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A Dynamic Model for the Development of New Technologies for Ship Systems[1]

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Abstract

In this age of constant influx of new technologies, organizations must continually adopt and exploit new technologies to ensure that the systems they procure and use meet changing performance requirements and long-term cost goals. Unfortunately, adopting new technologies may bring unexpected consequences for the systems the organization procures, and for the provision of the necessary services required for the organization's long-term sustainability.

The traditional systems engineering implementation process as practiced in many organizations can be thought of as the chief reