a long time back, and also that actions taken now may cause effects that are far displaced in time and space. Therefore, selecting an adequately long time horizon is very important. It was assumed that the technology development process takes two years to complete. Therefore, the time horizon of the technology development process was defined to be two years (104 weeks).

3.2 <u>Formulating Dynamic Hypotheses</u>

This is the next step in modeling in which a working theory is developed to explain the problem at hand. Since the theory should account for the dynamics of the behavior of the system based on the underlying feedbacks and interactions between its different components, it is called a dynamic hypothesis. The role of the modeler is to elicit the views of the decision-makers that can affect the problem in the system, and to develop hypotheses to explain the problem.

3.2.1 Endogenous Explanation

System Dynamics seeks endogenous explanations for phenomena rather than exogenous ones. Explanations based on exogenous (see Glossary (Appendix A)) entities/variables are not of much interest as they articulate dynamics of endogenous (see Glossary (Appendix A)) variables in terms of other variables whose behavior is assumed (Sterman, 2000). Exogenous variables are "outside" the system and therefore they are not affected dynamically by interactions and feedbacks among the variables/entities within the system. Hence, an explanation of the system behavior in terms of these exogenous variables cannot capture the dynamics of the system. There should be very few exogenous variables in the model of the system under study. A broad boundary should be determined for the system as opposed to a narrow limiting boundary.

The following hypotheses are proposed. Running simulations on the Technology Development model can test all the four hypotheses.

1) A lack of appropriate training causes cost overruns in the technology development process. The right people may not be available to accomplish the tasks necessary in technology development. Training is one of the important issues in the execution of any large-scale project. New people recruited have to be trained to get to the level of knowledge that experienced people have. In the case of technology development projects, training becomes all the more important given that technicians, engineers, and workers have to be adequately trained to get familiar with the new technology.

2) Rework in a project adds to the cost overruns. The notion of rework refers to the fact that not all work done in the course of a large project is flawless. Some fraction of it is less than satisfactory and must be redone. Unsatisfactory work is not found out right away, however. For some time it passes off as real progress, until the need for reworking the tasks involved resurfaces (see the model presented by Cooper (1980), Chapter 2, Section 2.4).

3) An increase in the complexity (see definition in Section 3.2.2 of this chapter) of the new technology causes an increase in the total costs incurred. As technology becomes more complex, it requires more effort to be put in technology development. As a result, total costs increase.

4) An increase in the maturity (see definition in Section 3.2.2 of this chapter) of the technology decreases the total costs incurred.

3.2.2 The system

The system was defined as the process that is responsible for the technology development, within the scope of the implementation of new technologies, on aircraft-carriers.

(Please see Appendix B for a system/subsystem diagram and brief descriptions of the various subsystems.)

In the development phase**,** new technologies are developed and/or assessed. The various technology development activities are research and development (R&D) activities that include project management, research, requirements definition, specification development, engineering, modeling and simulation, drawing development, hardware and software development, system architecture development, and testing.

Risk is another significant variable in this system, and results from the inherent difficulty in developing and/or implementing new technology. Regardless of whether the new technology is being developed, or is already developed and needs to be implemented, the technology risks need to be assessed for their impact on existing/future ship systems and operations.

Broadly, technology development has two main subtasks:

1) The development of the technology, and

2) The assessment of the new technology.

Technology development involves the following activities (based on NNS and Naval Sea Systems Command Cost Estimating group (NAVSEA) experts).

1) Up-front research and development: This involves research activities based on available literature and/or innovations and alterations to the existing technology designs available in the literature. Various alternatives are studied in the technology field to gain an initial insight as to which alternative would best meet the operational requirements.
2) Prototype development: Based on the chosen technology alternative, this activity involves the development of a prototype or miniature physical model that provides for the desired process/project requirements and objectives.
3) Testing of prototypes: In this activity, the developed prototypes are tested for compliance with all desired requirements. Testing is fundamentally concerned

with an assessment of how well the technology performs with respect to technical requirements/aspects.

4) Adaptability studies: These studies are conducted to assess the adaptability of the technology within the operating environment of the ship. This means how well the technology can ease into the existing operations on the ship without causing much disruption to other processes that are not directly related to the operation for which the technology is being developed.
5) Development of drawing specifications: Once the prototype has been developed and tested favorably as a first iteration, the drawing specifications are developed for the full-size unit of the technology product. Drawing specifications are a detailed list of the physical components, characteristics, and dimensions of the technological unit to be fabricated.
6) Development of component drawings: Based on the drawing specifications of the previous stage, this activity involves the development of detailed drawings for the various components of the technological unit.
7) Incorporate flexibility as it relates to the life cycle of the new technology: One of the important issues in the successful implementation of new technologies is to account for the fact that technologies might become obsolete quicker than their planned/expected life-term. This is very important in the case of electronic and computer hardware and software technologies. The technology development process needs to address flexibility and plan for the possible technology upgrades and replacements before the expected or anticipated life-term of the technological unit.

8) The design of the infrastructure support processes: New technology implementation on ships is fraught with the possibility that the depot services might lack the infrastructure support material and equipment for maintenance of the new technology. The technology development process should plan for the anticipated support requirements and design the same if they are non-existent in the current depot facilities.

All the above activities except testing were aggregated as one activity, namely, technology development, in the model. The aggregation level was as desired by the experts.

3.3 Variable Definitions

The variables of the system were identified as a part of the group modeling exercise as presented by Richardson and Pugh (1981), Roberts et al. (1983), Vennix et al. (1992), and Andersen et al. (1997), and discussed in Chapter 2, Section 2.2. Each participant in the group modeling process was asked to list the key variables she or he felt were important in the system. A consensus was then built on a common list of variables for the system. A similar exercise was undertaken to obtain the definitions of the identified variables.

Definitions of the Identified Variables in the Technology Development Process

1) Funding – It is the amount of money provided (from sources outside the system and allocated by the program management) to carry out all the work required in the system. The variable is measured using cost (units are Year 2001 dollars).

2) Technology Maturity – It is defined as the state of development of a new technology, i.e., how mature it is. Increased technology maturity implies reduced development or procurement risk, because the technology is better defined. It is a dimensionless variable measured using a relative scale (varying from 1 to 5; 1=very immature, 2=immature, 3=medium maturity, 4=mature, and 5=very mature).

3) Technology Development – This is the effort (including both labor and materials) required to develop the new technology. It is a measure of the "largeness" of the development activity. Technology Development includes all activities except testing. It is measured using human effort time (units are man-hours).

4) Actual Testing Results – These are the actual results produced from testing the technology being developed. Testing results are measured with respect to the technical performance issues related to the new technology. It is a dimensionless variable measured using a relative scale (varying from 0 to 1; 0 corresponds to total failure and 1 corresponds to total success).

5) Target Testing Results – These are the desired results from testing the technology being developed. They are drawn from the specifications or high-level requirements of the operational characteristics of the new technology. It is a dimensionless variable measured using a relative scale (varying from 0 to 1; 0 corresponds to total failure and 1 corresponds to total success, model-user specified it as 1).

6) Integration Risk – It is a measure of the risk involved in integrating the technology onboard ship. This is separate from the risk involved in actually developing the technology. Integration Risk is a dimensionless variable measured using a relative scale (varying from 1 to 10; increasing from a very low risk at 1 to a very high risk at 10).

7) Technology Development Technical Performance – This is a measure of how favorable the technology being developed is, i.e., how likely it is to be successful for the intended application. This variable is a direct translation of the final Actual Testing Results obtained at the end of the Technology Development phase, i.e., at the end of two years. It is a dimensionless variable measured using a relative scale (varying from 0 to 1; 0 corresponds to total failure and 1 corresponds to total success).

8) Technology Development Risk – It is defined as a measure of the risk involved in developing the new technology. This is separate from the risk involved in integrating the new technology onboard the ship. It is a dimensionless variable measured using a relative scale (varying from 1 to 10; increasing from a very low risk at 1 to a very high risk at 10).

9) Complexity of New Technology – This is a measure of how complex the new technology is. Increased complexity implies increased technology development effort. It is a dimensionless variable measured using a relative scale (varying from 1 to 5; 1=very low complexity, 2=low complexity, 3=medium complexity, 4=high complexity, 5=very high complexity).

10) Technology Development Management – This is a measure of the effort required to manage and administratively support the technology development process, the testing process, and the management of the cost overruns. It is measured using human effort time (units are man-hours).

11) Technology Development Redevelopment fraction – This is the amount of redevelopment that has to be done to narrow the discrepancy between the actual and target testing results. It is a dimensionless variable measured as a decimal value between 0 and 1.

12) Technology Development Results Discrepancy – It is the difference between the actual and target testing results. It is a dimensionless variable measured as a decimal value between 0 and 1.

13) Training – It is defined as the amount of training imparted to the technical professionals in the technology development process. It is measured using cost (units are Year 2001 dollars).

14) Testing Effort – It is the effort (including both labor and materials) required to test the new technology. It is a function of the amount of work done in technology development. It is measured using human effort time (units are man-hours).

15) Actual Costs – It is the cumulative costs associated with the technology development, testing effort, and technology development management effort. It is measured using cost (units are Year 2001 dollars).

16) Cost Overrun fraction – It is defined as the amount by which the actual costs exceed the allotted funding (as a fraction of the allotted funding) for the various activities in the technology development phase. It is a dimensionless variable measured as a decimal value greater than or equal to 0.

17) Funding Stability – It is defined as a measure of how stable the external funding source is. It is a dimensionless variable measured using a relative scale (varying

from 1 to 10; increasing from a very low stability at 1 to a very high stability at 10).

Assumptions of the model

The following assumptions of the model were obtained from the group modeling sessions.

1) Funding stability has a positive effect on the amount of funding received for the technology development phase. A high funding stability ensures a steady flow of funding whereas a low stability means a dwindling of the funding rate.
2) A low funding stability calls for an increased effort in project management, as the management has to perform a juggling act to make things happen within a funding constraint.
3) A cost overrun compels a reduction in the planned technology development activity so as to try to meet the budget constraints.
4) The more complex a technology is, the more is the anticipated technology development effort.
5) A redevelopment effort drives up the actual testing results obtained in the testing process. The assumption is that redevelopment is carried out with an aim to reduce the discrepancy between the actual and target testing results, and it results in an increase in the actual state (testing results) of the system.
6) The more mature the technology is, the lesser is the technology integration (on the ship) risk, the lesser is the amount of effort required for technology development, and the lesser is the technology development risk.

7) An increase in the actual technical performance of the technology drives down the risk associated with integrating the technology on board the ship.

8) Complexity of technology, funding, funding stability, target testing results, and technology maturity are exogenous variables to this system. They are not influenced directly by any other variables from within the system. The user of the model defines these parameters.

3.4 The Causal Loop Diagram

The feedback structure of complex systems is qualitatively mapped using causal diagrams. A Causal Loop Diagram (CLD) consists of variables connected by causal links, shown by arrows. Each link has a polarity. A positive (denoted by "+" on the arrow) link implies that if the cause increases (decreases), the effect increases (decreases) *above (below) what it would otherwise have been*. A negative (denoted by "-" on the arrow) link implies that if the cause increases (decreases), the effect decreases (increases) *below (above) what it would otherwise have been* (Sterman, 2000).

For example:

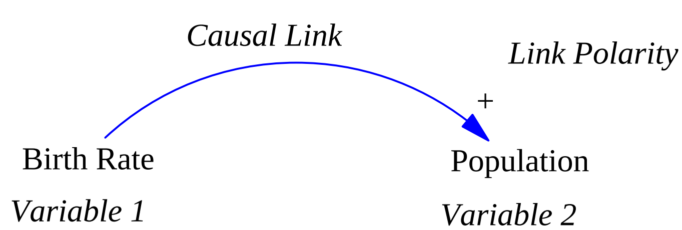

Figure 3.2 Example of a Causal Link

3.4.1 Causal Loop Diagram Notation

Positive linkages are presented with blue colored arrows and negative linkages are presented with red colored arrows. The main causal loops identified for the technology development system (depicted by Figure 3.3) are as follows:

COM-R: Cost Overrun-Management reinforcing loop

DCO-B: Development-Cost Overrun balancing loop

TCO-B: Testing-Cost Overrun balancing loop

MCOD-B: Management-Cost Overrun-Development balancing loop

MCODT-B: Management-Cost Overrun-Development-Testing balancing loop

DTrR-B: Development-Training-Risk balancing loop

ReTDis-B: Redevelopment-Testing Results-Discrepancy balancing loop

The Causal Loop Diagram was obtained from the group modeling sessions. Figure 3.3 is the final version of the causal loop diagram. Previous versions are included in Appendix C.

3.4.2 Technology Development Causal Loop Diagram

The overall causal loop diagram of the system is shown in Figure 3.3.

<u>Description of the Technology Development Causal Loop Diagram</u>

The various feedback loops manifested in the causal loop diagram are described in detail herewith.

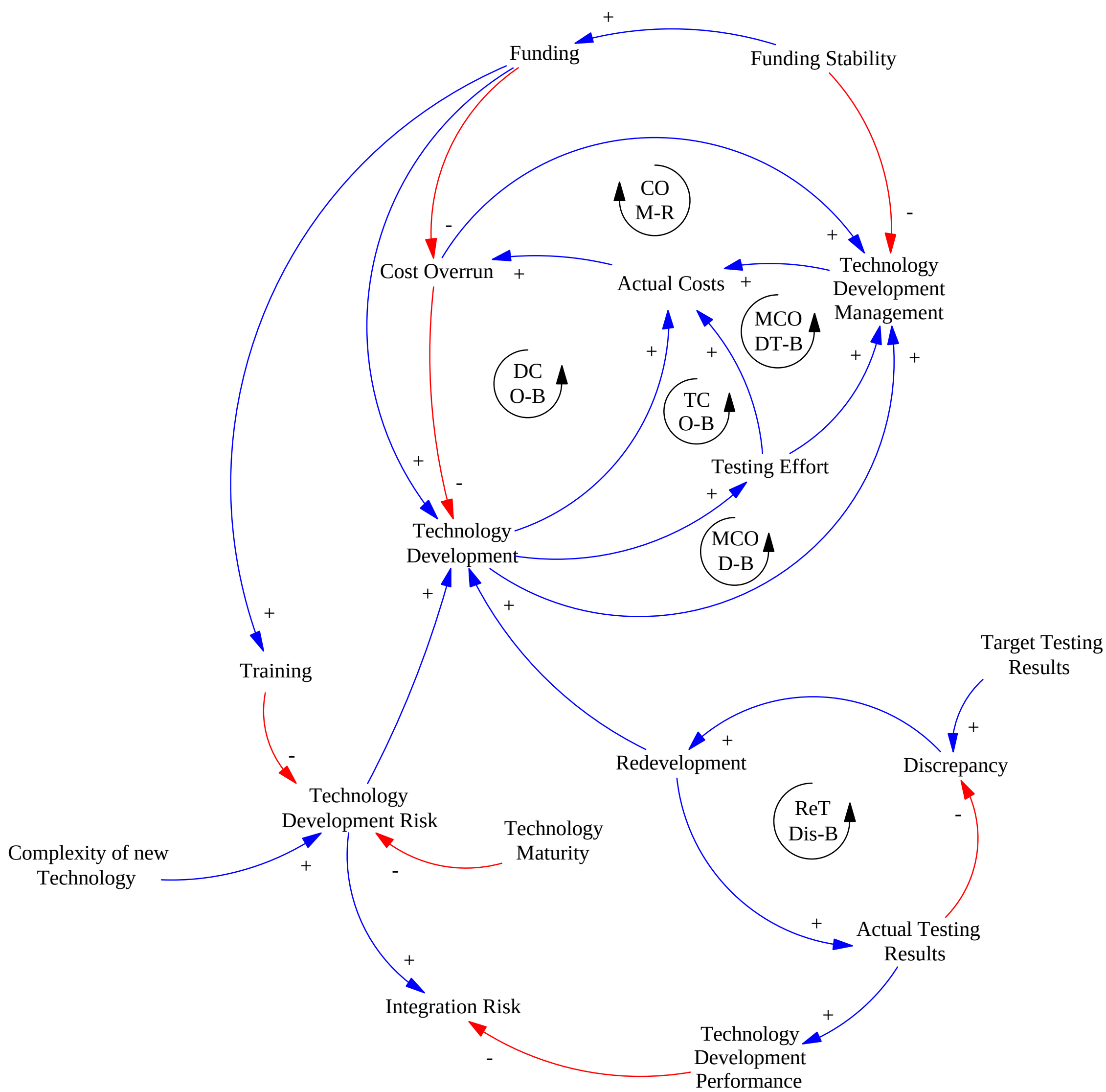

Figure 3.3 Integrated Technology Development Causal Loop Diagram

<u>Cost Overrun-Management Reinforcing Loop (COM-R)</u>

Cost Overruns are defined as the amount by which the actual costs exceed the available funding during the technology development phase of the new technology implementation process. As cost overruns increase (decrease), the management group within the technology development phase has to increase (decrease) its management effort associated with juggling the available funds among various activities occurring in the phase. Or in other words, the financial management effort increases (decreases) as the cost overruns increase (decrease). Now the management effort itself is expressed as the man-hours required to complete the actual effort. So, as the management effort increases (decreases), the actual costs in the technology development phase go up (down), thus further driving up (down) the cost overruns. This loop behaves as a reinforcing loop.

Development-Cost Overrun Balancing Loop (DCO-B)

As technology development effort goes up (down), the man-hours required to carry out the actual effort goes up (down). This drives up (down) the actual costs of the technology development phase. As the costs increase (decrease), the cost overruns increase (decrease). An increase (decrease) in the cost overruns fuels a decrease (increase) in the technology development activity as a control feedback mechanism. This loop behaves as a balancing loop.

Testing-Cost Overrun Balancing Loop (TCO-B)

When the technology development effort increases (decreases), it leads to an increase (decrease) in the testing effort associated with the amount of technology development taking place. An increase (decrease) in testing effort implies an increase (decrease) in the man-hours associated with the actual effort exerted. This drives up (down) the actual costs of the technology development phase, in turn driving up (down) the cost overruns. An increase (decrease) in the cost overruns fuels a decrease (increase) in the technology development activity as a control feedback mechanism. This loop behaves as a balancing loop.

Management-Cost Overrun-Development Balancing Loop (MCOD-B)

As the technology development effort increases (decreases), the accompanying management effort associated with the management process of the technology development activity increases (decreases) as well. The implied increase (decrease) in man-hours associated with the actual effort results in an increase (decrease) in the actual costs of the technology development phase, in turn driving up (down) the cost overruns. An increase (decrease) in the cost overruns fuels a decrease (increase) in the technology development activity as a control feedback mechanism. This loop behaves as a balancing loop.

Management-Cost Overrun-Development-Testing Balancing Loop (MCODT-B)

When Technology development effort increases (decreases), it leads to an increase (decrease) in the testing effort associated with the amount of technology development taking place. This in turn results in an increase (decrease) in the technology development management activity to manage the testing effort. An increase (decrease) in management effort implies an increase (decrease) in the man-hours associated with the actual effort put in. This drives up (down) the actual costs of the technology development phase, in turn driving up (down) the cost overruns. An increase (decrease) in the cost overruns fuels a decrease (increase) in the technology development activity as a control feedback mechanism. This loop behaves as a balancing loop.

Redevelopment-Testing Results-Discrepancy Balancing Loop (ReTDis-B)

An increase (decrease) in the redevelopment activity leads to an increase (decrease) in the actual state of the system. This means that the testing results get better and closer to the target testing results. An increase (decrease) in actual testing results leads to a decrease (increase) in the discrepancy from the target testing results. As this discrepancy decreases (increases), the redevelopment rate also decreases (increases), as there is a lower (higher) rate need for development improvement to achieve the target performance. This loop behaves as a balancing loop. This loop can be used to test the second hypothesis stated earlier in this chapter.

An increase (decrease) in funding stability decreases (increases) the amount of financial management effort associated with juggling the funding obtained. An increase (decrease) in funding causes an increase (decrease) in the technology development effort. It also leads to a decrease (increase) in the cost overruns.

It should be noted here that there is no feedback loop in the model that will test the third and fourth dynamic hypotheses of the model. These hypotheses are imbedded in the relationship defined between complexity/maturity and technology development risk (Equation 3.24). Furthermore, there is no direct linkage between the integration risk and the development effort or any other activity in this subsystem. However, this notion of integration risk is used in the technology integration and operation, support, and disposal subsystems and impacts activities in these subsystems.

An increase (decrease) in complexity of the new technology leads to an increase (decrease) in the technology development effort. An increase (decrease) in technology maturity results in a decrease (increase) in the risk associated with technology development, which consequently leads to a decrease (increase) in the technology development effort and the risk associated with integration of the technology onboard the ship.

An increase (decrease) in the redevelopment rate increases (decreases) the technology development effort. An increase (decrease) in the actual state of the system that is reflected in the actual testing results, leads to an increase (decrease) in the overall technology development technical performance. This increase (decrease) in the overall technology development technical performance causes a decrease (increase) in the risk associated with the integration of the technology onboard the ship. However, as noted earlier, the integration risk variable is not part of a feedback mechanism in this subsystem but affects activities in the technology integration and operations, support, and disposal subsystems.

3.5 <u>The Quantitative Description: Formulating a Simulation Model</u>

This next step in modeling involves setting up a formal model complete with equations, parameters and initial conditions that represent the system. Sometimes the dynamic hypotheses can be tested directly through data collection or experiments in the real system. However, in many situations, real-world experiments are often impractical and infeasible due to a number of reasons. To be able to test dynamic hypotheses by conducting experiments in the real system, one would have to conduct the experiments several times over with different starting parameters or with changes in the different interactions between the entities of the system. The costs to conduct several experiments in the real system are often prohibitive. In addition, if the testing of a dynamic hypothesis involves conducting several experiments with some different parameters but in the same time frame, it is infeasible. Therefore, a simulation model needs to be developed in the virtual realm. The involvement of the decision-makers at all these steps of the modeling process is very crucial. Their views and active participation in the problem definition, hypothesis formulation, and simulation modeling are very important for successful and meaningful modeling.

In the group modeling sessions, the equations describing the relationships between the various variables were elicited from the clients. They were asked for their inputs on the units for measurement of different variables, the functional form of the various equations between variables, parameters of these equations (elicited through graphical portrayal of key relationships), and the initial values of all stock variables.

3.5.1 Stocks and Flows

Causal loops are used effectively at the start of a modeling project to capture mental models. However, one of the most important limitations of the causal diagrams is their inability to capture stock and flow structure of systems. Stocks and flows, along with feedback, are the two central concepts of dynamic systems theory. Stocks are accumulations that occur as a result of a difference in input and output flow rates to a process/component in a system. Stocks give the systems inertia and memory, based on which decisions and actions are taken. Stocks also create delays in a system and generate disequilibria (Sterman, 2000).

Stock and Flow Notation:

All stock and flow structures are composed of stocks (represented by rectangles), inflows (represented by arrows pointing into the stock), outflows (represented by arrows pointing out from the stock), valves, and sources and sinks for flows (represented by clouds).

General Structure

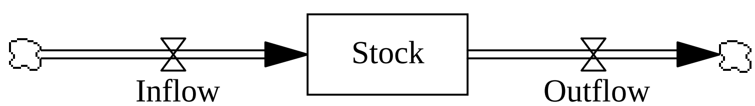

Figure 3.4 General Structure of a Stock and Flow

Mathematical Representation of Stocks and Flows

$$\text{Stock}(t) = \text{Stock}(t_0) + \int [\text{Inflow}(t) - \text{Outflow}(t)]\, dt \qquad (3.1)$$

Stocks are the state variables or integrals in the system. They accumulate (integrate) their inflows less their outflows. Flows are all the variables that are rates or derivatives. Were a snapshot of a system to be taken at any instant of time, what would be seen is the state of different processes or components of the system. These are the stocks in the systems. The inflows and outflows are what have been frozen and so cannot be identified. Stock and flow networks undoubtedly follow the laws of conservation of material. The contents of the stock and flow networks are conserved in the sense that items entering a stock remain there until they flow out. When an item flows from one stock to another, the first stock loses exactly as much as the second one gains. Stocks follow the mechanism of physical flow wherein items in a stock physically move to another stock, thus depleting the first stock and augmenting the second.

Stock and Flow Diagram Notation

The technology development stock and flow diagram is represented by Figure 3.5. In this figure, TD represents Technology Development.

The stock and flow structure has a one-to-one correspondence to the causal loop structure presented earlier. A causal loop diagram is a graphical tool to qualitatively capture the mental models of the decision-makers. A stock and flow diagram is a more detailed graphical tool to help quantify what has already been captured in the causal loop diagram. Variables and concepts in the causal loop diagram are manifested as stock and flow structures in the stock and flow diagram. There are eight stock-and-flow structures in the stock and flow diagram and they are discussed herewith.

Technology Development Stock and Flow Diagram

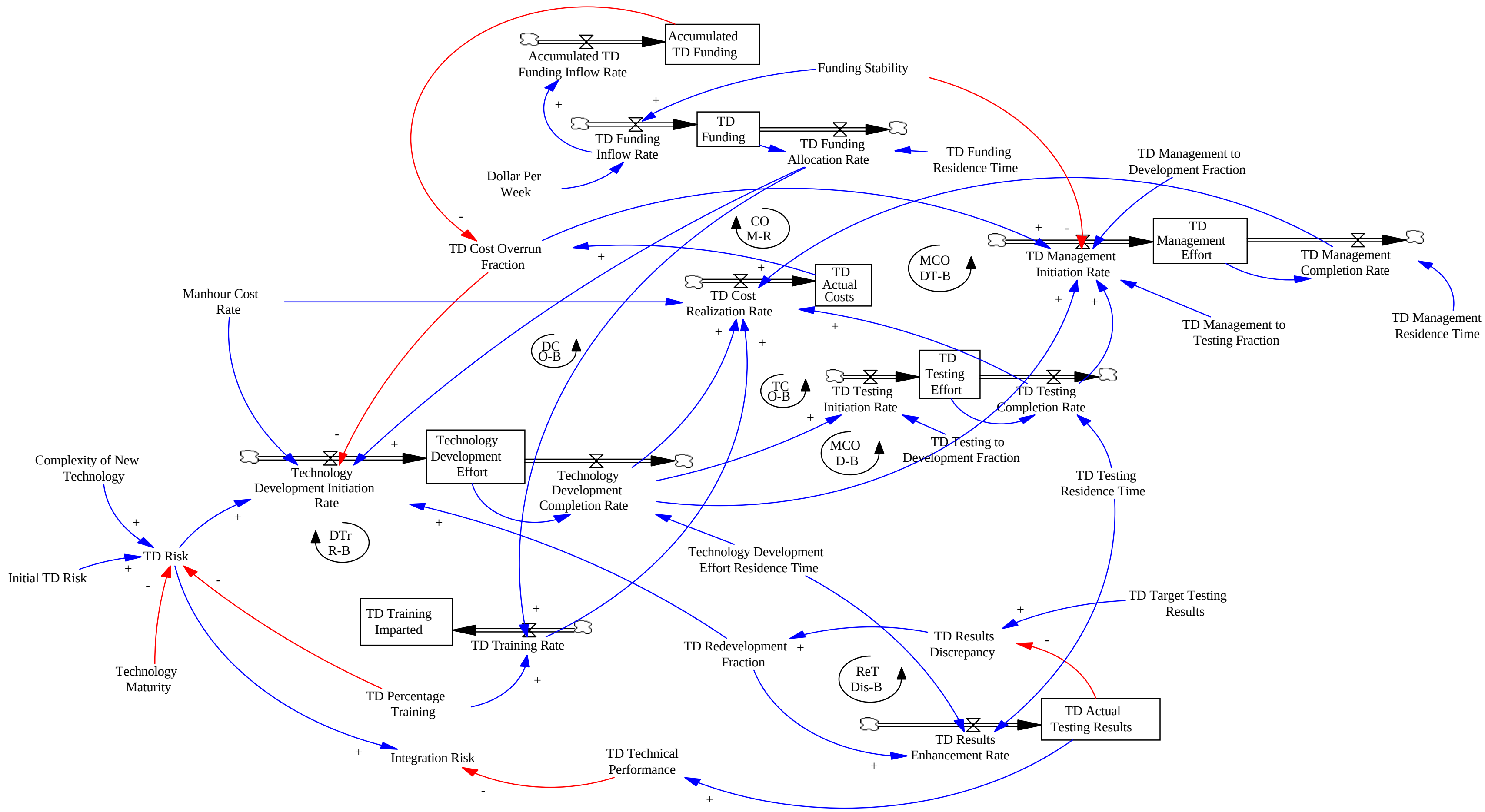

Figure 3.5 Technology Development Stock and Flow Diagram

3.5.2 TD Funding Stock and Flow Structure

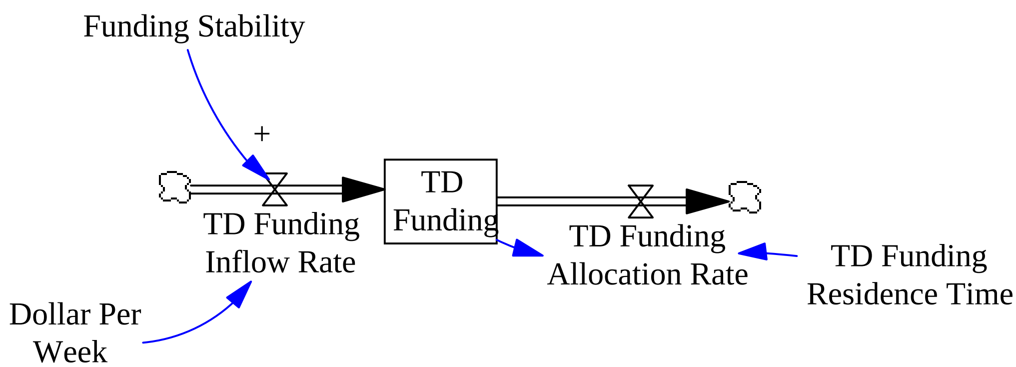

Figure 3.6 TD Funding Stock and Flow Structure

The TD Funding stock (dollars) is fed into by a TD Funding Inflow Rate (dollars/week) and is depleted by a TD Funding Allocation Rate (dollars/week). The TD Funding stock variable is an integral of the TD Funding Inflow Rate less the TD Funding Allocation Rate.

$$\text{TD Funding } (t) = \text{TD Funding } (0) + \int [\text{TD Funding Inflow Rate} - \text{TD Funding Allocation Rate}]\, dt \qquad (3.2)$$

TD Funding (0) = 0

The TD Funding Inflow Rate has a base value of $25000/week (NNS and NAVSEA experts, and is obtained from the program management subsystem). An increase (decrease) in Funding Stability leads to an increase (decrease) in the TD Funding Inflow Rate. Funding Stability (on a scale of 1 to 10; with 1 being most unstable, increasing in stability up to 10 being the most stable) effects the base value of TD Funding Inflow Rate by a divisive factor. When Funding Stability is 10, the divisive factor is 1. When Funding Stability is 4, the divisive factor is 1.1. When Funding Stability is 1, the divisive factor is 1.3. A quadratic curve (of the form $y = ax^2+bx+c$) was fitted through the three points to obtain an analytical expression capturing the effect of Funding Stability on the TD Funding Inflow Rate. A quadratic curve was assumed based on the visual shape of the curve elicited from the clients for the effect of Funding Stability on the TD Funding Inflow Rate. The curve fitting was done manually. The graph depicted below (Figure 3.7) was plotted in MS Excel 2000.

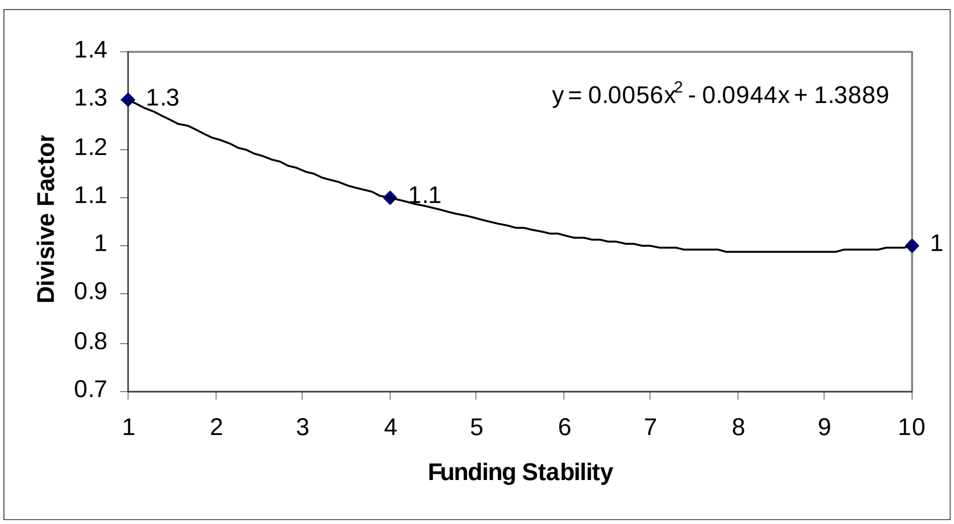

Figure 3.7 Impact of Funding Stability on TD Funding Inflow Rate

The overall equation (with inputs from NNS, NAVSEA experts) to describe the relationship is:

$$\text{TD Funding Inflow Rate} = 25000 / (0.0056*\text{Funding Stability}^2 - 0.0944*\text{Funding Stability} + 1.3889) * \text{Dollar Per Week} \quad (3.3)$$

The TD Funding Allocation Rate is a first order delay (see Glossary (Appendix A)) of the TD Funding stock.

TD Funding Allocation Rate = TD Funding / TD Funding Residence Time (3.4)

The TD Funding Residence Time is the average time the incoming funding stays in the stock before being allocated.

3.5.3 Technology Development Effort Stock and Flow Structure

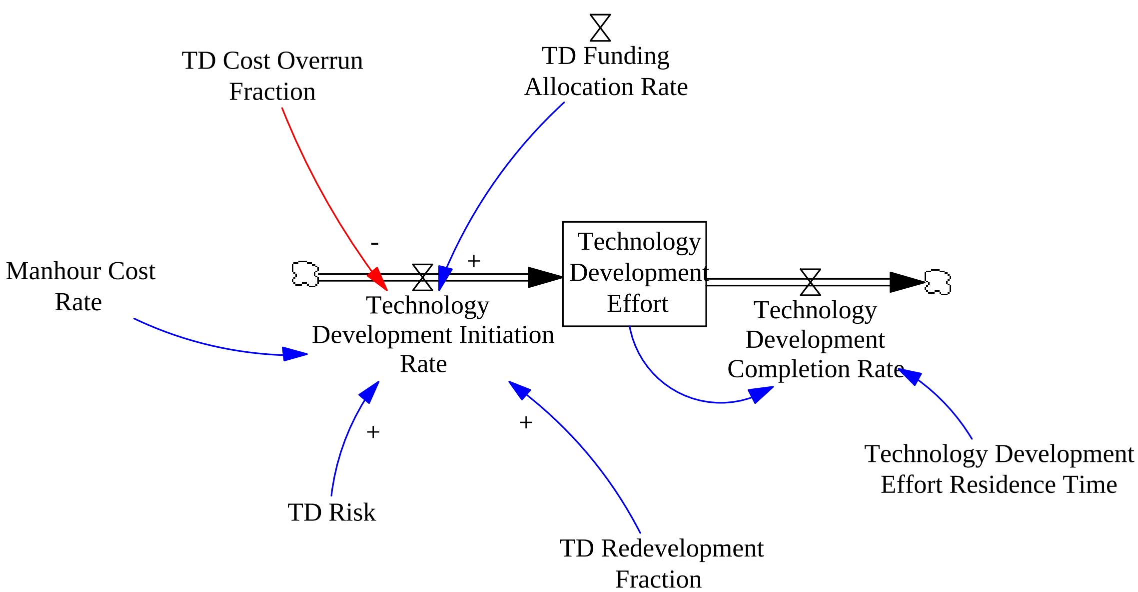

Figure 3.8 Technology Development Effort Stock and Flow Structure

The Technology Development Effort stock (man-hours) is fed into by a Technology Development Initiation Rate (man-hours/week) and is depleted by a Technology Development Completion Rate (man-hours/week). The Technology Development Effort stock variable is an integral of the Technology Development Initiation Rate less the Technology Development Completion Rate.

Technology Development Effort (t) = Technology Development Effort (0)

+ ∫ [Technology Development Initiation Rate

– TD Funding Allocation Rate] dt (3.5)

Technology Development Effort (0) = 0

The Technology Development Initiation Rate is primarily driven by the TD Funding Allocation Rate. Three-fourths of the funding is allocated for technology development activities. The Manhour Cost Rate (dollars/man-hour) is the cost of labor and is used to convert the funding rate units into development rate units (man-hours). The TD Redevelopment Fraction is a dimensionless variable that captures the amount of redevelopment done as a fraction of the development activity assigned in the first place. The amount of redevelopment done adds to the Technology Development Initiation Rate. The TD Cost Overrun Fraction is a dimensionless variable that captures the amount of cost overruns over the total allocated funding, as a fraction of the total allocated funding. It imposes a penalty on the technology development activities by reducing the Technology Development Initiation Rate at twice the rate of cost overruns. An increase (decrease) in TD Risk leads to an increase (decrease) in the Technology Development Initiation Rate. TD Risk (on a scale of 1 to 10; with 1 being very low risk, increasing in risk up to 10 being very high risk) effects the Technology Development Initiation Rate by a multiplicative factor. At TD Risk equals 10, the multiplicative factor is 5. At TD Risk equals 8, the multiplicative factor is 2.2. At TD Risk equals 7, the multiplicative factor is

1.8. At TD Risk equals 1, the multiplicative factor is 1. An ellipse curve (of the form $x^2/a^2 + y^2/b^2 = 1$) was fitted through the four points to obtain an analytical expression capturing the effect of the TD Risk on the Technology Development Initiation Rate. An ellipse curve was assumed based on the visual shape of the curve elicited from the experts for the effect of the TD Risk on the Technology Development Initiation Rate. The curve fitting was done manually. The graph depicted below (Figure 3.9) was plotted in MS Excel 2000.

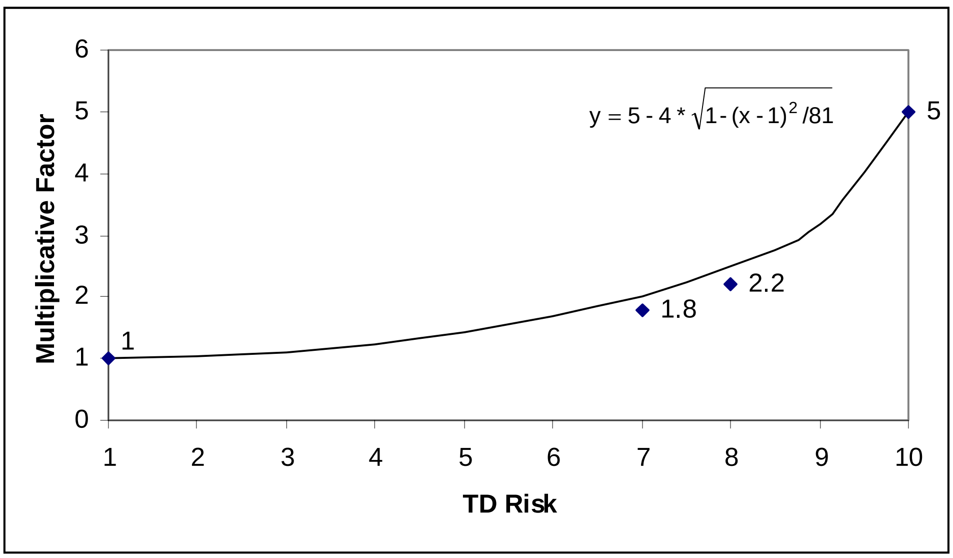

Figure 3.9 The Impact of TD Risk on the rate of Technology Development

The overall equation (with inputs from NNS, NAVSEA experts) to describe the relationship is:

Technology Development = TD Funding Allocation Rate / Manhour Cost Rate * 0.75

Initiation Rate * (1+TD Redevelopment Fraction)

* (1-2*TD Cost Overrun Fraction)

$$* (5-4*\sqrt{1-(TDRisk-1)^2/81}) \quad (3.6)$$

The Technology Development Completion Rate is a first order delay of the Technology Development Effort stock.

Technology Development Completion Rate = Technology Development Effort / Technology Development Effort Residence Time (3.7)

3.5.4 TD Testing Effort Stock and Flow Structure

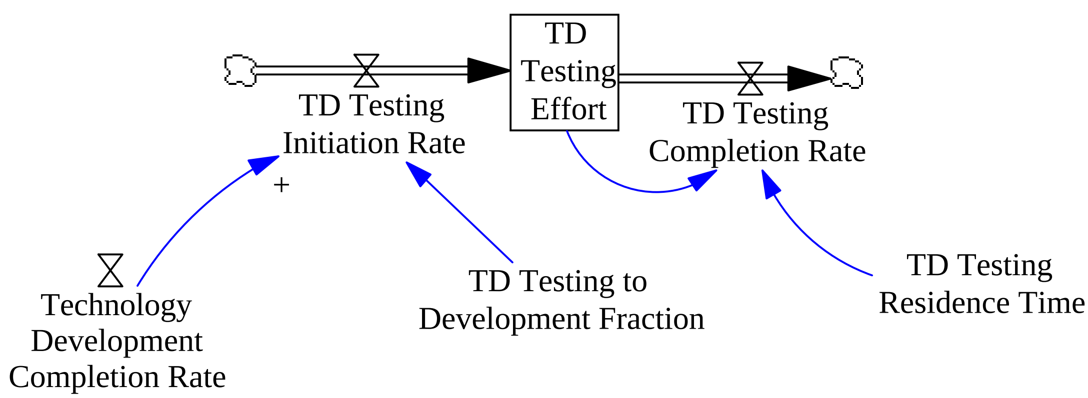

Figure 3.10 TD Testing Effort Stock and Flow Structure

The TD Testing Effort stock (man-hours) is fed into by a TD Testing Initiation Rate (man-hours/week) and is depleted by a TD Testing Completion Rate (man-hours/week). The TD Testing Effort stock is an integral of the TD Testing Initiation Rate less the TD Testing Completion Rate.

TD Testing Effort (t) = TD Testing Effort (0) + ∫ [TD Testing Initiation Rate – TD Testing Completion Rate] dt (3.8)

TD Testing Effort (0) = 0

The TD Testing Initiation rate is primarily driven by the Technology Development Completion Rate. The amount of testing done (in man-hours/week) is a fraction of the amount of technology development completed (in man-hours/week).

TD Testing Initiation Rate = Technology Development Completion Rate

* TD Testing to Development Fraction (3.9)

The TD Testing Completion Rate is a first order delay of the TD Testing Effort stock.

TD Testing Completion Rate = TD Testing Effort / TD Testing Residence Time

(3.10)

3.5.5 TD Actual Testing Results Stock and Flow Structure

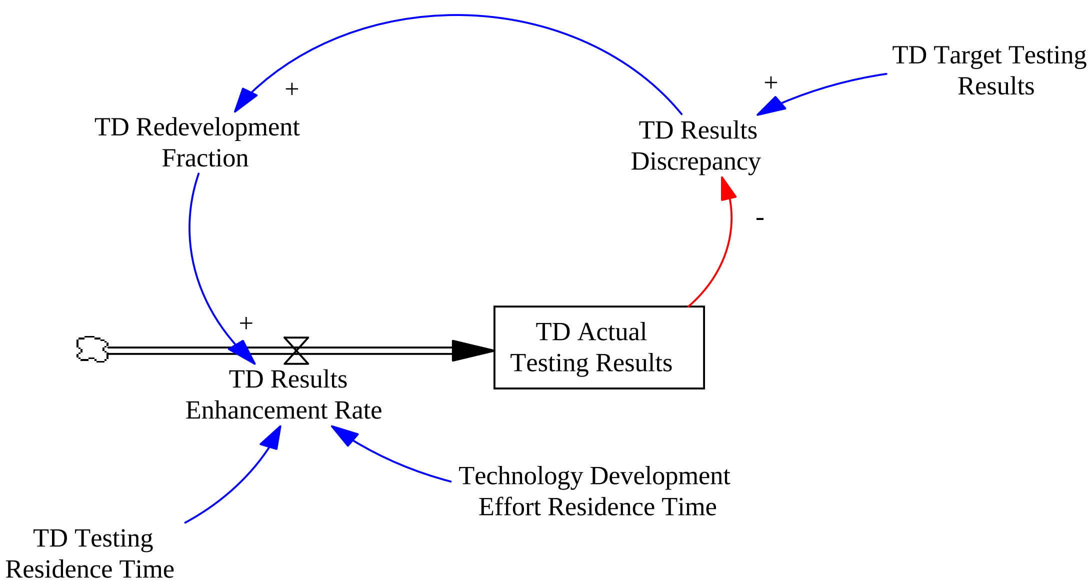

Figure 3.11 TD Actual Testing Results Stock and Flow Structure

The TD Actual Testing Results stock (dimensionless) is fed by a TD Results Enhancement Rate ($week^{-1}$). The TD Actual Testing Results stock variable is an integral of the TD Results Enhancement Rate.

$$\text{TD Actual Testing Results (t)} = \text{TD Actual Testing Results (0)} + \int [\text{TD Results Enhancement Rate}]\, dt \qquad (3.11)$$

It is assumed that the technology development activity yields an initial testing results value of 0.6; i.e., sixth-tenths of the desired goal is met with respect to technology development when the activity is done for the first time (NNS and NAVSEA experts). Subsequent redevelopment activity is carried out and it is assumed that redevelopment enhances the technical performance of the technology developed and hence better testing results are obtained.

TD Actual Testing Results (0) = 0.6

The TD Results Enhancement Rate is a function of the TD Redevelopment Fraction. As the TD Redevelopment Fraction increases (decreases), the rate at which testing results get better increase (decrease). Results get enhanced as redevelopment is done, and this enhancement occurs over a time span of the technology development delay plus the testing delay (NNS and NAVSEA experts).

The overall equation (with inputs from NNS and NAVSEA experts) to describe the relationship is:

$$\text{TD Results Enhancement Rate} = \text{TD Redevelopment Fraction} / (\text{Technology Development Effort Residence Time} + \text{TD Testing Residence Time}) \qquad (3.12)$$

The TD Results Discrepancy (dimensionless) is the difference between the TD Target Testing Results (dimensionless, user-defined to be equal to 1) and the TD Actual Testing Results (dimensionless; varying between 0 and 1).

TD Results Discrepancy = TD Target Testing Results-TD Actual Testing Results

(3.13)

The TD Redevelopment Fraction is a dimensionless variable that captures the amount of redevelopment done as a fraction of the development activity assigned in the first place. It is effected by the TD Results Discrepancy. An increase (decrease) in TD Results discrepancy leads to an increase (decrease) in the redevelopment efforts to correct the discrepancy. At a TD Results Discrepancy value of 0.4, the TD Redevelopment Fraction is 0.3. It declines to a value of 0.15 when the TD Results Discrepancy decreases to a value of 0.35. It further declines to a value of 0 as the TD Results Discrepancy decreases to a value of 0 (NNS and NAVSEA experts). An ellipse curve (of the form $x^2/a^2 + y^2/b^2 = 1$) was fitted through the three points to obtain an analytical expression capturing the effect of TD Results Discrepancy on the TD Redevelopment Fraction. An ellipse curve was assumed based on the visual shape of the curve elicited from the clients for the effect of TD Results Discrepancy on the TD Redevelopment Fraction. The curve fitting was done manually. The graph depicted below (Figure 3.12) was plotted in MS Excel 2000.

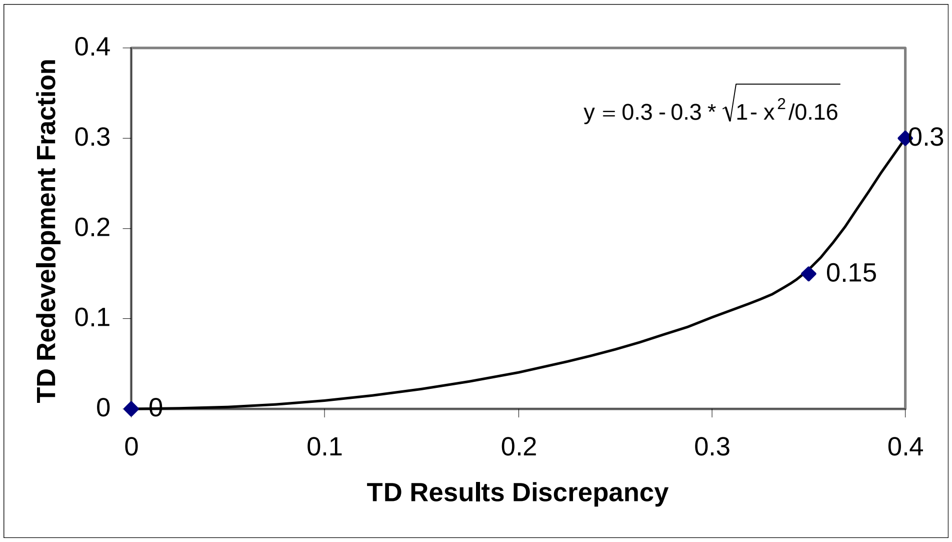

Figure 3.12 Impact of TD Results Discrepancy on TD Redevelopment Fraction

The overall equation (with inputs from NNS, NAVSEA experts) to describe the relationship is:

TD Redevelopment Fraction = $0.3 - 0.3 * \sqrt{1 - TDResultsDiscrepancy^2 / 0.16}$

(3.14)

3.5.6 TD Management Effort Stock and Flow Structure

The TD Management Effort stock (man-hours) is fed into by a TD Management Initiation Rate (man-hours/week) and is depleted by a TD Management Completion Rate (man-hours/week). The TD Management Effort stock is an integral of the TD Management Initiation Rate less the TD Management Completion Rate.

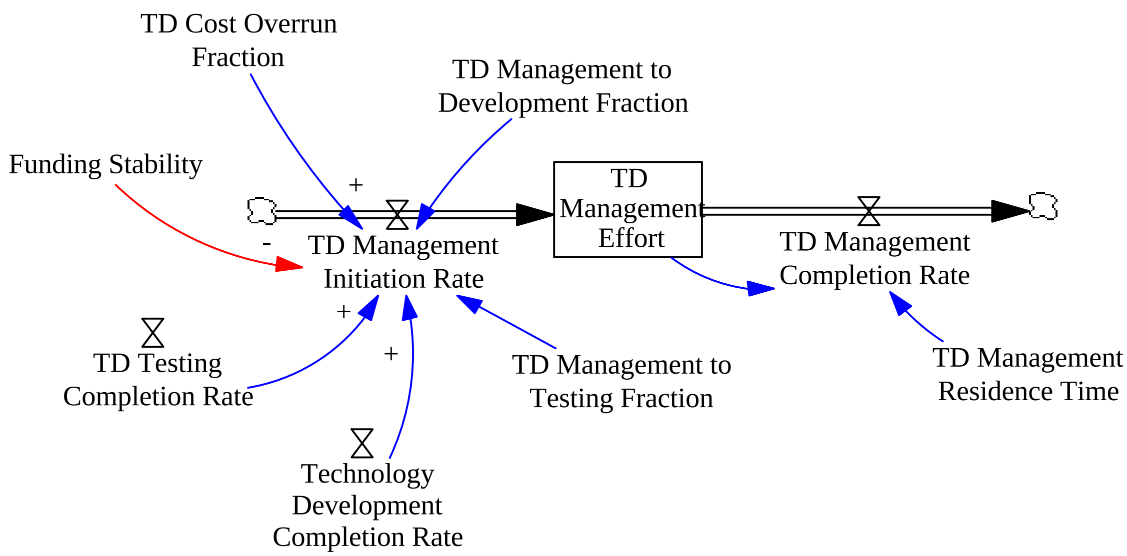

Figure 3.13 TD Management Effort Stock and Flow Structure

$$\text{TD Management Effort (t)} = \text{TD Management Effort (0)} + \int [\text{TD Management Initiation Rate} - \text{TD Management Completion Rate}]\, dt \quad (3.15)$$

TD Management Effort (0) = 0

The TD Management Initiation rate is primarily driven by the Technology Development Completion Rate and the TD Testing Completion Rate. The amount of management done (in man-hours/week) is an additive sum of the amount of management required for the technology development activity and the amount of management required for the testing activity. The TD Cost Overrun Fraction is a dimensionless variable that captures the amount of cost overruns over the total allocated funding, as a fraction of the total allocated funding. As cost overruns increase (decrease), the management effort associated with juggling the available funds among various activities occurring in the phase increases (decreases). Or in other words, the financial management effort increases (decreases) as the cost overruns increase (decrease). The TD Management Initiation Rate increases at ten percent of the rate of increase in cost overruns (NNS and NAVSEA experts). An increase (decrease) in Funding Stability leads to a decrease (increase) in the TD Management Initiation Rate. Funding Stability (on a scale of 1 to 10; with 1 being most unstable, increasing in stability up to 10 being the most stable) effects the value of TD Management Initiation Rate by a multiplicative factor. At Funding Stability equals 10, the multiplicative factor is 1. At Funding Stability equals 4, the multiplicative factor is 1.1. At Funding Stability equals 1, the multiplicative factor is 1.3. A quadratic curve (of the form $y = ax^2+bx+c$) was fitted through the three points to obtain an analytical expression capturing the effect of Funding Stability on the TD Management Initiation Rate. This equation is exactly the same as the equation for the effect of Funding Stability on the TD Funding Inflow Rate.

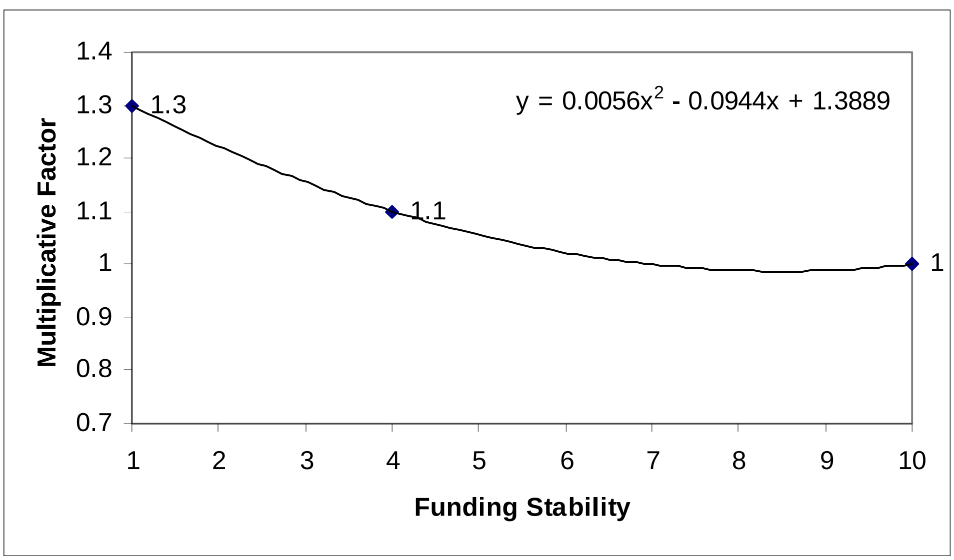

Figure 3.14 Impact of Funding Stability on Management Initiation Rate

The overall equation (with inputs from NNS, NAVSEA experts) to describe the relationship is:

TD Management Initiation Rate = (Technology Development Completion Rate

*TD Management to Development Fraction

+TD Testing Completion Rate

*TD Management to Testing Fraction)

* (1+0.1*TD Cost Overrun Fraction)

* (0.0056*Funding Stability^2 - 0.0944

*Funding Stability + 1.3889) (3.16)

The TD Management Completion Rate is a delay function of the TD Management Effort stock.

TD Management Completion Rate = TD Management Effort /

TD Management Residence Time (3.17)

3.5.7 TD Actual Costs Stock and Flow Structure

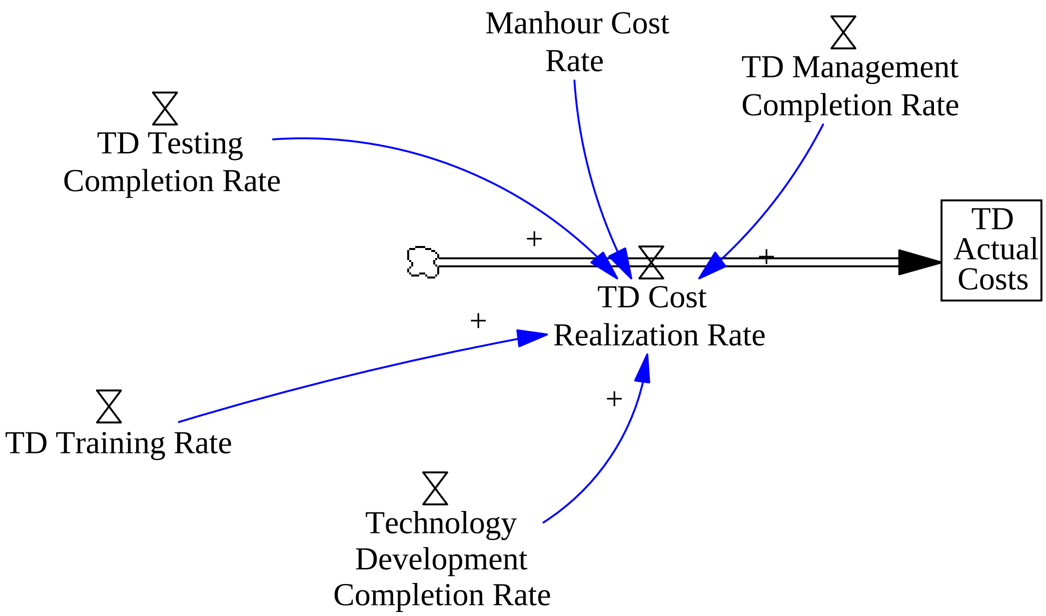

Figure 3.15 TD Actual Costs Stock and Flow Structure

The TD Actual Costs stock (dollars) is fed by a TD Cost Realization Rate (dollars/week). The TD Actual Costs stock variable is an integral of the TD Cost Realization Rate.

TD Actual Costs (t) = TD Actual Costs (0)

$$+ \int [\text{TD Cost Realization Rate}]\, dt \quad (3.18)$$

TD Actual Costs (0) = 0

The TD Cost Realization Rate is driven by the man-hour rates of technology development, testing, and management activities. The Manhour Cost Rate (dollars/man-hour) is the cost of labor and is used to convert the various activities' rate units (man-hours/week) into the TD Cost Realization Rate units (dollars/week). The training rate (dollars/week) also adds to the costs realized per week.

The overall equation to describe the relationship is:

TD Cost Realization Rate = (Technology Development Completion Rate
+TD Management Completion Rate
+TD Testing Completion Rate)*Manhour Cost Rate
+ TD Training Rate (3.19)

3.5.8 TD Cost Overrun Fraction Structure

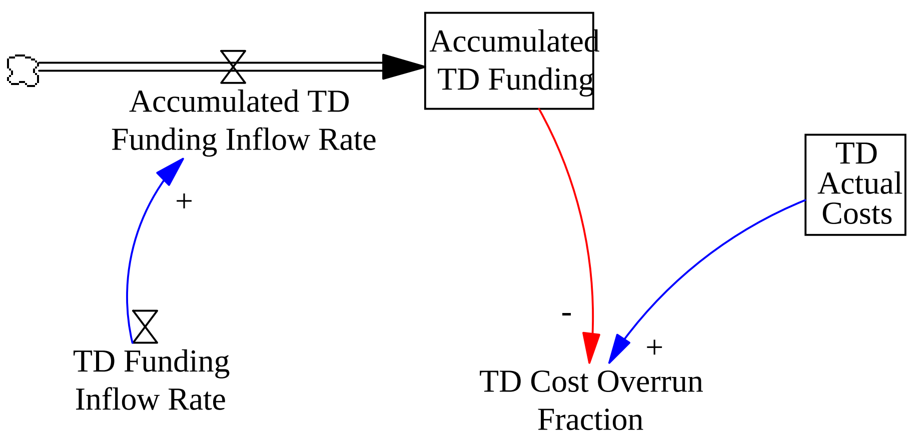

Figure 3.16 TD Cost Overrun Fraction Structure

The Accumulated TD Funding stock (dollars) is fed by the Accumulated TD Funding Inflow Rate (dollars/week). The Accumulated TD Funding stock variable is an integral of the Accumulated TD Funding Inflow Rate. It keeps track of the total amount of funding received at any instant of time.

$$\text{Accumulated TD Funding}(t) = \text{Accumulated TD Funding}(0) + \int [\text{Accumulated TD Funding Inflow Rate}]\, dt \quad (3.20)$$

Accumulated TD Funding (0) = 0

The Accumulated TD Funding Inflow Rate is identical to the TD Funding Inflow Rate.

$$\text{Accumulated TD Funding Inflow Rate} = \text{TD Funding Inflow Rate} \quad (3.21)$$

The TD Cost Overrun Fraction is a dimensionless variable that captures the amount of cost overruns over the total allocated funding, as a fraction of the total allocated funding. It has a value of 0 if the TD Actual Costs are less than the Accumulated TD Funding at a certain instant of time. When TD Actual Costs are greater than the Accumulated TD Funding, a cost overrun results. This cost overrun is captured in the TD Cost Overrun Fraction variable as a fraction of the Accumulated TD Funding.

$$\text{TD Cost Overrun Fraction} = \text{MAX}\,[(\text{TD Actual Costs}-\text{Accumulated TD Funding})/\text{Accumulated TD Funding}, 0] \quad (3.22)$$

where, MAX refers to the maximum function.

3.5.9 TD Training Imparted Stock and Flow Structure

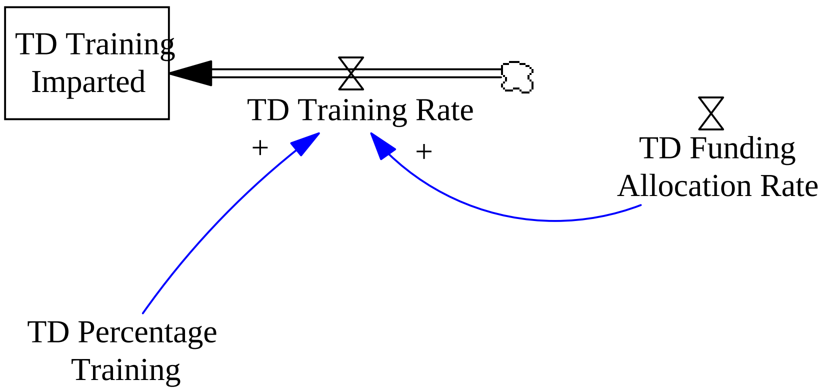

Figure 3.17 TD Training Imparted Stock and Flow Structure

The TD Training Imparted stock (dollars) is fed by a TD Training Rate (dollars/week). The TD Training Imparted stock variable is an integral of the TD Training Rate. It keeps track of the total amount of training imparted to the technology development technical work force at any instant of time.

TD Training Imparted (t) = TD Training Imparted (0) + ∫ [TD Training Rate] dt

(3.23)

TD Training Imparted (0) = 0

The TD Training Rate is determined as a percentage of the TD Funding Allocation Rate.

TD Training Rate = TD Funding Allocation Rate * TD Percentage Training

(3.24)

3.5.10 TD Risk Structure

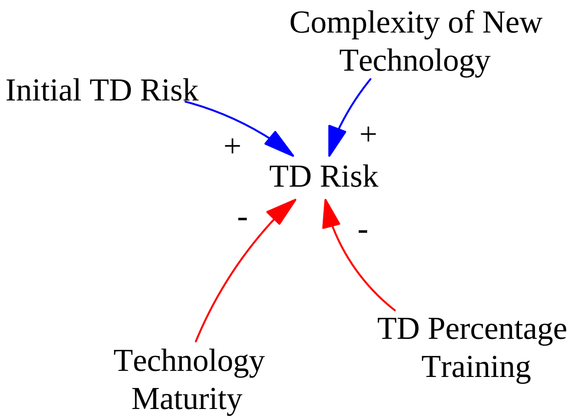

Figure 3.18 TD Risk Structure

The TD Risk is a dimensionless variable that measures the risk associated in the development of new technology. It is measured on a scale of 1 to 10. The TD Risk is driven by a user-input Initial TD Risk value (input values can be 2=very low risk, 3.5=low risk, 5=average risk, 6.5=high risk, and 8=very high risk). An increase (decrease) in the percentage training received by the work force leads to a decrease (increase) in the TD Risk. The rate of change of TD Risk with the change in TD Percentage Training is linear, and has different rates of change for different values of Initial TD Risk (NNS and NAVSEA experts). The following graphical relationship between TD Risk and TD Percentage Training at different values of Initial TD Risk (ITDR) was elicited from NNS and NAVSEA experts.

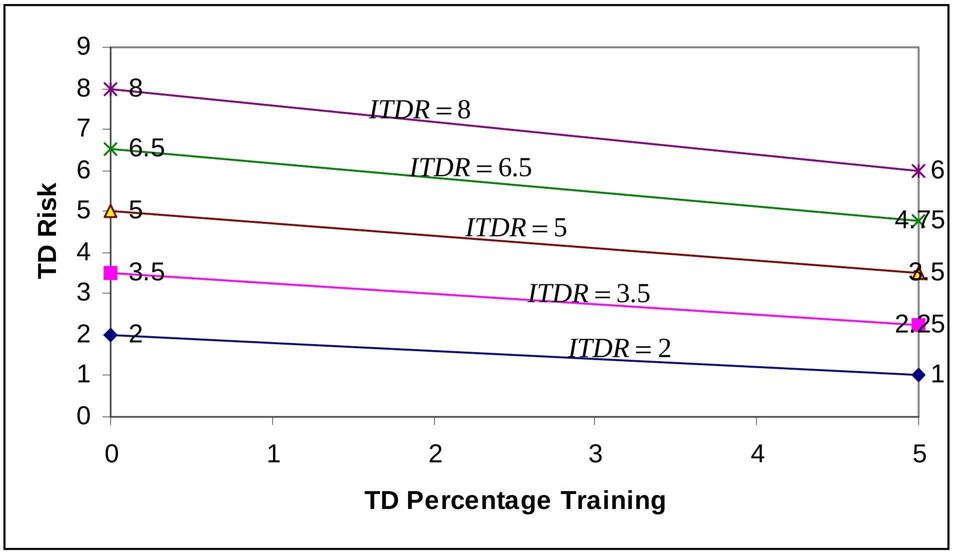

Figure 3.19 Impact of TD Percentage Training on TD Risk

The equations for the above shown lines are y=8-40x (at ITDR=8), y=6.5-35x (at ITDR=6.5), y=5-30x (at ITDR=5), y=3.5-25x (at ITDR=3.5), and y=2-20x (at ITDR=2). As there is a symmetric change of slope across the five ITDR values, the above five equations can be combined into one as:

$$y = ITDR - (20+5*(ITDR-2)/1.5) * x$$

where x is the TD percentage training and y is the TD risk.

An increase (decrease) in Complexity of New Technology leads to an increase (decrease) in the TD Risk. Complexity of New Technology (on a scale of 1 to 5; with 1=very low complexity, 2=low complexity, 3=medium complexity, 4=high complexity, 5=very high complexity) effects the TD Risk by a multiplicative factor. When the complexity of New Technology equals 1, the multiplicative factor is 0.8. It is assumed to follow a linear relationship with the Complexity of New Technology up to a value of 5, where the multiplicative factor is 1.2. A straight line (of the form y = mx+c) was fitted through the two points to obtain an analytical expression capturing the effect of Complexity of New Technology on the TD Risk. The curve fitting was done manually. The graph depicted below (Figure 3.20) was plotted in MS Excel 2000.

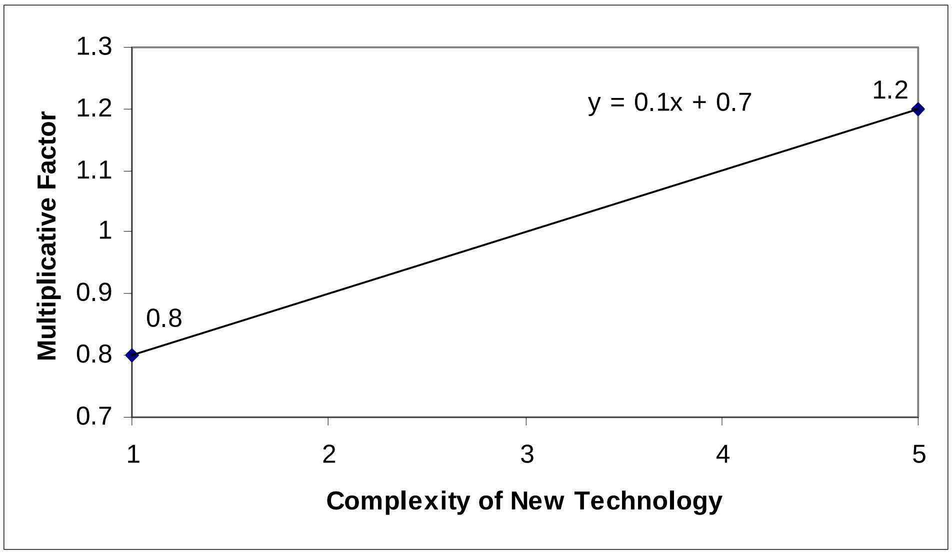

Figure 3.20 Impact of Complexity of New Technology on TD Risk

An increase (decrease) in Technology Maturity leads to an decrease (increase) in the TD Risk. Technology Maturity (on a scale of 1 to 5; with 1=very immature, 2=immature, 3=medium mature, 4=mature, and 5=very mature) effects the TD Risk by a multiplicative factor. At Technology Maturity equals 1, the multiplicative factor is 1.2. It follows a linear relationship with the Technology Maturity up to a value of 5, where the multiplicative factor is 0.8. A straight line (of the form y = mx+c) was fitted through the two points to obtain an analytical expression capturing the effect of Technology Maturity on the TD Risk. The curve fitting was done manually. The graph depicted below (Figure 3.21) was plotted in MS Excel 2000.

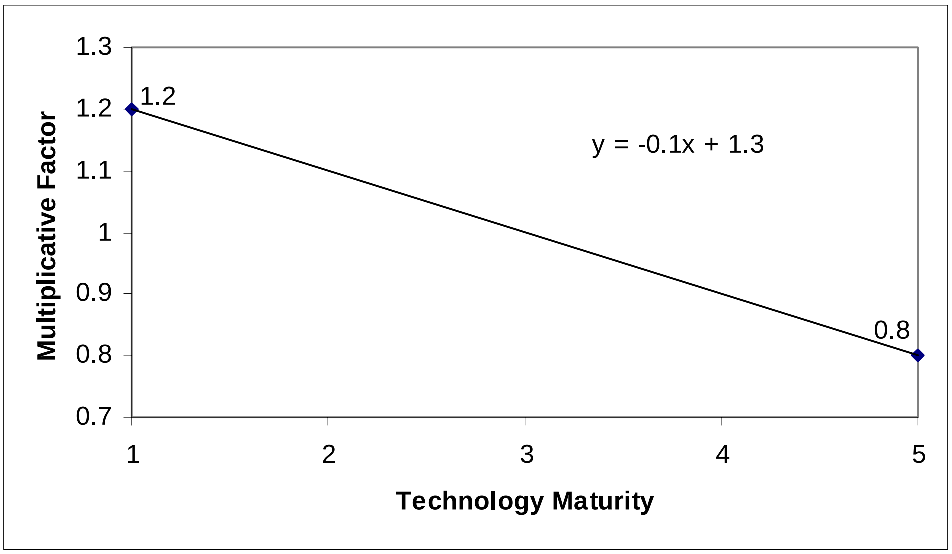

Figure 3.21 Impact of Technology Maturity on TD Risk

The overall equation (with inputs from NNS, NAVSEA experts) to describe the relationship is:

TD Risk = (Initial TD Risk - (20+5*(Initial TD Risk-2)/1.5)*TD Percentage Training)

* (0.7+0.1*Complexity of New Technology)

* (1.3-0.1*Technology Maturity) (3.25)

Chapter 4. Results, Testing, Sensitivity Analysis, Validation and Verification

The model presented in Chapter 3 was programmed in VENSIM Professional 4.0 software. The model was simulated for a specific technology whereby NNS and NAVSEA experts provided the user-input parameters. For a different technology, there would have been a different set of parameters. The results obtained from running the simulation are discussed in this chapter. The dynamic hypotheses discussed in Chapter 3, Section 3.2 were tested using the model developed in VENSIM Professional 4.0 by varying parameters and observing the changes in the subsequent results from the simulation. Some sensitivity analysis was also performed on the model. The simulation was run using three sets of key parameter combinations, namely, (1) very high technology complexity-very immature technology-no training, (2) medium technology complexity-medium mature technology-average training, and (3) very low technology complexity-very mature technology-high training. These were chosen to represent two extreme condition scenarios and an average condition scenario. The results obtained are presented in this chapter.

Validation and verification of the model seeks to enable experts and modelers to have a better understanding of the system and share their views. This step involves the testing of the model as to whether it replicates the behavior of the real-world system. Another important task of validation and verification is to verify whether the variables and parameters of the model have a meaningful concept in the real world. When models are subjected to extreme conditions, their robustness is determined. A model should not just be a means to mirror field data exactly. In addition, its elements should have a sound conceptual basis for being in the model. The process of judging the validity of a system dynamics model includes a number of objective tests (Richardson and Pugh, 1981, and Sterman, 2000) that are discussed extensively in this chapter in Section 4.4.

4.1 Results

The simulation for the model was run with the following parameters:

4.1.1 Simulation Control Parameters

FINAL TIME (The final time for the simulation) = 104 Weeks

The implementation of the model was for a specific technology whereby a time horizon of two years was used based on inputs from NNS and NAVSEA experts. For another technology, a different time horizon would have been used.

INITIAL TIME (The initial time for the simulation) = 0 Week

TIME STEP (The time step for the simulation) = 0.03125 Week

A time step of 0.03125 week was used so as to give smooth time profiles for the different variables in the model.

4.1.2 User defined parameters

TD Management to Development Fraction (This represents the average effort (in man-hours) spent in management activities as a fraction of the effort (in man-hours) spent in technology development activities.) = 0.15

TD Testing to Development Fraction (This represents the average effort (in man-hours) spent in testing activities as a fraction of the effort (in man-hours) spent in technology development activities.) = 1/6

TD Management Residence Time (This represents the average delay for management activities.) = 1 Week

TD Management to Testing Fraction (This represents the average effort (in man-hours) spent in management activities as a fraction of the effort (in man-hours) spent in testing activities.) = 0.1

Initial TD Risk = 6.5 (High Risk)

The implementation of the model was for a specific technology whereby the Initial TD Risk was set as High Risk (6.5) based on inputs from NNS and NAVSEA experts. For another technology, a different Initial TD Risk would have been used.

TD Percentage Training (This represents the percentage of total available funds spent for training activities) = 0.5 % of Total Funding

TD Funding Residence Time (This represents the average delay of funds in the subsystem.) = 1 Week

Technology Development Effort Residence Time (This represents the average technology development time.) = 8 Weeks

TD Testing Residence Time (This represents the average testing time.) = 4 Weeks

Complexity of New Technology = 4 (High Complexity)

The implementation of the model was for a specific technology whereby the complexity of the technology was set as High Complexity (4) based on inputs from NNS and NAVSEA experts. For another technology, a different Complexity of New Technology would have been used.

Funding Stability = 8 (High funding stability)

The implementation of the model was for a specific technology whereby the Funding Stability was set as high (8) based on inputs from NNS and NAVSEA experts. For another technology, a different Funding Stability would have been used.

Manhour Cost Rate = 35 dollars/man-hour

NNS and NAVSEA experts provided the information that the average cost of labor was 35 dollars/man-hour.

Technology Maturity = 3 (Medium maturity)

The implementation of the model was for a specific technology whereby the Technology Maturity was set as medium (3) based on inputs from NNS and NAVSEA experts. For another technology, a different Technology Maturity would have been used.

The simulation runs showed two main modes of dynamic behavior. One dynamic behavior was the damped oscillation observed for the variables Technology Development Effort, TD Testing Effort, TD Management Effort, and TD Actual Costs Realization rate. The feedback structure causing this type of dynamic behavior is identified below in Figure 4.1.

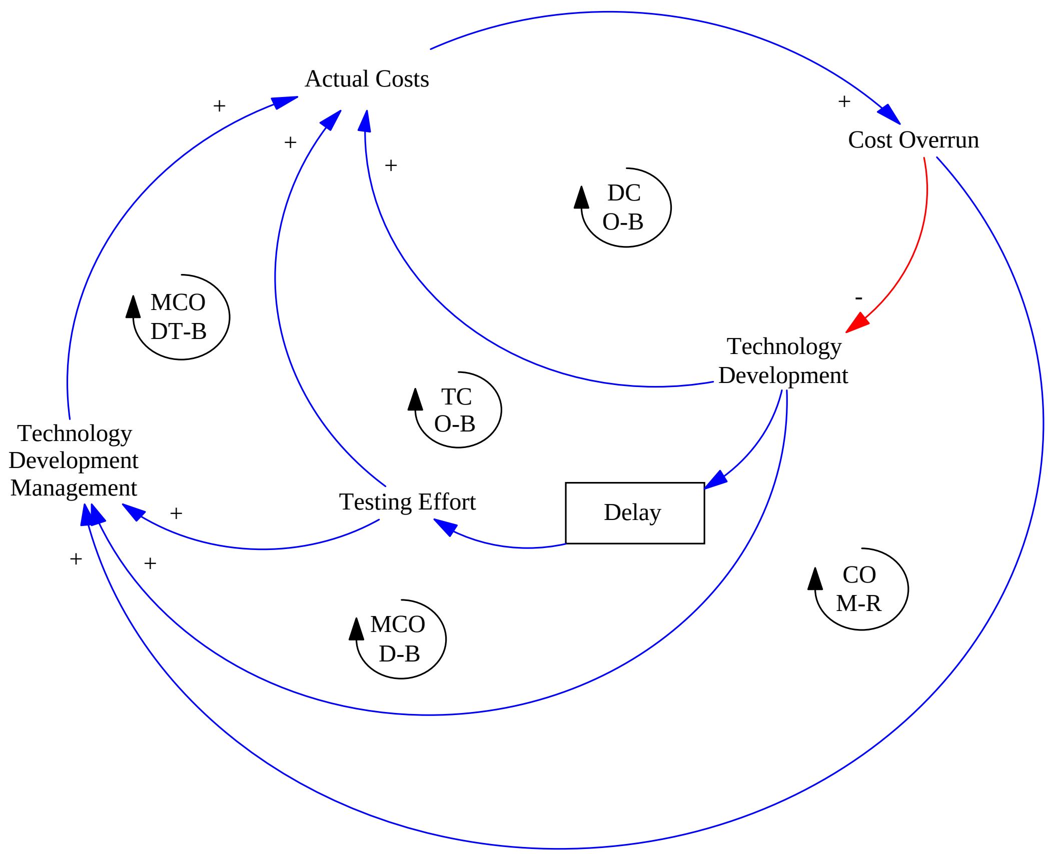

Figure 4.1 Feedback Structure Causing Damped Oscillation

Oscillation arises due to negative feedback with significant time delays (Sterman, 2000). Corrective action taken to restore the equilibrium state or to achieve the goal of the system continues to be taken even after the equilibrium has been reached due to time delays in identifying the effects of the actions on the system. Thus the goal is overshot. Corrective action taken again (negative feedback loop) leads to undershooting and hence oscillation. In a damped oscillation, as the name suggests, the oscillations die out as time passes. Sterman (2000) says that many real world oscillatory system structures are damped. Damped oscillatory structures are characterized by a set of negative feedback loops as can be seen in Figure 4.1 above. As technology development effort goes up (down), the man-hours required to carry out the actual effort goes up (down). The man-hour effort for associated testing and management activities goes up (down) too. This drives up (down) the actual costs of the technology development phase. As the costs increase (decrease), the cost overruns increase (decrease). An increase (decrease) in the cost overruns invokes corrective action taken to restore budgetary equilibrium by effecting a decrease (increase) in the technology development activity (as a control feedback mechanism). Corrective action taken to restore the budgetary equilibrium continues to be taken even after the equilibrium has been reached due to time delays in identifying the effects of the actions on the system. Thus the goal is overshot. Corrective action taken again leads to undershooting and hence oscillation.

4.1.3 Technology Development Effort

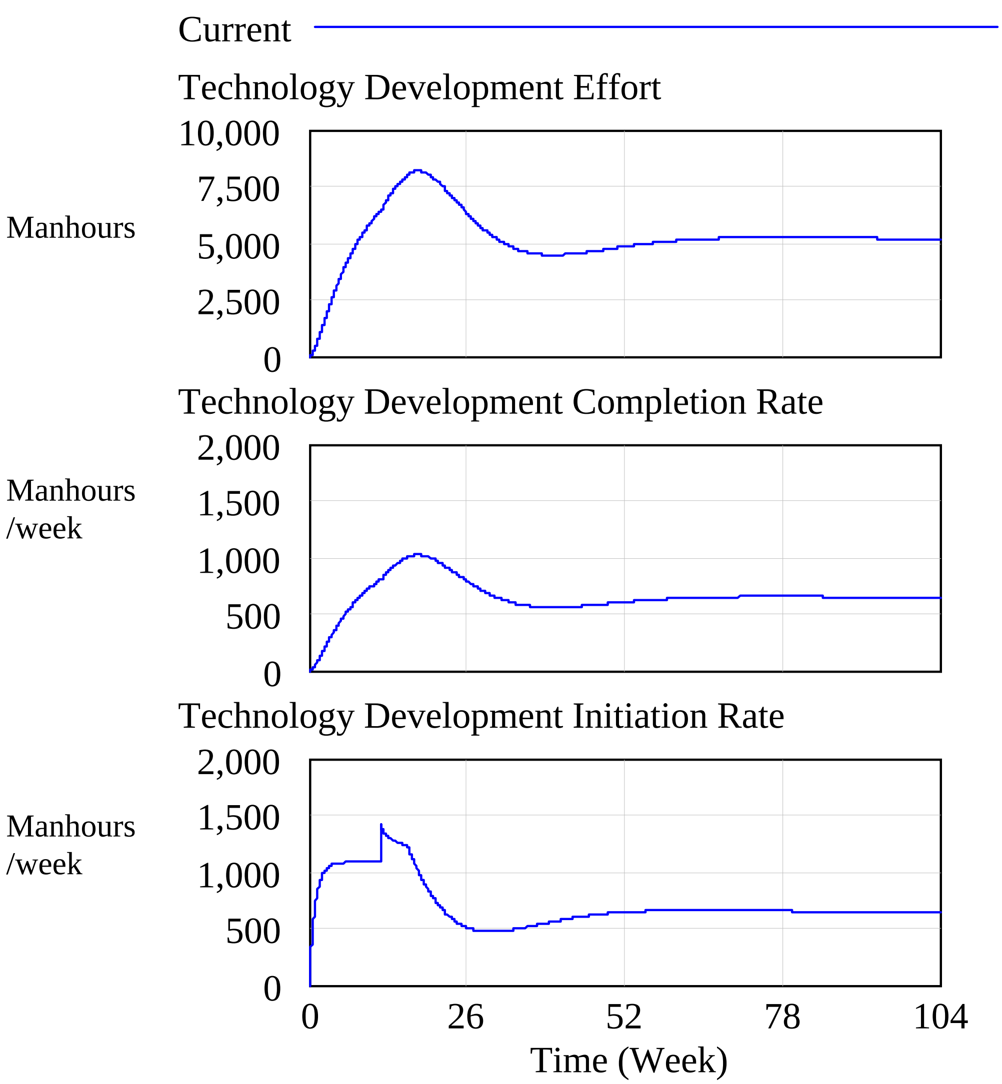

Figure 4.2 Technology Development Stock and Flows Behavior

The amount of technology development effort to be done builds up over time. As technology development effort that needs to be done is actually carried out, the costs associated with the technology development activity accumulate. Once the costs overshoot the incoming funding, the associated cost overruns dictate a slowdown in the technology development activity to help reduce costs and thus remain within the funding constraints. This slowdown is observed around week 16 and confines to week 32. The equilibrium value of the rate at which technology development needs to be done appears to be 652 man-hours/week on running the simulation. Figure 4.2 shows the damped oscillatory behavior observed on running the simulation. A sharp vertical jump is observed in the Technology Development Initiation Rate at week 12. This is attributed to the influx of the first Redevelopment activity based on the technology development and testing having been done till then.

4.1.4 TD Testing Effort

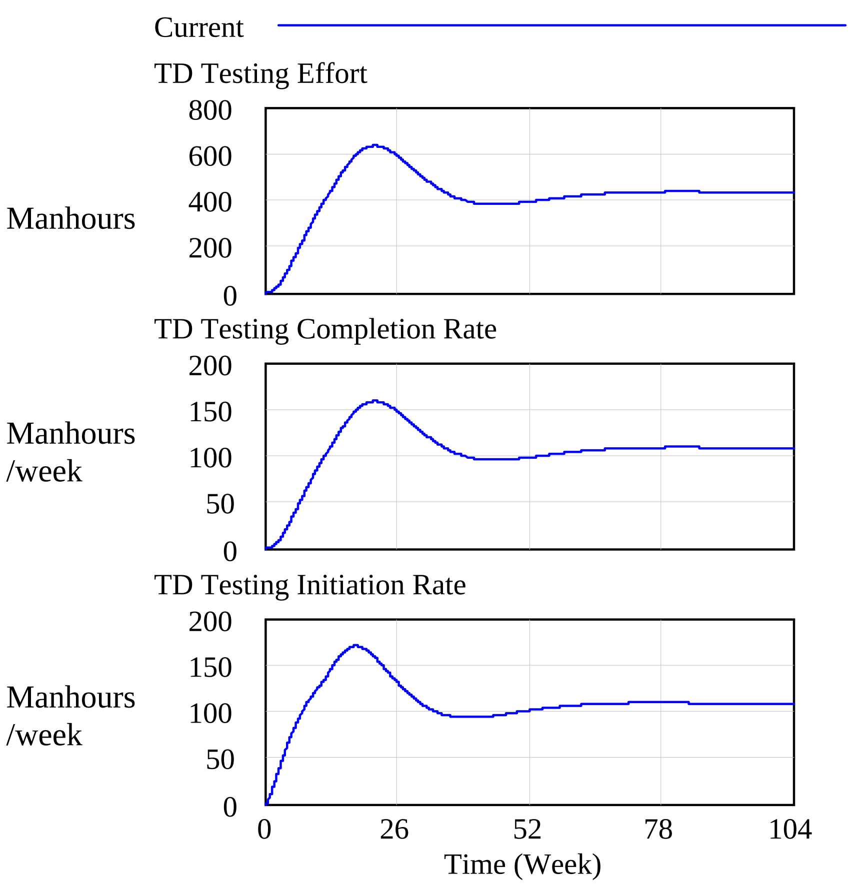

Figure 4.3 TD Testing Stock and Flows Behavior

The amount of technology development testing effort to be done builds up over time. As technology development testing effort that needs to be done is actually carried out, the costs associated with the technology development testing activity accumulate. Once the costs overshoot the incoming funding, the associated cost overruns dictate a slowdown in the technology development testing activity to help reduce costs and thus remain within the funding constraints. This slowdown is observed around week 20 and goes up to week 38. The equilibrium value of the rate at which TD testing needs to be done appears to be 108 man-hours/week on running the simulation. The figure (Figure 4.3) above shows the damped oscillatory behavior observed on running the simulation.

4.1.5 TD Management Effort

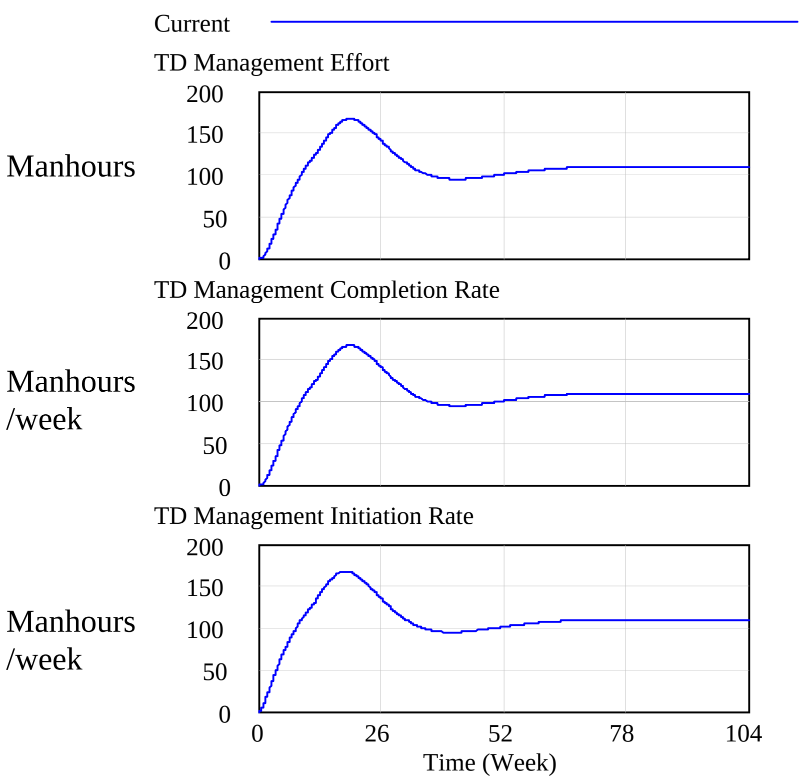

Figure 4.4 TD Management Stock and Flows Behavior

The amount of technology development management effort to be done builds up over time. As technology development management effort that needs to be done is actually carried out, the costs associated with the technology development management activity accumulate. Once the costs overshoot the incoming funding, the associated cost overruns dictate a slowdown in the technology development and testing activities to help reduce costs and thus remain within the funding constraints. This reduces the rate of management activity associated with the technology development and testing activities. This slowdown is observed around week 20 and goes up to week 40. On the other hand, cost overruns entail an increase in management effort to juggle the various activities taking place so as to remain within the funding constraints. However, this decrease in management activity as a result of a slow down in the technology development and testing activities dominates the increase in management activity associated with the financial management of cost overruns. The equilibrium value of the rate at which TD Management needs to be done appears to be 109 man-hours/week on running the simulation. The figure (Figure 4.4) above shows the damped oscillatory behavior observed on running the simulation.

4.1.6 TD Actual Costs

The rate at which costs are incurred in the technology development, testing and management efforts builds up over time. Once the costs overshoot the incoming funding, the associated cost overruns dictate a slowdown in the technology development and testing efforts to help reduce costs and thus remain within the funding constraints. This leads to a decrease in the cost realization rate. This slowdown is observed around week

20 and goes up to week 40. The equilibrium value of the rate at which costs are incurred appears to be 30,100 dollars/week on running the simulation. The figure (Figure 4.5) below shows the damped oscillatory behavior observed on running the simulation.

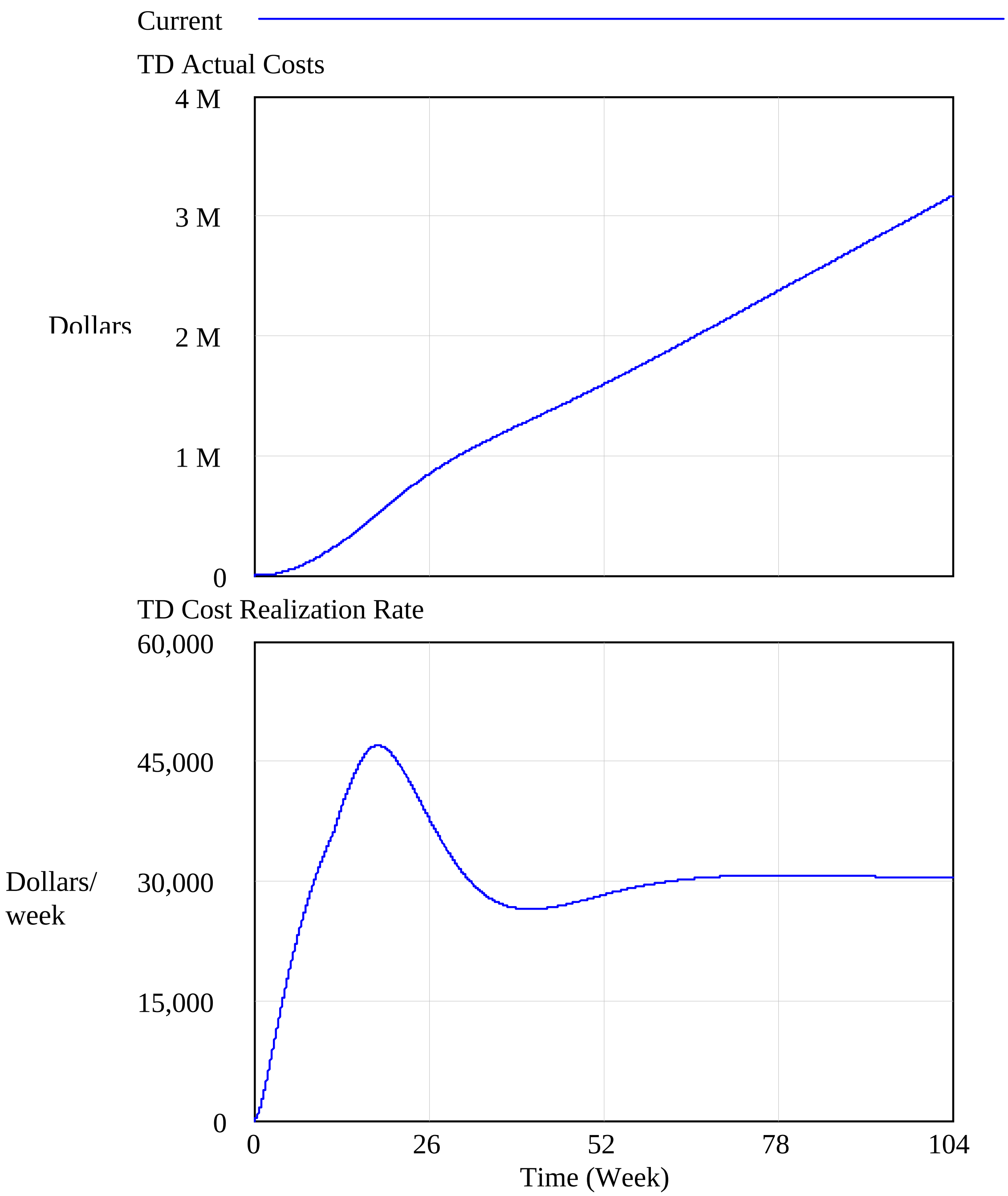

Figure 4.5 TD Actual Costs and Cost Realization Rate

The other dynamic behavior was the goal seeking observed for the variable Actual Testing results. The feedback structure causing this type of dynamic behavior is identified below.

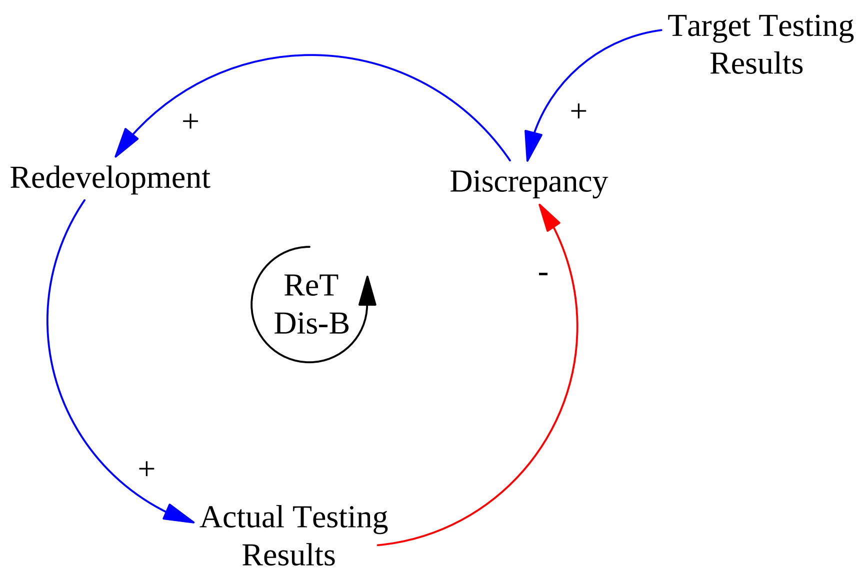

Figure 4.6 Feedback Structure Causing Goal Seeking

Goal seeking behavior arises from negative or self-controlling feedback (Sterman, 2000). Negative feedback loops tend to oppose any changes or deviations in the state of the system; they tend to restore equilibrium and hence are goal seeking. The rate of change diminishes as the goal is approached, such that there is a smooth attainment of the goal/equilibrium state of the system.

4.1.7 TD Redevelopment, TD Results Discrepancy, and Actual Testing Results

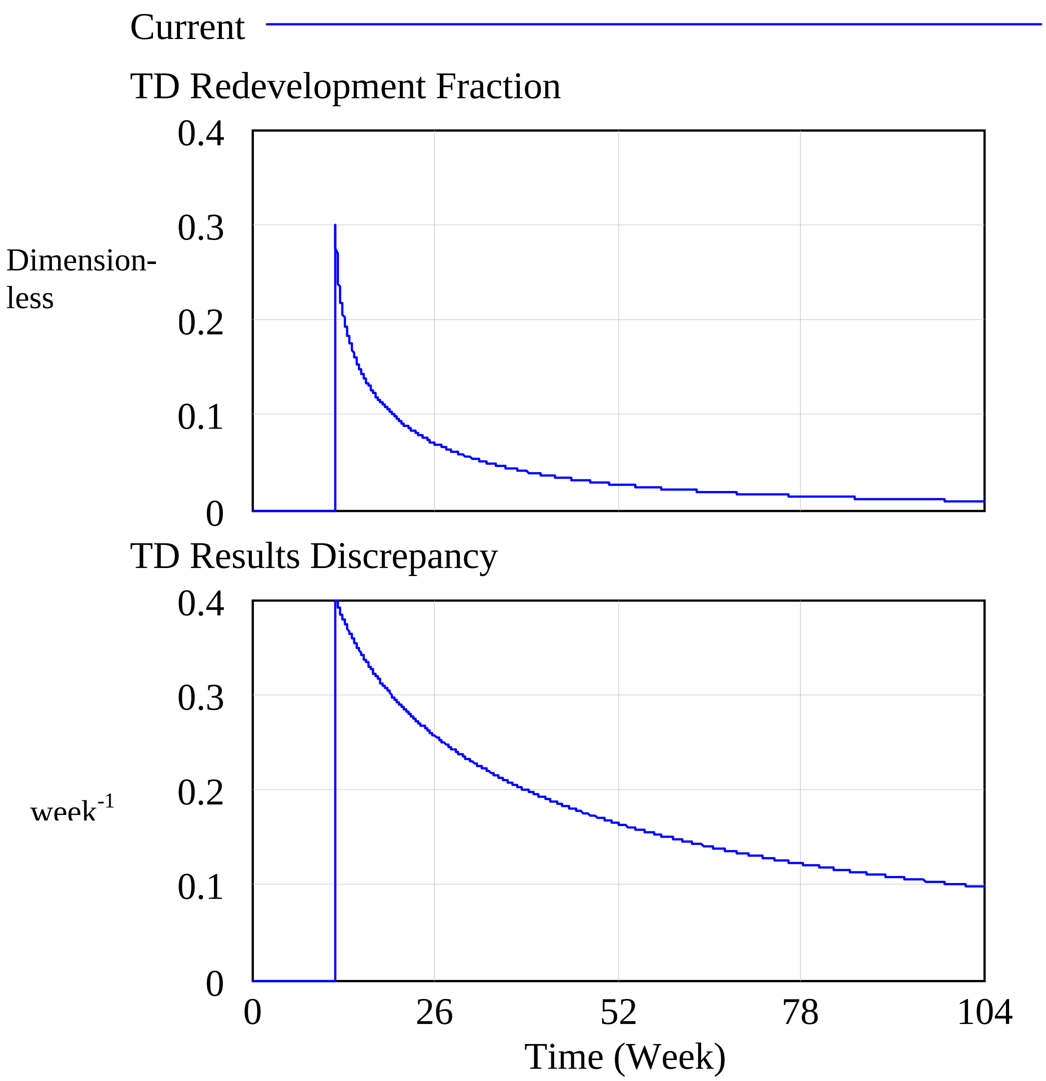

Figure 4.7 TD Redevelopment Fraction and Results Discrepancy

It was assumed for the model formulation that the technology development activity yields sixty percent of the desired results when it is carried out for the first time before any redevelopment activity has been initiated. The first testing results yield a forty percent discrepancy, based on which a redevelopment effort equal to thirty percent of the technology development activity is initiated. There is an observed delay associated with the redevelopment activity. This is attributed to the model formulation wherein it was assumed that the first redevelopment activity starts at week 12 once some technology development and testing activities have taken place. Once the initiated redevelopment activity is carried out and testing done on it, there is an increase in the actual testing results. Thus the testing results discrepancy decreases, hence decreasing the rate at which further redevelopment activity and testing results enhancement occurs. The figures above (Figure 4.7) and below (Figure 4.8) show the goal seeking behavior observed on running the simulation.

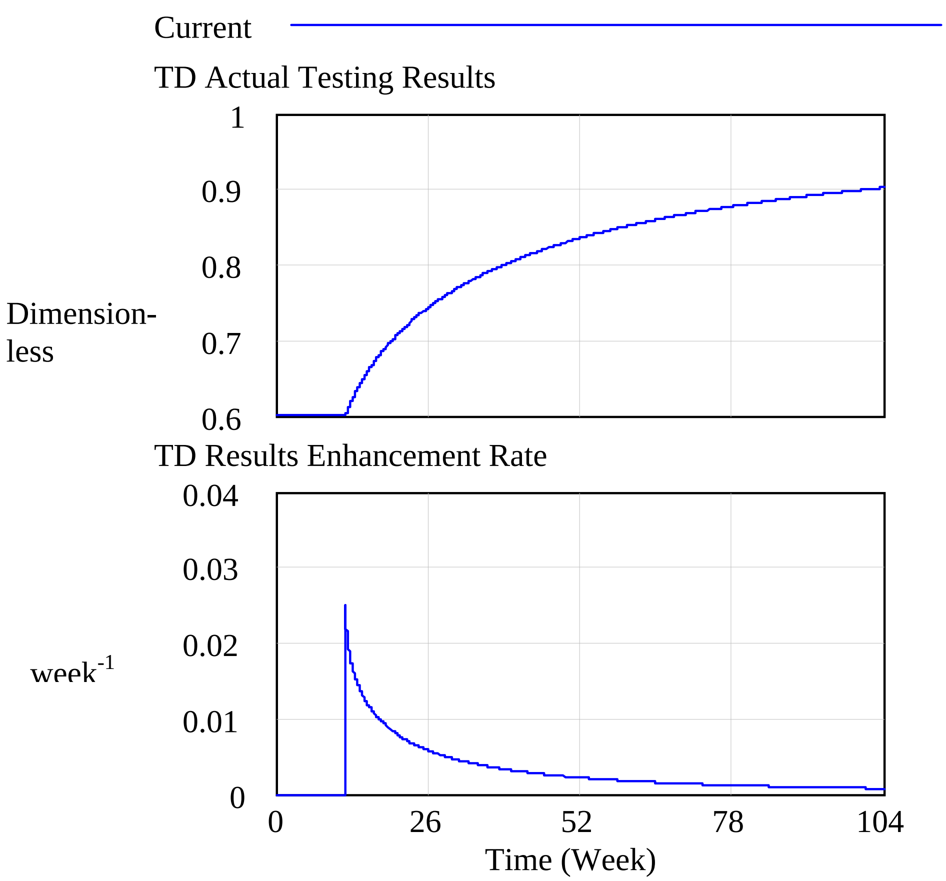

Figure 4.8 TD Results Enhancement Rate and Actual Testing Results

4.2 Hypotheses Testing: Cost Performance Drivers

Hypothesis 1: A lack of appropriate training causes cost overruns and higher costs in the technology development process.

The simulation was run at three levels of TD Training Percentages. The first simulation was run at a TD training level being 0.5 % of the available funding. The second simulation was run at a TD training level being 2.0 % of the available funding. The third simulation was run at a TD training level being 4.5 % of the available funding. The results are shown in Figure 4.9.

It is observed that the TD Actual costs, the TD Cost Realization rate, and the TD Cost Overrun fraction decrease as the amount of training imparted (as a percentage of available funding) is increased. The results demonstrate that the hypothesis that increased training reduces the total costs and the cost overruns incurred is shown for the current structure of the model.

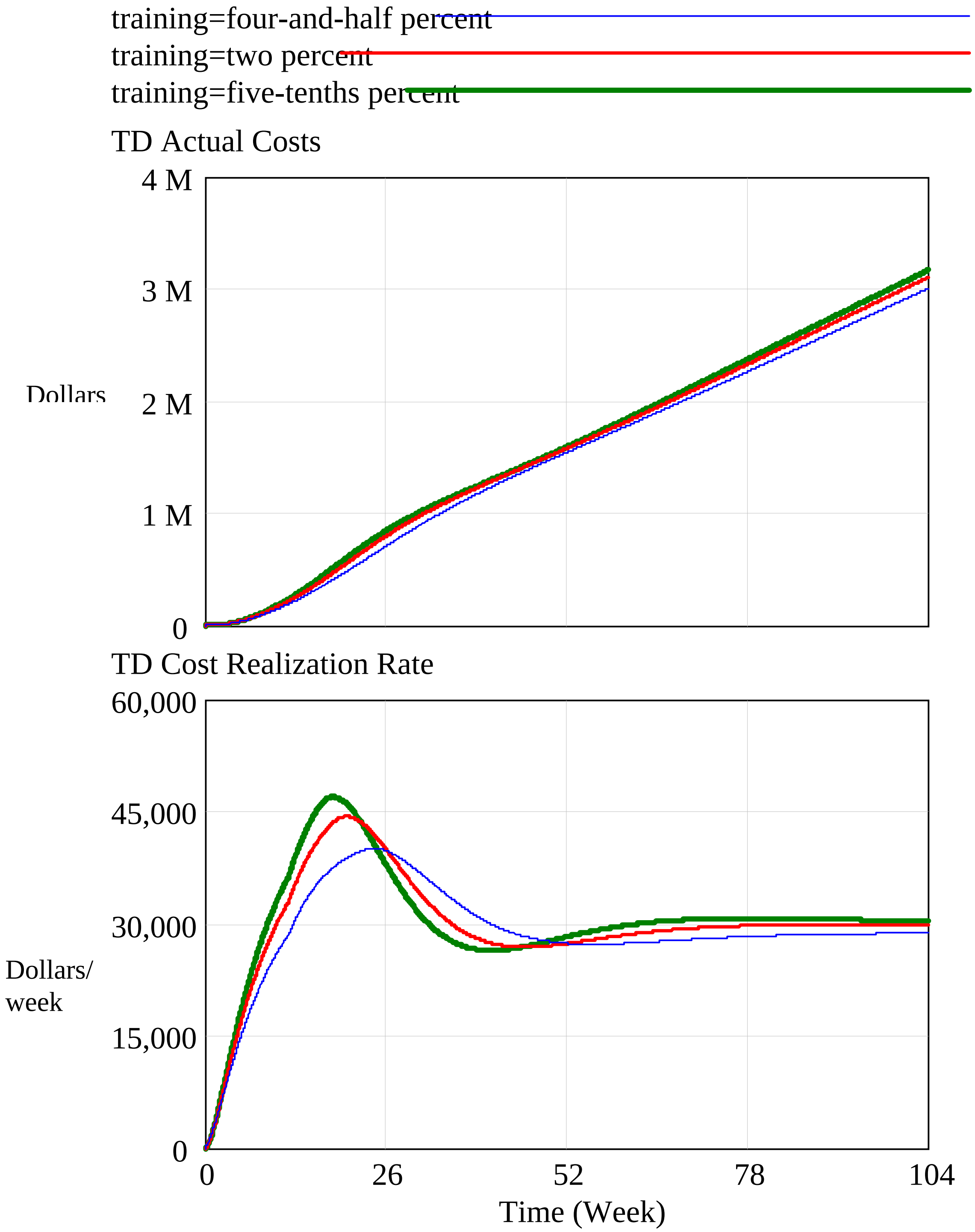

Figure 4.9 TD Costs at Three Training Levels

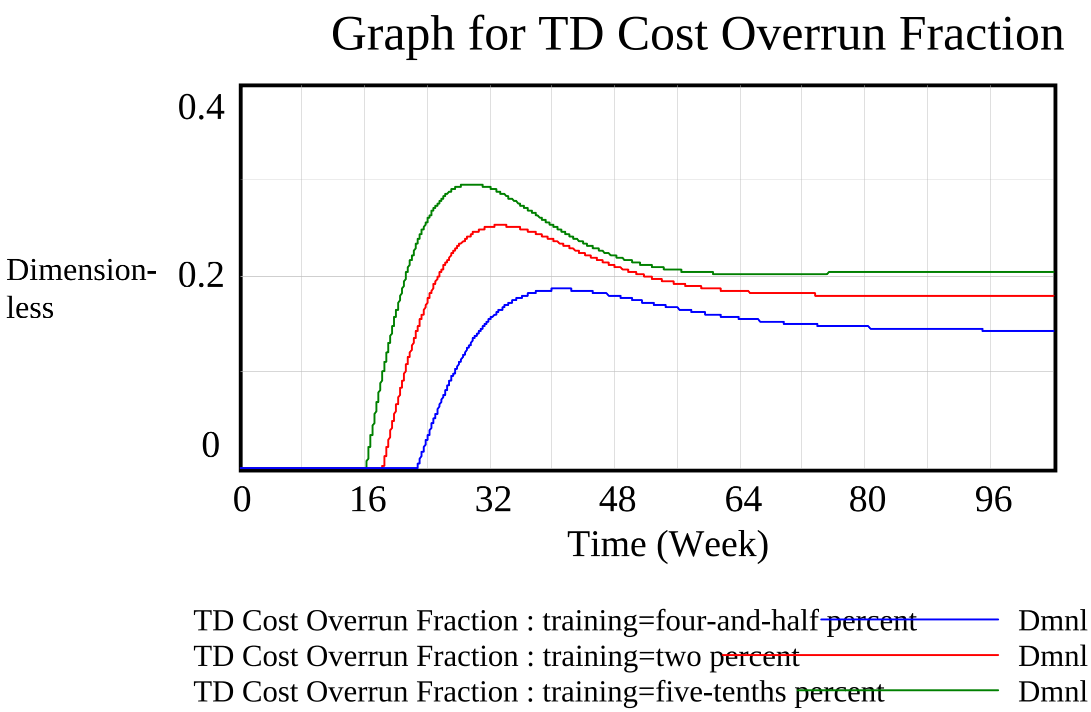

Figure 4.10 TD Cost Overrun Fraction at Three Training Levels

Hypothesis 2: Redevelopment activities completed in the technology development process add significantly to the cost overruns and the total costs incurred.

The simulation was run at three profiles of TD redevelopment fractions. The first simulation was run at a profile of TD redevelopment fraction versus TD Results discrepancy given by Equation 3.13:

$$\text{TD Redevelopment Fraction} = 0.3 - 0.3 * \sqrt{1 - TDResultsDiscrepancy^2 / 0.16}$$

The TD Redevelopment Fraction is a dimensionless variable that captures the amount of redevelopment done as a fraction of the development activity assigned in the first place.

It is determined by the TD Results Discrepancy. An increase (decrease) in TD Results discrepancy leads to an increase (decrease) in the redevelopment efforts to correct the discrepancy.

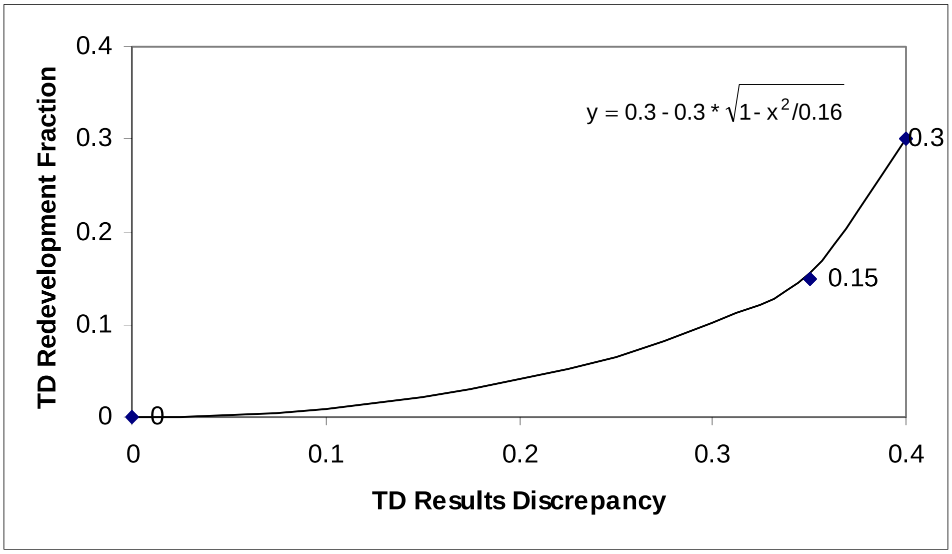

Figure 4.11 Impact of TD Results Discrepancy on TD Redevelopment Fraction

Figure 4.11 (which is the same as Figure 3.12) depicts the relationship between the TD Redevelopment Fraction and TD Results Discrepancy as elicited from NNS and NAVSEA experts.

The second simulation was run at a thirty-five percent higher redevelopment versus discrepancy profile,

TD Redevelopment Fraction = 1.35 * [0.3 – 0.3* $\sqrt{1 - TDResultsDiscrepancy^2 / 0.16}$)]

The third simulation was run at a seventy percent higher redevelopment versus discrepancy profile, TD Redevelopment Fraction = 1.70 * [0.3 – 0.3* $\sqrt{1 - TDResultsDiscrepancy^2 / 0.16}$)]

The results are shown below in Figure 4.12 and Figure 4.13.

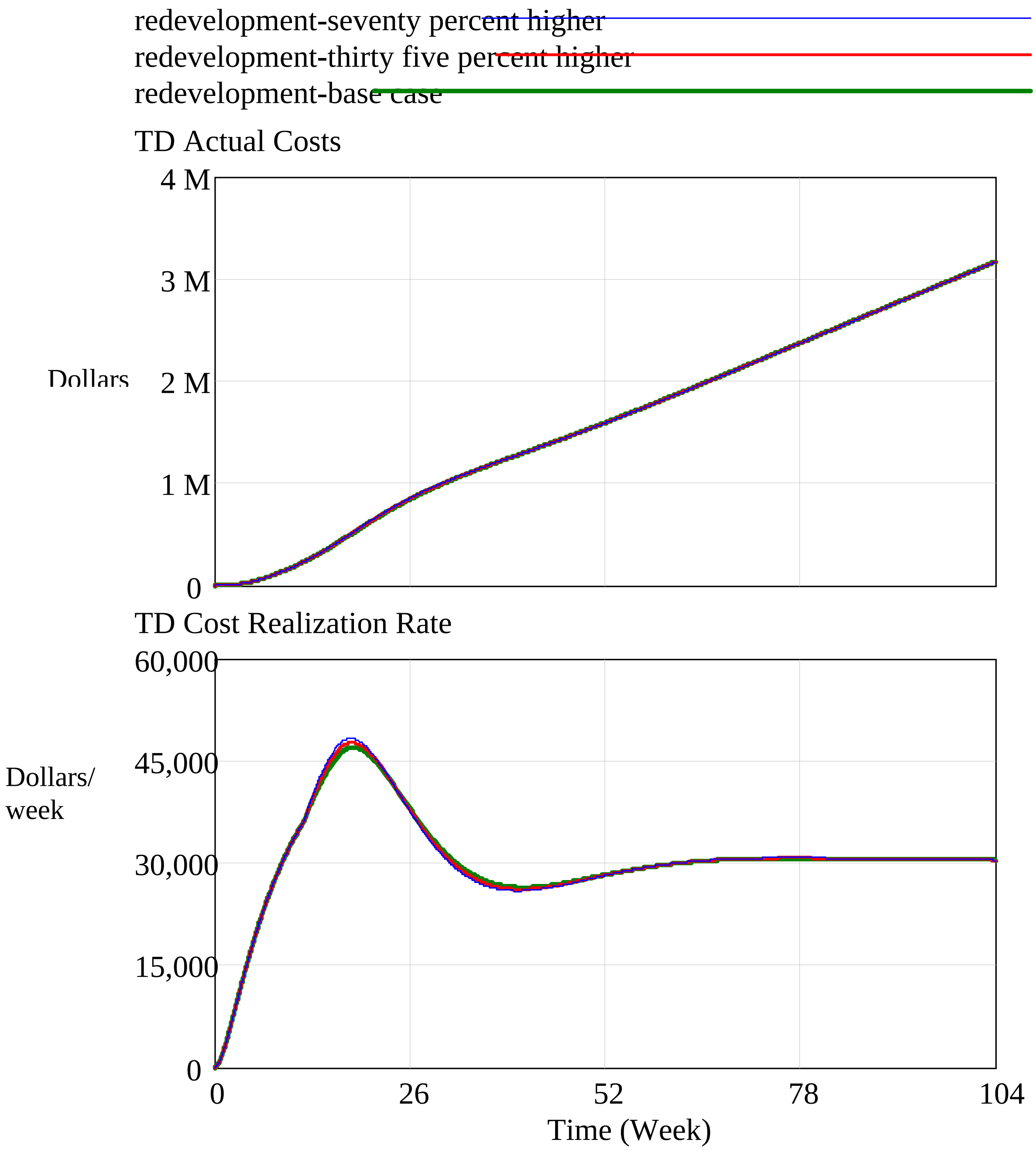

Figure 4.12 TD Costs at Three Redevelopment Levels

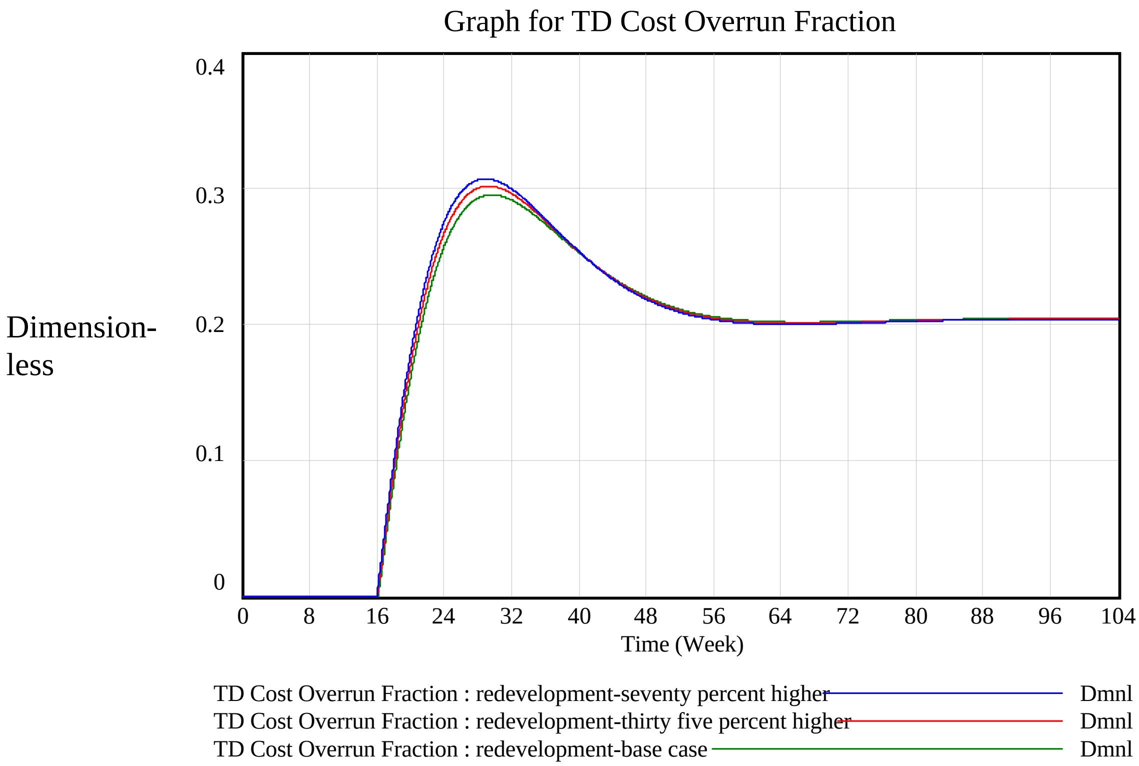

Figure 4.13 TD Cost Overrun Fraction at Three Redevelopment Levels

The results show that the increase in amount of redevelopment done as a fraction of the technology development activity does not substantially increase the total incurred costs. However, analysis of the effect of the increase in TD redevelopment fractions on the TD Testing Results show (see Figure 4.14 below) a significant increase in testing results when the redevelopment activity is increased. The conclusion that can be drawn from this is that an increase in redevelopment fraction increases the rate at which results are enhanced. Therefore, a faster decrease in the discrepancy between the target testing results and the actual testing results leads to a decrease in the amount of redevelopment that needs to be done further on. This could be a possible explanation for the dynamics wherein the costs do not increase when redevelopment is increased. So, within the limitations and assumptions made for the model, insufficient understanding exists to show the hypothesis true. On the other hand, the hypothesis testing brought forth an interesting observation of the testing results getting better when the redevelopment fraction is increased, without an increase in the total costs incurred. One of the reasons for this could be that the rate at which results enhancement is set up in the model is too fast. This means that when redevelopment is done, the results get better at a very fast rate compared to the rate at which redevelopment is done. Therefore, redevelopment activities do not contribute substantially to the increase in costs.

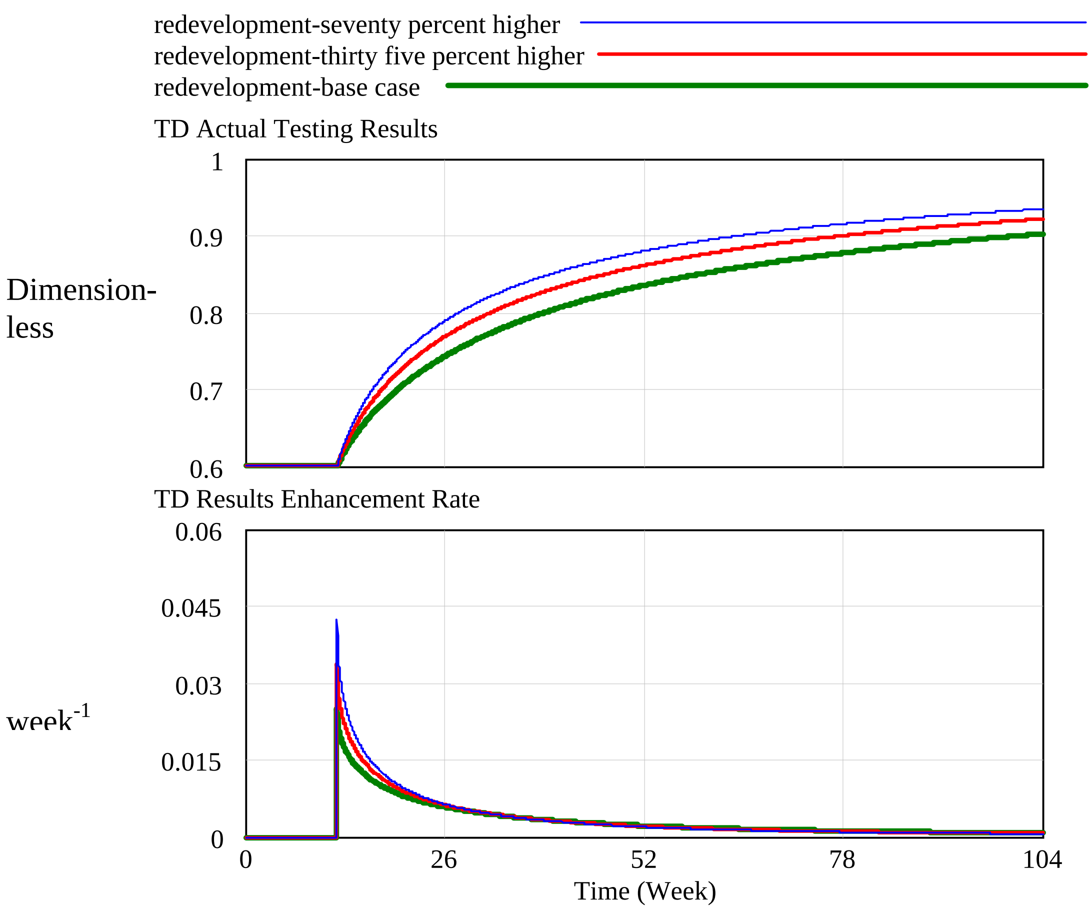

Figure 4.14 TD Results Enhancement Rate and Actual Results at Three Redevelopment Levels

Hypothesis 3: An increase in the complexity of the new technology causes an increase in the total costs incurred.

The simulation was run at three levels of Complexity of New Technology. The first simulation was run at a Complexity of New Technology being 1 (Very Low Complexity). The second simulation was run at a Complexity of New Technology being 3 (Medium Complexity). The third simulation was run at a Complexity of New Technology being 5 (Very High Complexity). The results are shown in Figure 4.15.

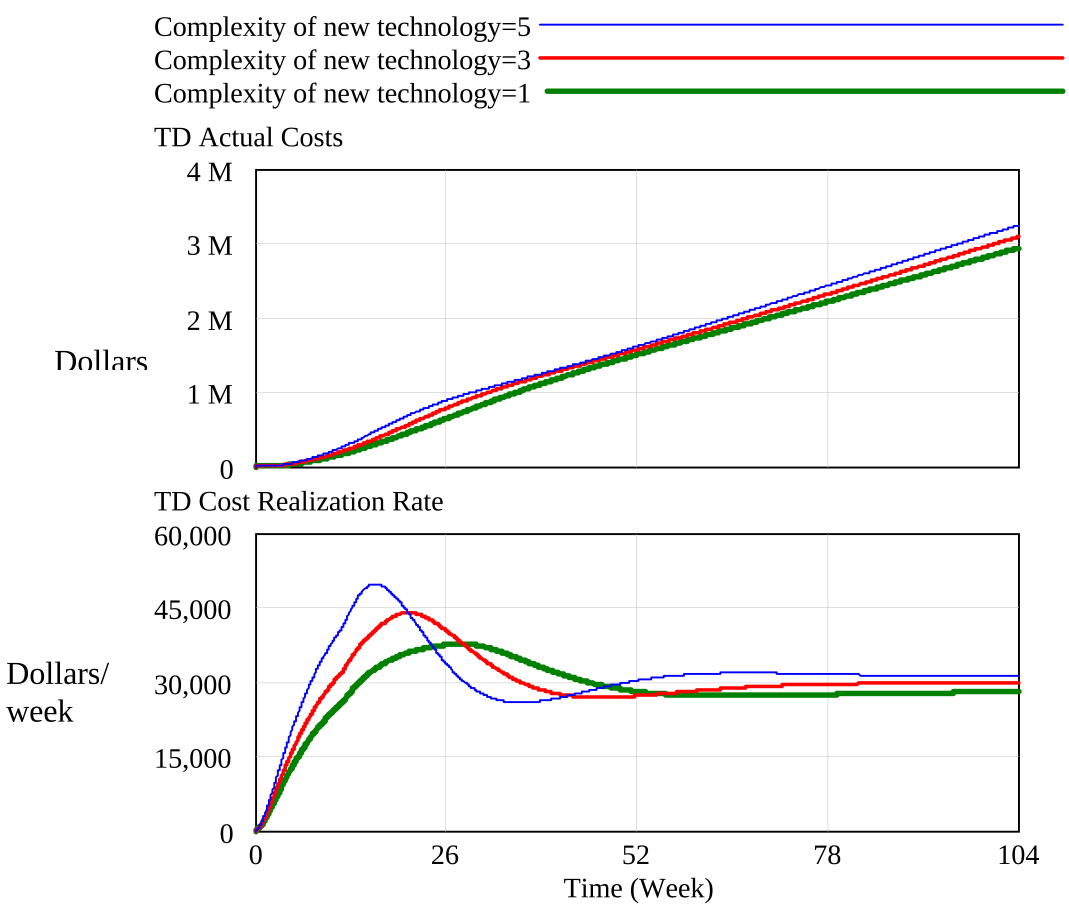

Figure 4.15 TD Costs at Three Levels of Complexity

It is observed that the TD Actual costs and the TD Cost Realization rate increase as the Complexity of New Technology increases. The results demonstrate that the hypothesis that increased Complexity of New Technology increases the total costs incurred is shown for the current structure of the model. The costs increase by about 11% when the complexity of technology increase from 1 (very simple) to 5 (very complex).

Hypothesis 4: An increase in the maturity of the new technology causes a decrease in the total costs incurred.

The simulation was run at three levels of Technology Maturity. The first simulation was run at a Technology Maturity being 1 (Very Immature). The second simulation was run at a Technology Maturity being 3 (Medium Mature). The third simulation was run at a Technology Maturity being 5 (Very Mature). The results are shown below in Figure 4.16.

It is observed that the TD Actual costs and the TD Cost Realization rate decrease as the Technology Maturity increases. The results demonstrate that the hypothesis that increased Maturity of New Technology decreases the total costs incurred is shown for the current structure of the model. A reduction of about 12% in costs is seen when the technology maturity increases from 1 (least mature) to 5 (very mature).

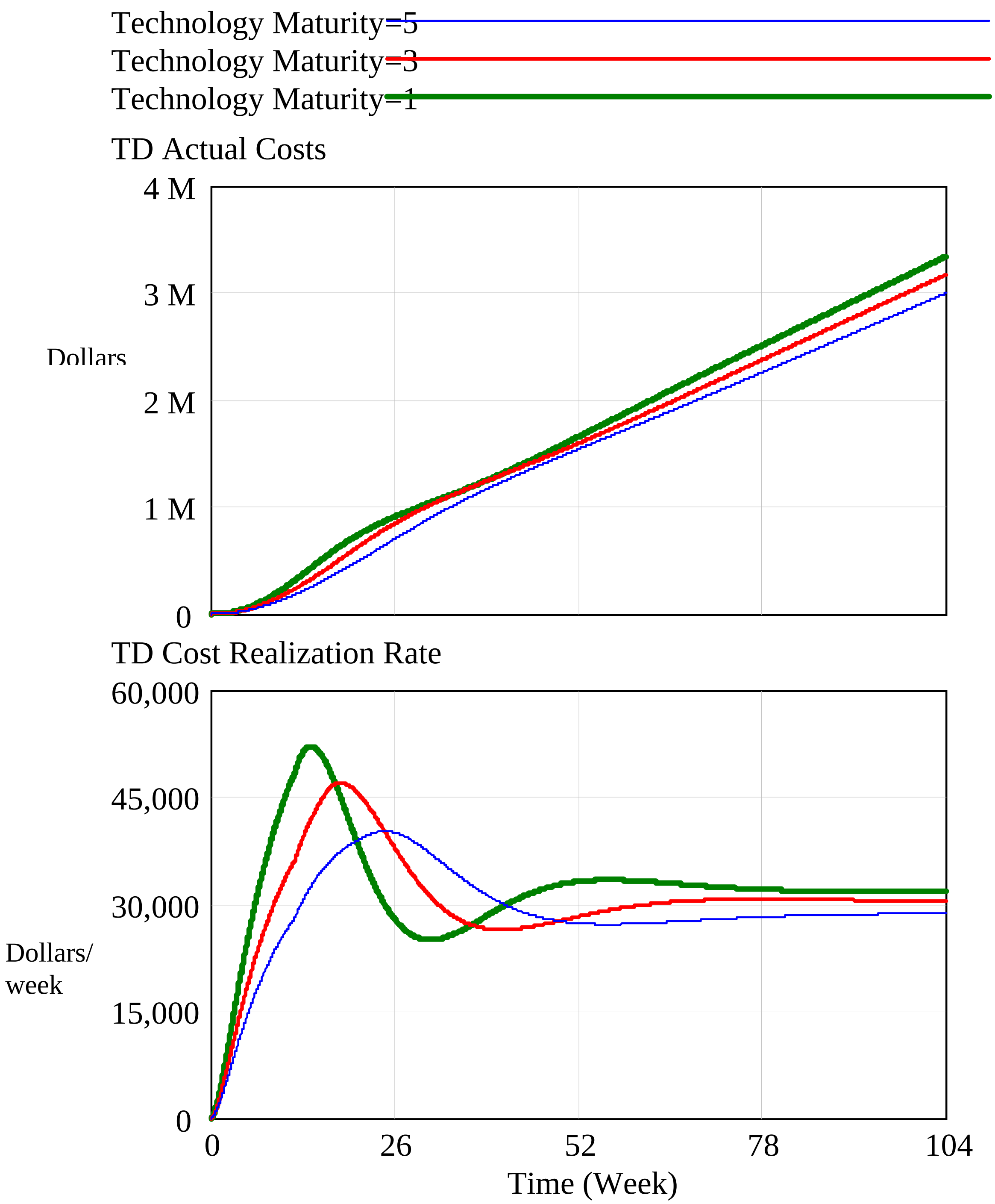

Figure 4.16 TD Costs at Three Levels of Technology Maturity

4.3 Sensitivity Analysis

The model was simulated with three sets of key parameter combinations, namely, (1) very high technology complexity-very immature technology-no training, (2) medium technology complexity-medium mature technology-average training, and (3) very low technology complexity-very mature technology-high training. These were chosen to represent two extreme condition scenarios and an average condition scenario. This helped in understanding the sensitivity of the model results for different conditions of technology maturity, technology complexity, and the amount of training imparted to workers, technicians, and professionals involved in the technology development process. The results are shown below in Figure 4.17 and Figure 4.18.

The parameter sets were:

Parameter Set 1:

Very High Complexity (Complexity of New Technology=5)

Very Immature technology (Technology Maturity=1)

No training (Percentage Training=0%)

Parameter Set 2:

Medium Complexity (Complexity of New Technology=3)

Average Mature technology (Technology Maturity=3)

Average training (Percentage Training=2.5%)

Parameter Set 3:

Very Low Complexity (Complexity of New Technology=1)

Very Mature technology (Technology Maturity=5)

High training (Percentage Training=5%)

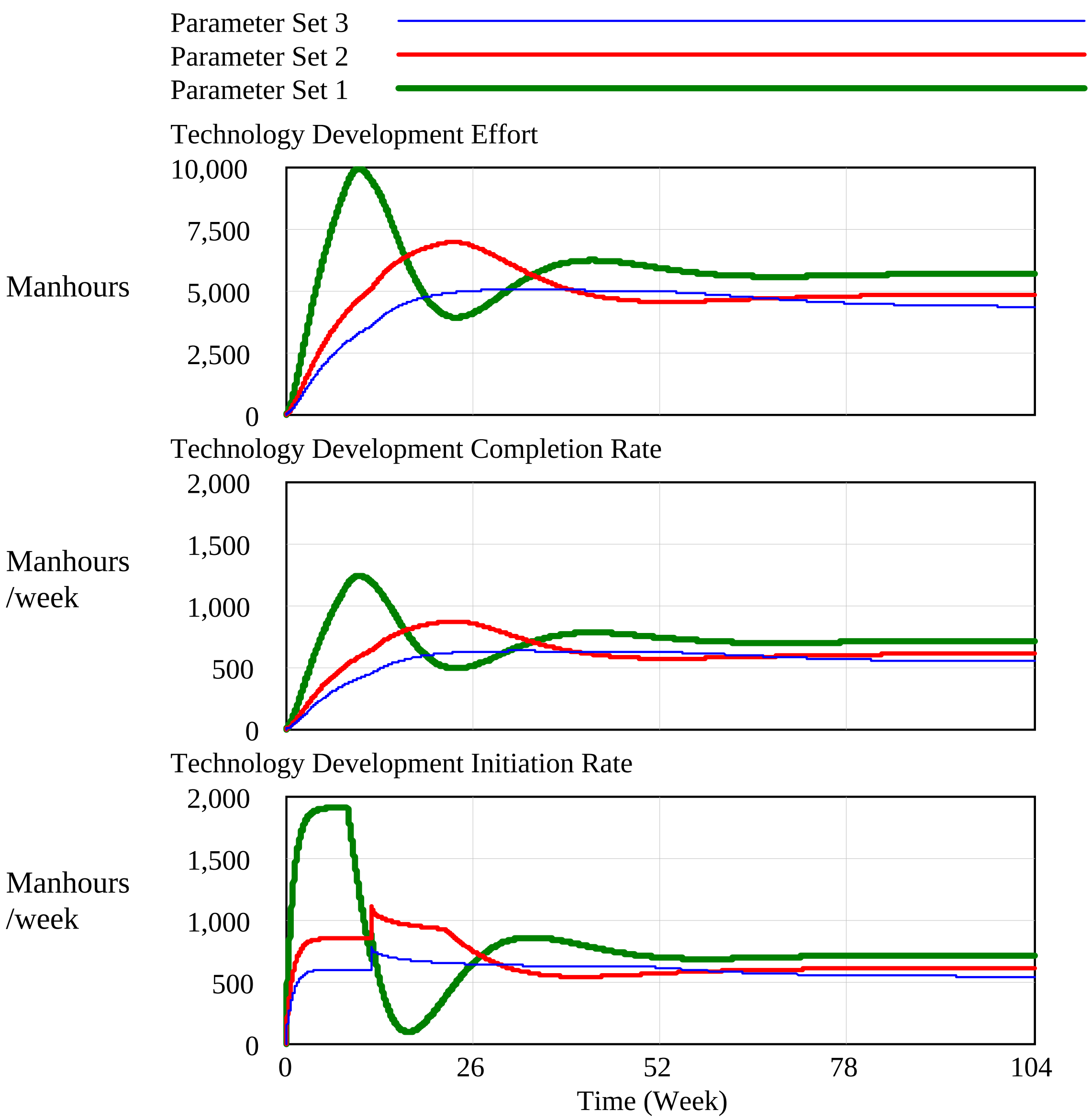

Figure 4.17 Technology Development at Three Sets of Parameter Inputs

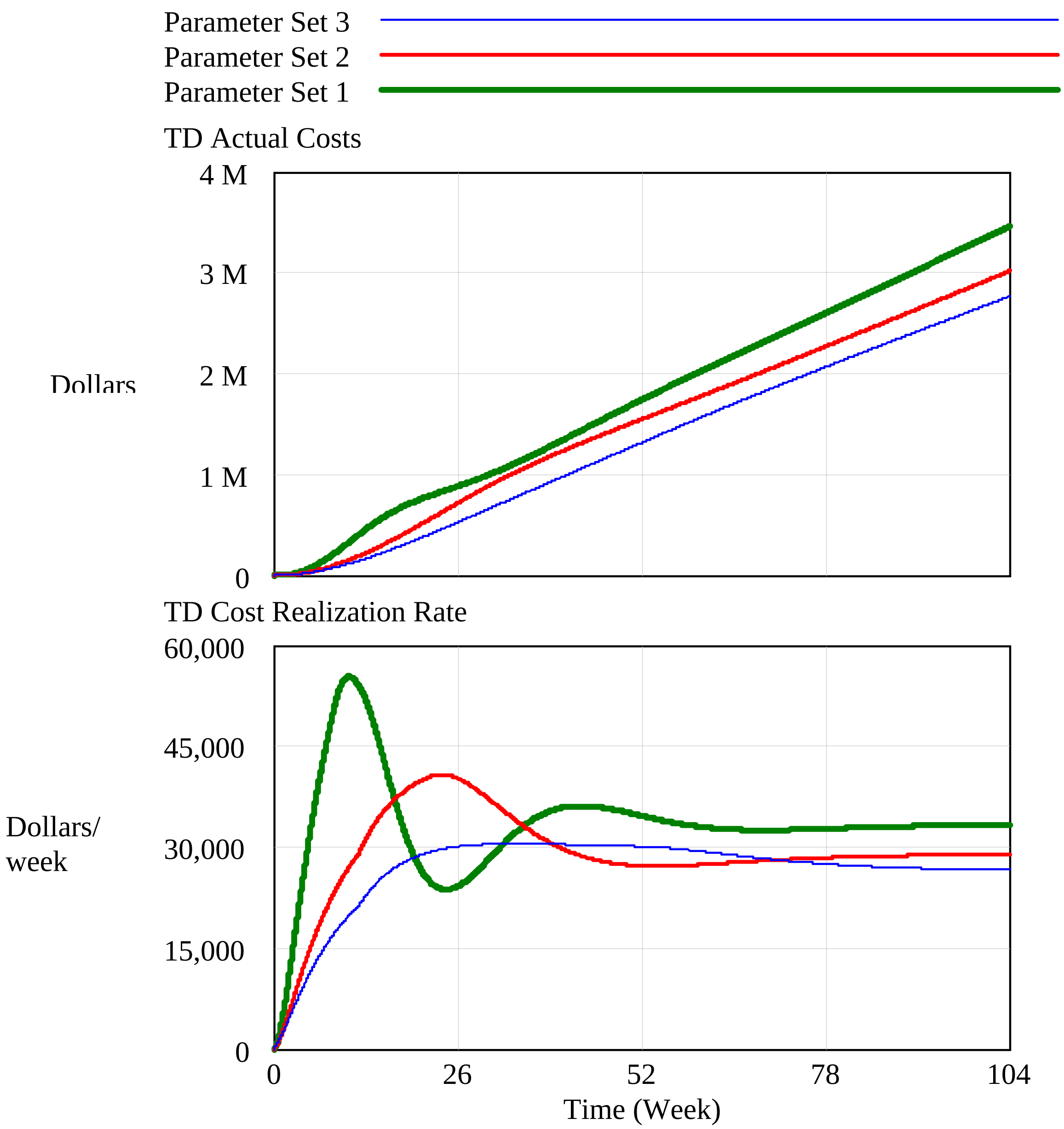

Figure 4.18 TD Costs at Three Sets of Parameter Inputs

The simulated results were in agreement with expected outcomes. Parameter Set 1 was representative of the worst-case scenario where the technology was very immature, it was very complex, and absolutely no training was imparted to the workers, technicians, and professionals involved in the technology development phase. This set of parameters gave the highest cumulative costs and the highest values for rates at which technology development needs to be done. Parameter Set 2 was representative of the average-case scenario where the technology was average mature, it was average complex, and an average level of training was imparted to the workers, technicians, and professionals involved in the technology development phase. This set of parameters gave lower cumulative costs and the lower values for rates at which technology development needs to be done. Parameter Set 3 was representative of the best-case scenario where the technology was very mature, it was very complex, and a high level of training was imparted to the workers, technicians, and professionals involved in the technology development phase. This set of parameters gave the lowest cumulative costs and the lowest values for rates at which technology development needs to be done.

4.4 Testing, Verification, and Validation

Sterman (2000) outlines model testing as an iterative process that starts at the beginning of the modeling process. A wide range of tests helps the modeler understand the robustness and limitations of the SD model. These tests involve direct inspection of equations, simulations of the whole model, and a qualitative or quantitative (or both) assessment of historical fit. An important task of testing is to verify whether the variables and parameters of the model have a meaningful interpretation in the real world. When models are subjected to extreme conditions, their robustness is determined. A model should not just be a means to mirror historical data exactly. In addition, its elements should have a sound conceptual basis for being in the model.

Models seek to represent real world systems in a simplified manner. They differ from reality in an infinite number of small and big ways. It is thus, impossible to "validate" a model. Many modelers and system thinkers are of the opinion that models can be falsified, if not verified (Bell and Senge, 1980). However, there is a flip side to that view. Any theoretical proposition can be rescued from apparent falsification. Invoking auxiliary hypotheses that blunt any falsification agents or data that might be applied to the original proposition, can do this. Say, for example, a theoretical proposition fails to satisfy one particular instance among a wide number of instances for which the proposition has been successfully tested. An auxiliary hypothesis that the theoretical proposition is true except in cases similar to the exceptional instance can be invoked and the proposition guarded against complete rejection. Validation is also intrinsically social. It seeks to enable decision-makers, modelers, and other affected groups to have a better understanding of the system and share and concur in their views.

The process of judging the validity of a system dynamics model includes a number of objective tests (Richardson and Pugh, 1981, and Sterman, 2000). They include:

4.4.1 Face Validity

This is an exercise to qualitatively test the fit between the stock/flow/feedback structure of the model and the essential characteristics of the real system. The NNS and NAVSEA experts involved in the research project confirmed the system's causal flow, stock and flow, and feedback structures in the final version of the model's causal flow and stock and flow diagrams. In fact, face validity was a continuous process. An initial causal loop structure diagram was developed with inputs from and participation of NNS, NAVSEA, and Virginia Tech System Performance Laboratory (VT SPL) group members. This causal loop diagram was discussed and refined upon in an iterative manner over the course of three to four modeling sessions. The evolution of the causal loop diagrams is provided in Appendix C. A similar interactive process was followed in developing the stock and flow structure for the model.

4.4.2 Structure Assessment Tests

Structure assessment tests are carried out to check whether the model is consistent with the knowledge of the real system relevant to the purpose. The tests focus on the level of aggregation and the conformance of the model to the basic physical conservation laws.

NNS and NAVSEA experts confirmed the level of aggregation of the variables and concepts in the SD model. The model is to serve the purpose of understanding the dynamic behavior of the system engineering implementation process as it pertains to the introduction and implementation of new technologies in ship systems. The expert team (NNS and NAVSEA) desired the variables and concepts in the model to be at an aggregation level at which the model could be applied for any new technology. The system dynamics model was built with active participation and consensus from the expert members on the variable identification, their real-world meanings, and the concepts they represented.

Structure assessment tests also focus on the conformance of the model to the basic physical conservation laws. Common violations of physical law involve stocks that can become negative. Stocks of real quantities in the model such as the amount of technology development to be done (Technology Development Effort stock), the amount of testing to be done (TD Testing Effort stock), and the amount of management required (TD Management stock) cannot be negative. Therefore, the outflow rates from these stocks, viz., Technology Development Completion Rate, TD Testing Completion Rate, and TD Management Completion Rate must approach zero as the stock approaches zero. This was tested by direct inspection of the equations (Sterman, 2000) and found to be true.

4.4.3 Dimensional Consistency Tests

Dimensional consistency tests seek to verify that each model equation is dimensionally consistent without the use of parameters that do not have a real world meaning. The tests can be carried out by the direct inspection of the equations and the actual simulation of the model (Sterman, 2000).

The model was simulated (using VENSIM software) and the simulation (as it is in the final form) did not generate any dimensional consistency errors. Results were obtained and they have been presented in the earlier section of this chapter. Furthermore, the equations were directly inspected and they were found to be dimensionally consistent without the use of any arbitrary parameters that have no real world meaning.

4.4.4 Integration Error Tests

Integration error tests are conducted to check for the model's sensitivity to the choice of the simulation time step. The simulation should be run with different integration time steps. Ideally, the results of the model should not be sensitive to the choice of the time step.

The simulation was run for three different integral time steps. The first simulation was run at an Integration Time Step of 0.125 week. The second simulation was run at an Integration Time Step of 0.03125 week. The third simulation was run at an Integration Time Step of 0.0078125 week. The results obtained for TD Actual costs and the TD Cost Realization Rate are shown below in Figure 4.19, Figure 4.20, and Figure 4.21.

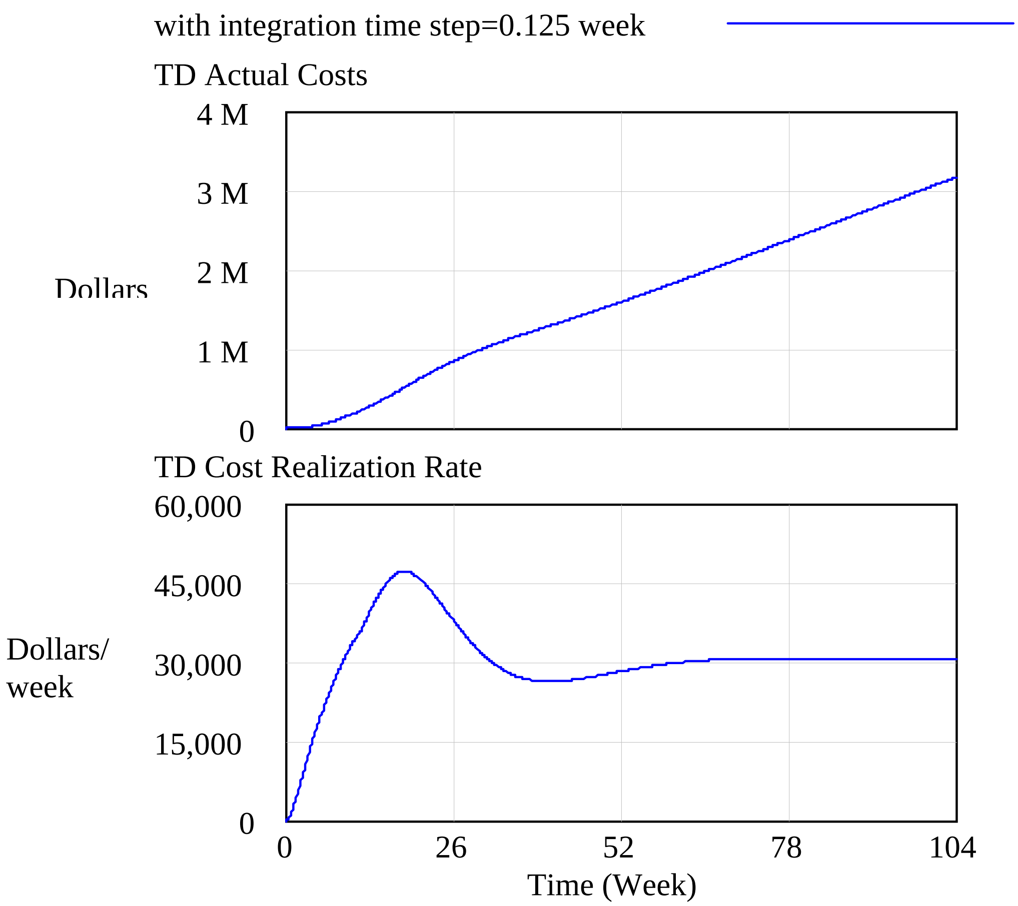

Figure 4.19 TD Costs for a Simulation Run with the Integration Time Step=0.125 week

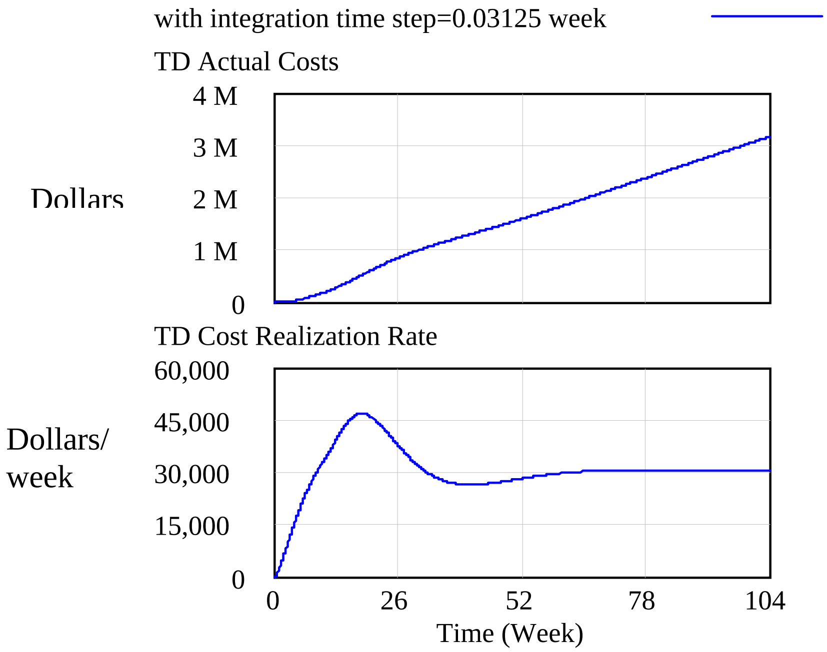

Figure 4.20 TD Costs for a Simulation Run with the Integration Time Step=0.03125 week

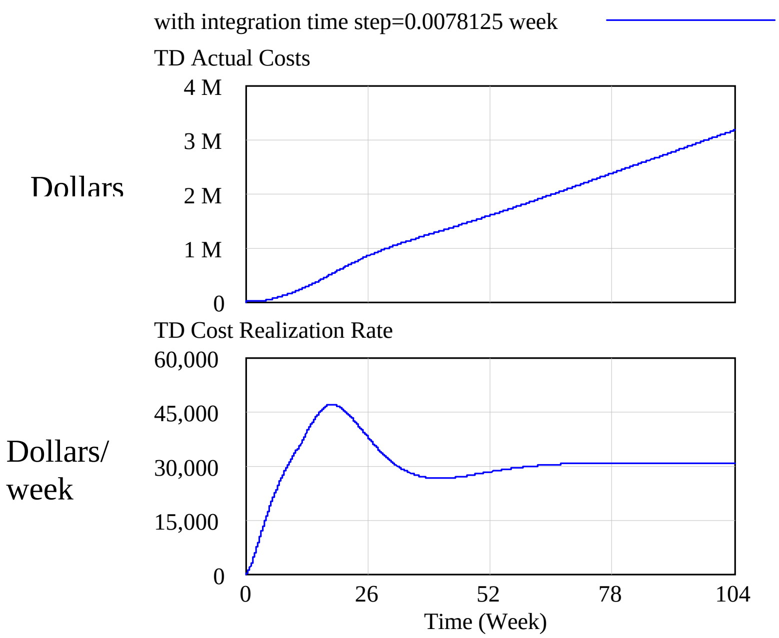

Figure 4.21 TD Costs for a Simulation Run with the Integration Time Step=0.0078125 week

The results show that the model is not sensitive to the choice of the Integration Time Step for the simulation runs.

4.4.5 Behavior Reproduction Tests

Behavior reproduction tests are conducted to check whether the model reproduces the behavior of interest in the system, either qualitatively, or quantitatively, or both.

The main performance metrics in the technology development process cited by NNS and NAVSEA experts were costs and technical performance or testing results.

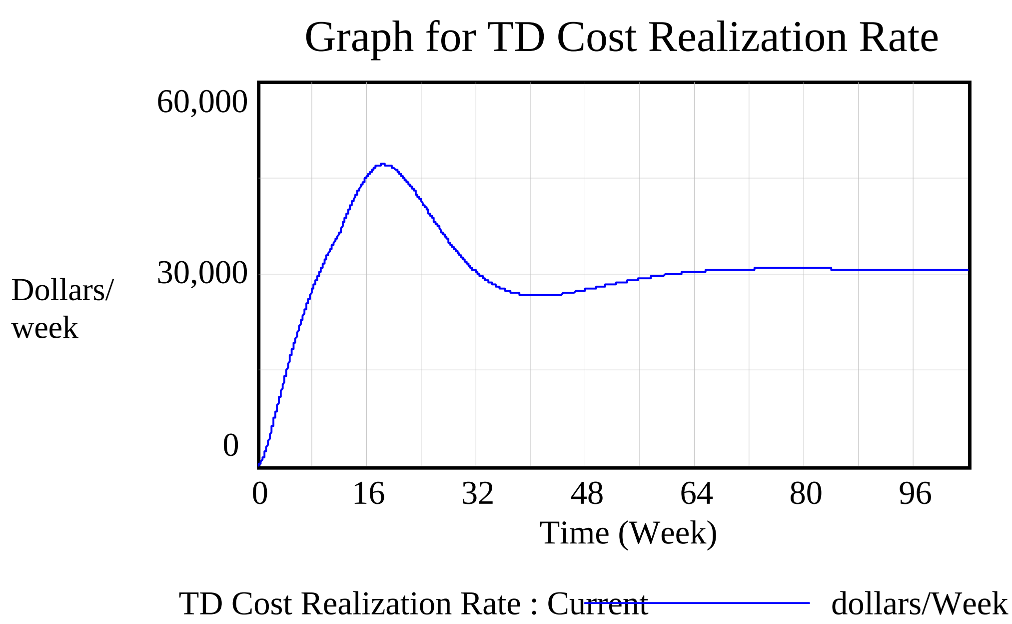

Figure 4.22 TD Cost Realization Rate

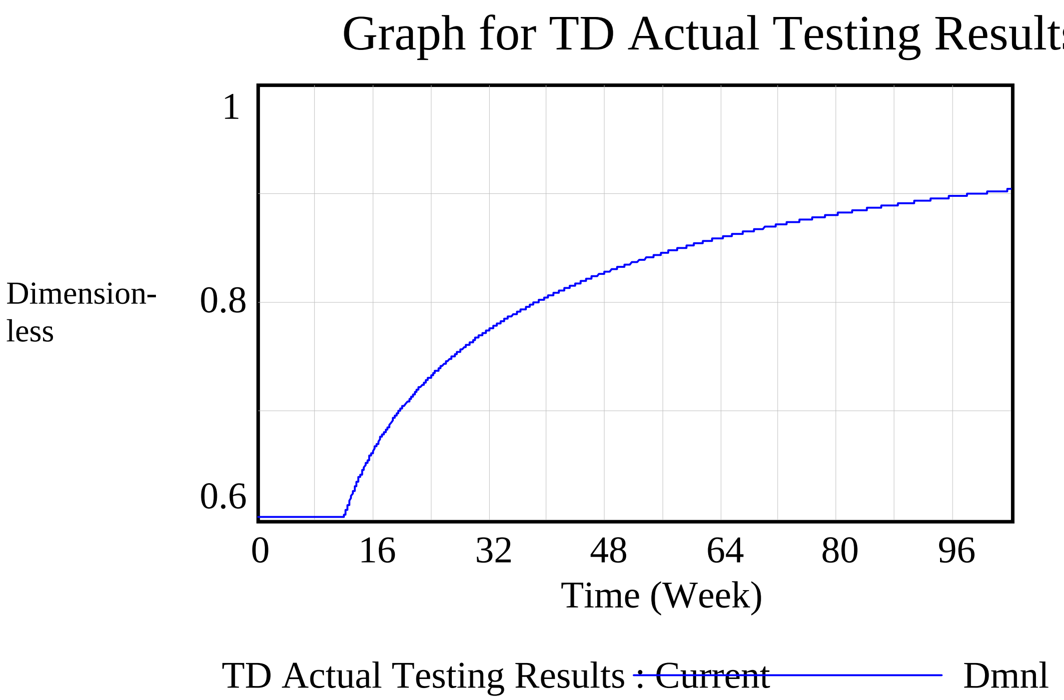

Figure 4.23 TD Actual Testing Results

The above two figures (Figure 4.22 and Figure 4.23) show the results obtained from simulation runs on the model. The profiles of costs and technical performance versus time observed in the figures above are similar in form to the behavior profiles of the variables cost and technical performance versus time in real world as elicited from the NNS and NAVSEA experts (see Reference Modes in Chapter 3).

Chapter 5. Conclusion

5.1 <u>Overview of the Results</u>

The System Dynamics Technology Development model was simulated for a specific technology whereby NNS and NAVSEA experts provided the user-input parameters. For a different technology, there would have been a different set of parameters. The results obtained on running the simulation were discussed in detail in the last chapter. The simulation was run for two years (104 weeks), the time horizon of the technology development process. The simulation runs showed two main modes of dynamic behavior. One dynamic behavior was the damped oscillation observed for the variables Technology Development Effort, TD Testing Effort, TD Management Effort, and TD Actual Costs Realization rate. This was attributed to the presence of oscillatory structures (in the overall causal loop and stock and flow structures) that are characterized by a set of negative feedback loops as was seen in Figure 4.1. The other dynamic behavior observed was the goal seeking observed for the variable Actual Testing results. The feedback structure causing this type of dynamic behavior was identified in Figure 4.6.

5.2 <u>Verification of the Dynamic Hypotheses</u>

The dynamic hypotheses discussed in Chapter 3, Section 3.2 were tested using the SD model developed in VENSIM Professional 4.0 by varying parameters and observing the changes in the subsequent results from the simulation. The first hypothesis was that a lack of appropriate training causes cost overruns and higher costs in the technology development process. From the hypothesis testing simulation results, it was observed that the TD Actual costs, the TD Cost Realization rate, and the TD Cost Overrun fraction decreased as the amount of training imparted (as a percentage of available funding) was increased. The results demonstrated that the hypothesis that increased training reduces the total costs and the cost overruns incurred was shown for the current structure of the model.

The second hypothesis was that redevelopment activities completed in the technology development process add significantly to the cost overruns and the total costs incurred. From the hypothesis testing simulation results, it was observed that an increase in the amount of redevelopment done as a fraction of the technology development activity did not substantially increase the total incurred costs. So, within the limitations and assumptions made for the current structure of the model, insufficient understanding exists to prove the hypothesis true. However, analysis of the effect of the increase in TD redevelopment fractions on the TD Testing Results showed a significant increase in testing results when the redevelopment activity was increased.

The third hypothesis was that an increase in the complexity of the new technology causes an increase in the total costs incurred. From the hypothesis testing simulation results, it was observed that the TD Actual costs and the TD Cost Realization rate increased as the Complexity of New Technology increased. The results demonstrated that the hypothesis that increased Complexity of New Technology increases the total costs incurred was shown for the current structure of the model.

The fourth hypothesis was that an increase in the maturity of the new technology causes a decrease in the total costs incurred. From the hypothesis testing simulation results, it was observed that the TD Actual costs and the TD Cost Realization rate decreased as the Technology Maturity increased. The results demonstrated that the hypothesis that increased Maturity of New Technology decreases the total costs incurred was shown for the current structure of the model.

5.3 Policy Suggestions

Based on the results and testing done on the SD model, certain policy suggestions can be made. Training was observed to have a substantial impact on cost reductions. It would make sense as a policy shift to devote more resources and attention to training in large technology development projects. This issue gains much more importance in the context of new technologies. Technical issues continuously challenge new technology development processes during the entire time horizon of the process due to the lack of a historical perspective and understanding with respect to the new technology. As seen by the hypothesis testing on the impact of training on costs and cost overruns, it would be a wise policy shift to allocate more funds and effort to training activities and is usually done in current technology development projects.

The thrust of new technology implementations should be towards spending more funds on academic research to try and understand the technology better before attempting to implement it on aircraft carriers. It was seen from the hypothesis testing on impact of complexity of technology on costs and cost overruns that a simpler technology incurs lower costs than a complex one. It can be conjectured that pursuing more academic research on a new technology would enhance its understanding and thus reduce the complexity of the technology, which in turn would reduce the costs incurred during its implementation on aircraft carriers.

Another policy shift could be in deciding when to actually implement the technology on the aircraft carriers. New technology implementations that are mainly in telecommunications and Information Technology sectors are often time sensitive. They need to be incorporated fast to keep pace with the technological challenges and needs. However, the drawback to this is that an immature technology entails increased costs as was seen in Chapter 4 during the hypothesis testing of impact of technology maturity on costs. The other critical issue is that some technologies become obsolete very fast. Therefore, if a technology implementation were not very sensitive to when exactly it was done, it would be wise to postpone the process. It would serve as a double-edged advantage. The first is that increased technology maturity would reduce costs incurred. The second is that if the technology still needs to be implemented after a substantially postponed schedule, it would indicate that the technology is relatively not very volatile in terms of how soon it becomes obsolete.

5.4 Future Issues

System Dynamics modeling is inherently iterative. One of the main issues in SD modeling is the level of abstraction in the model (Sterman 2000). The assumptions made in a system dynamics model determine what concepts have been included in the model and what concepts and variables that have been left out. Furthermore they also determine the level of detail to which the concepts are treated in the model. One of the main issues for further research is going to a more detailed level of abstraction for the Technology Development variable. In its current form in the model formulation, technology development is at a very high level in the scheme of things, and it includes activities like up-front research and development, adaptability studies, development of drawing specifications, development of component drawings, and prototype development all grouped together. Breaking down the Technology Development variable into the daughter activities and studying their dynamics individually could be one of the future research issues.

Another issue for future research would be incorporating schedule overruns in the model. The current model structure ignores the issue of schedule overruns. Similar to cost overruns, schedule overruns could form part of a significant feedback mechanism within the model affecting other key variables. This is a definite research area to be explored.

The current structure of the model formulation assumes a steady inflow of funding per week for activities taking place in the Technology Development phase. In real-life, the funding profile could be conjectured to follow a more erratic time profile than a steady constant flow. It would be interesting to incorporate a new funding inflow profile into the model, and observe and analyze the subsequent dynamics of the behavior of the system based on the altered model formulation.

Another future research issue deals with the “effort” variables in the current model formulation. The “effort” variables in the model as of now are assumed to be at a very high level in the system and are translated as the number of man-hours expended in the respective activities and efforts. However, at a further level of detail, one could think of these efforts to be comprised mainly of labor and material flows. Thus separating the efforts into labor and material streams and studying them as co-flows will be another issue and area for further research.

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Appendix A. Glossary

Condition Readiness: The Navy has three Conditions of Readiness. A Condition I battle readiness requires all operational systems fully manned and operating and no maintenance actions except urgent repairs. A Condition II limited action requires all possible operating stations manned and ready and urgent preventive maintenance actions and administrative functions performed. A Condition III cruising requires operating stations manned only as necessary and normal underway-preventive maintenance actions and administration functions performed.

Endogenous: It is defined as “arising from within”, that is, from inside the boundary of the model.

Exogenous: It is defined as “arising from without”, that is, from outside the boundary of the model.

Facilitator: A facilitator conducts and manages the group session, with an aim of facilitating the expression of views of all the key players involved in the modeling exercise.

First Order Delay: A first order delay is a stock and flow dynamics characterized by the outflow rate being proportional to the stock size. Some units have lower residence time than the average delay time while others have greater residence times than the average delay time.

Gatekeeper: A gatekeeper is a contact person within the target organization who helps select the appropriate people to work within the organization with, helps plan the modeling sessions, and works closely with the modeling group.

Mapping System Structure: It is the process of mapping the boundary of the model and representing its causal structure.

Modeler: A modeler's role is to be a keen observer in the modeling exercise, listening and capturing the ideas and views of different session members and providing inputs on the technical modeling aspects as and when required.

Model Boundary Chart: It lists the key endogenous and exogenous variables of the model.

Process Coach: A process coach ensures that the modeling group does not stray substantially from the modeling agenda, and provides feedback to the facilitator in terms of the effectiveness of the modeling process being followed.

Recorder: A recorder takes detailed notes on the various session activities and developments.

Refresh: A technology refresh refers to an upgrade of the technology features or operational capabilities.

Appendix B. System-subsystem structure

System

The system is the system engineering process that is responsible for the development, implementation, maintenance, upgrade, and retirement of new technologies.

Subsystems

Four subsystems were identified for the overall system, namely, Program Management (Subsystem #1), Technology Development (Subsystem #2), Technology Integration (Subsystem #3), and Operations, Support & Disposal (Subsystem #4)

Subsystem #1: Program Management

Program Management is responsible for managing the technology implementation in response to validated operational requirements. It provides the coordination and direction of activities required to develop, integrate, operate, maintain, and dispose the new technology. It oversees cost and secures funds for the technology implementation activities.

Subsystem #2: Technology Development

In the *Technology Development* phase**,** new technologies are developed and/or assessed. The various activities for this subsystem include *R&D technology development activities* (technology research, requirements definition, specification development, engineering, modeling and simulation, drawing development, hardware and software development, system architecture development, and project management), *Project Management activities, and Testing activities.*

Subsystem #3: Technology Integration

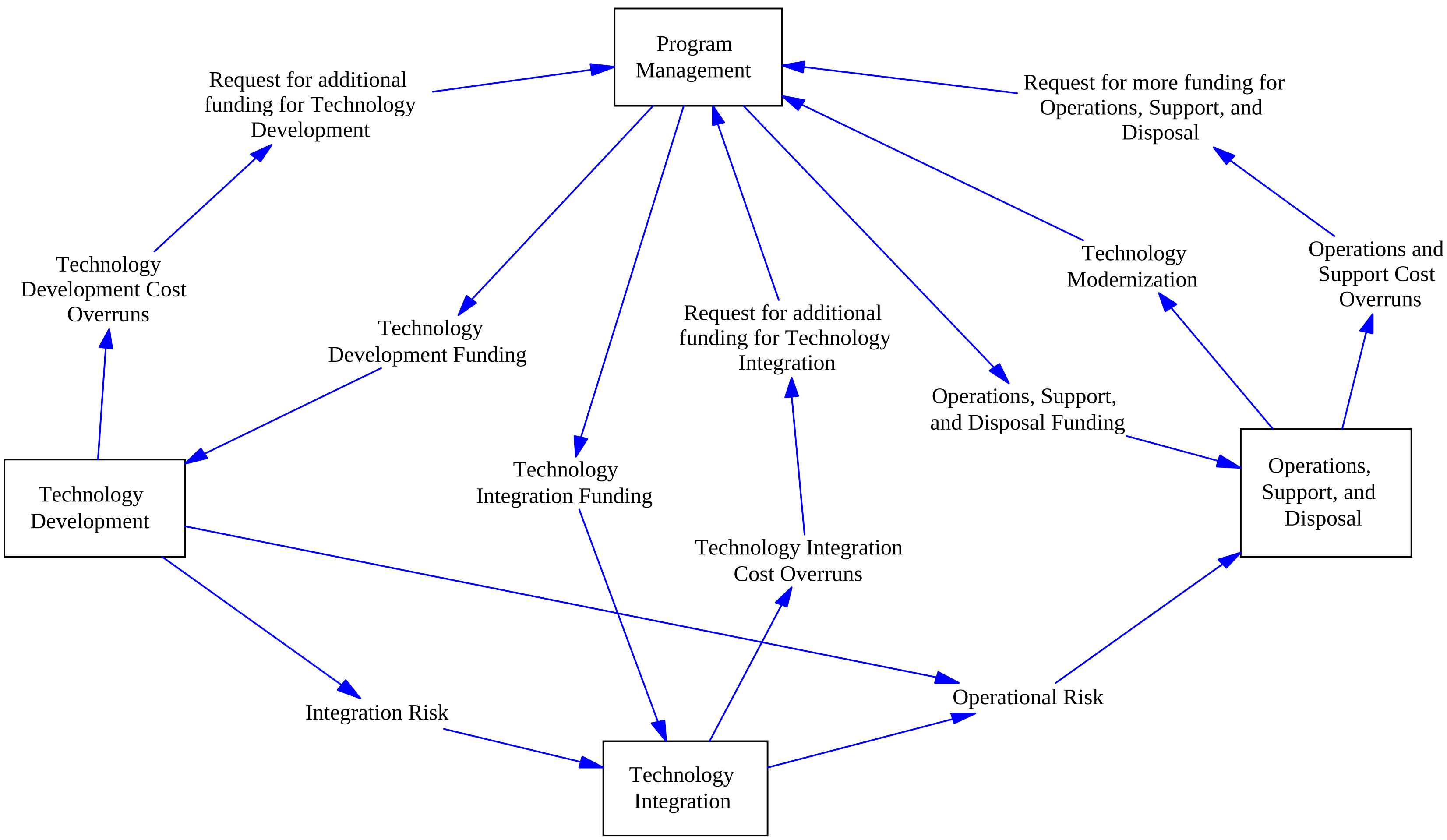
This subsystem is primarily responsible for the integration of the new technology into the ship operations. The various activities for this subsystem include *Engineering and Design* (feasibility evaluation of new designs, design, development and implementation of design specifications, development of drawings, and managing engineering changes), *Procurement and Fabrication* (Purchasing of parts, components, hardware, and software), *Assembly, Installation and Integration* (Integration of new technologies with existing technologies and operations, and technology installation), *Project Management* activities, and *Testing* activities

Subsystem #4: Operations, Support & Disposal

This subsystem is primarily responsible for all the activities necessary for the operations, support and disposal of the new technology. The various activities for this subsystem include *Shipboard Maintenance* (operation and maintenance of the systems onboard the ship), *Organizational and Intermediate Maintenance* (preventive and corrective actions requiring calibration, repair, and replacement of parts, components, and assemblies), *Depot Maintenance* (performing major overhauls or maintenance on a ship and associated equipment at centralized repair depots, or contractor repair facilities), *Other/Indirect/Sustaining Support* (course training for the ships crew to enable them to perform assigned maintenance and operational tasks), and *Operations and Support*

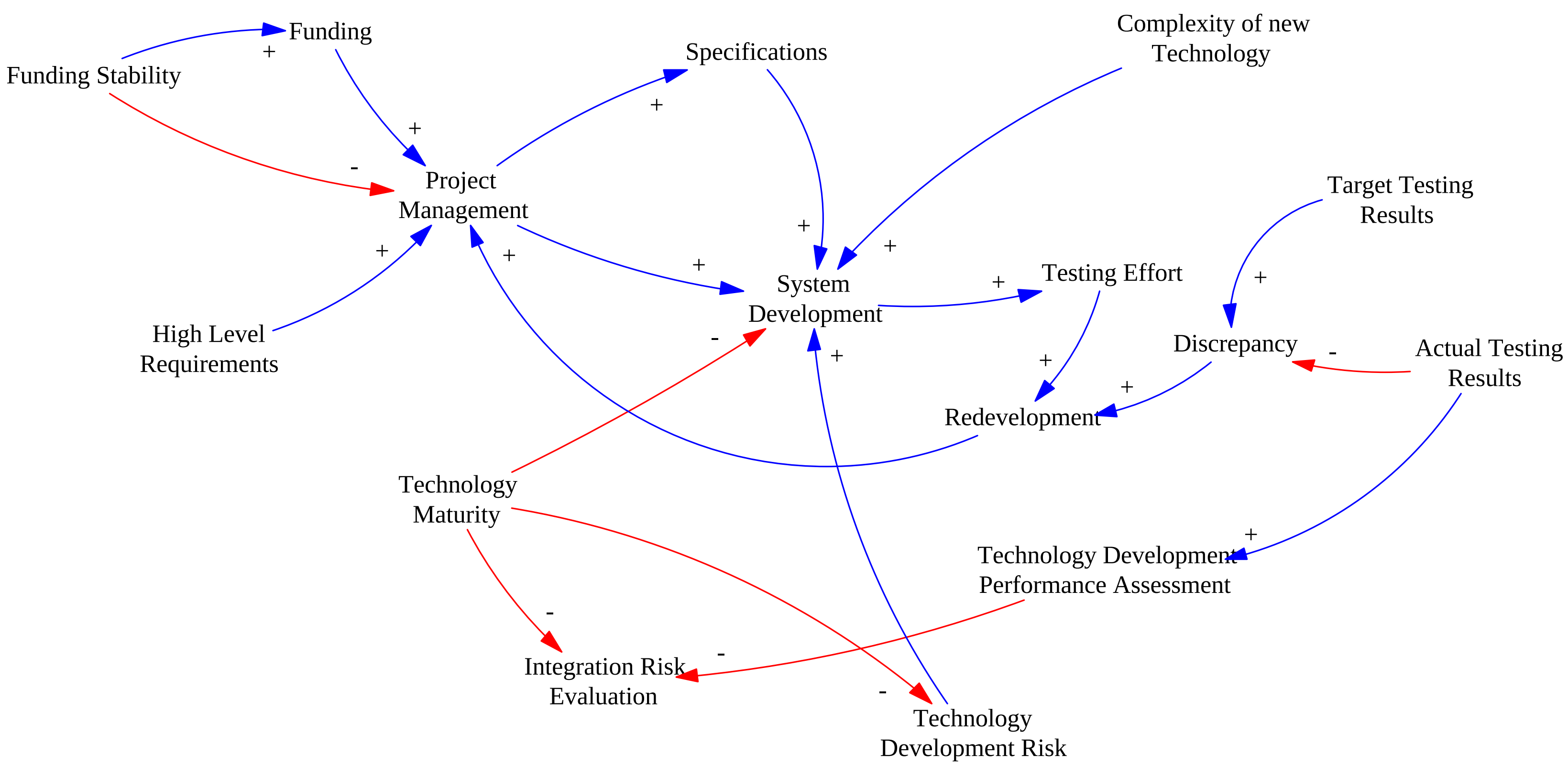
Disposal (compliance with Environmental/HAZAMAT laws and regulations and with handling and disposal of hazardous material during the operating life of the ship).

Overall System/Subsystem Diagram

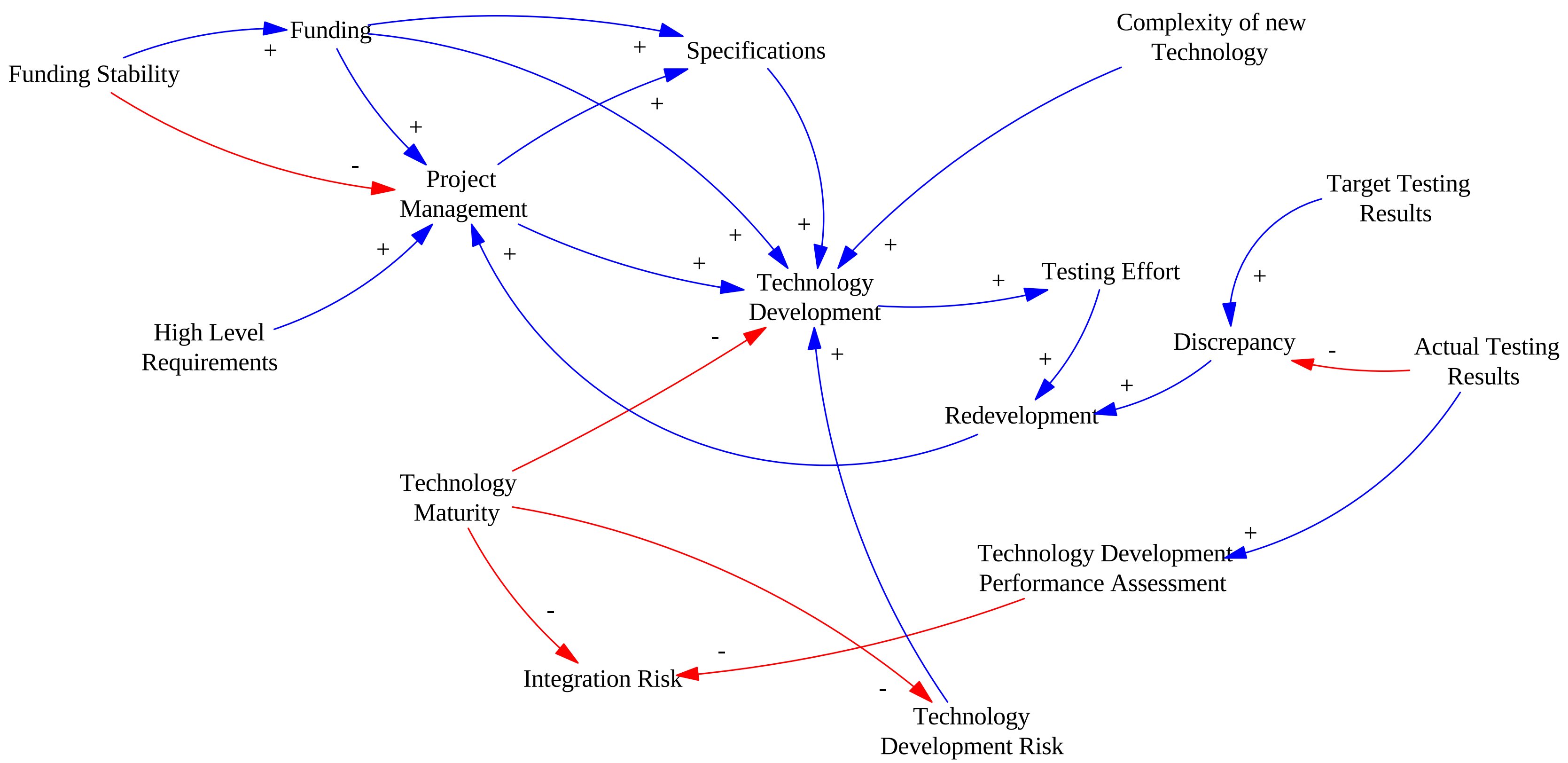


Appendix C. Evolution of Causal Loop Diagrams

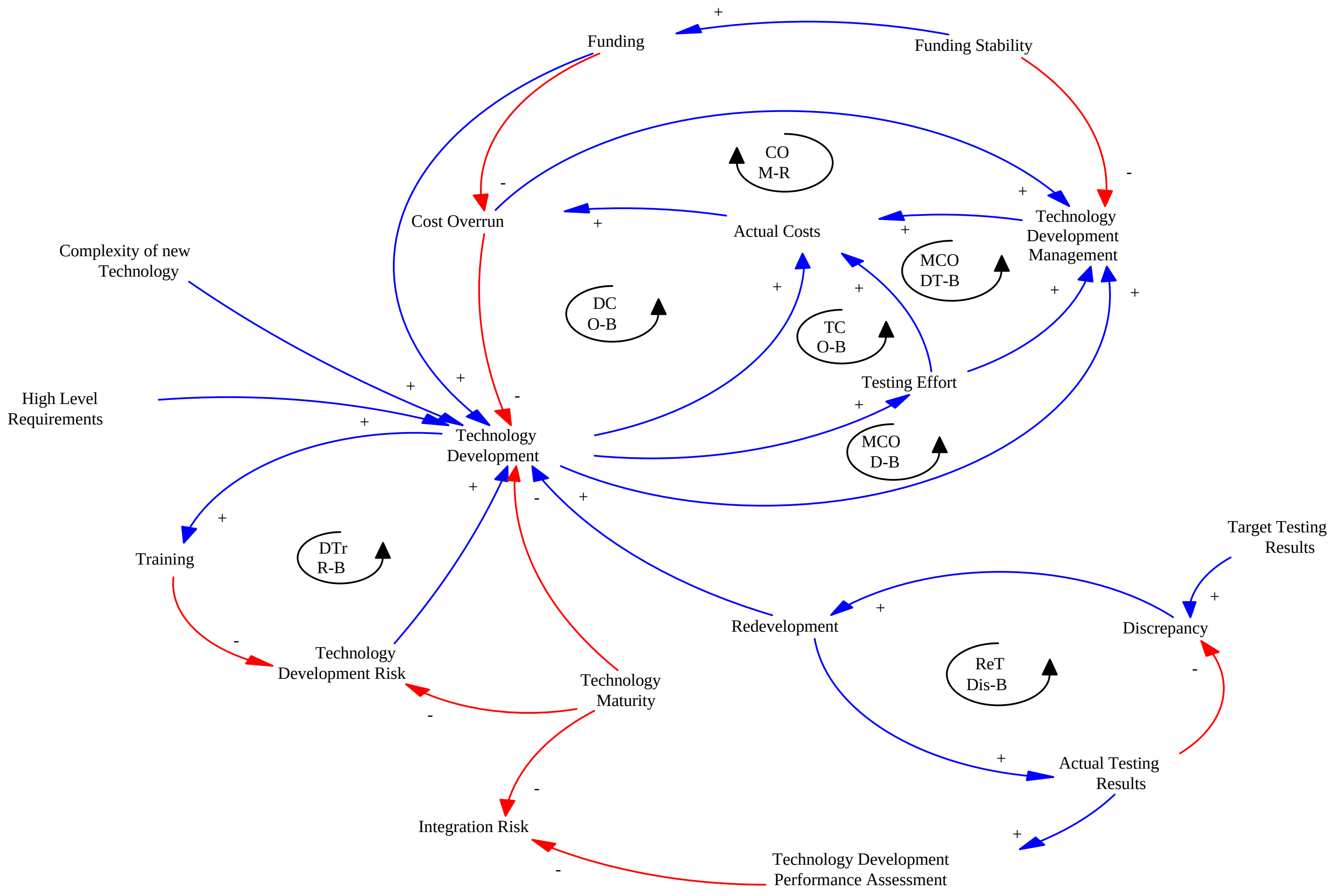
I. Causal loop diagram on April 06, 2001



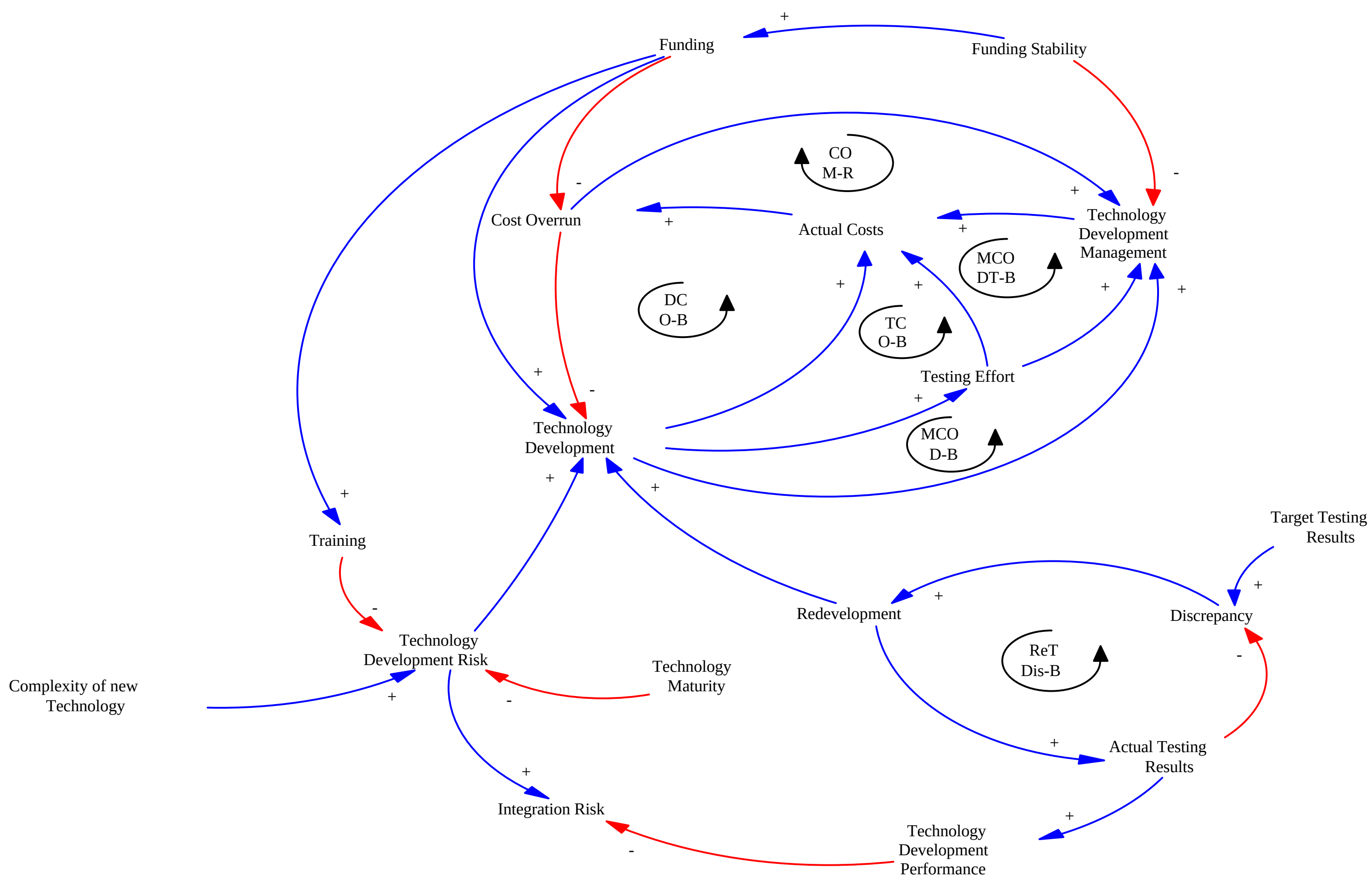
II. Causal loop diagram on April 19, 2001



III. Causal loop diagram on May 16, 2001



IV. <u>Causal loop diagram on May 29, 2001</u>



Vita

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Pavinder works as a Senior Policy Analyst at First USA Bank in Delaware, USA. He is involved with framing credit policies for new credit card applicants, analyzing portfolio performances, and making strategy recommendations for credit market expansion. His interests and expertise are in the areas of strategy decision management, derivatives risk management, data analytics and portfolio restructuring. Pavinder received his Master of Science degree in Operations Research from the department of Industrial and Systems Engineering at Virginia Tech., Blacksburg, U.S.A. He received his Bachelor of Technology (Honors) degree in Chemical Engineering from the Indian Institute of Technology, Kharagpur, India.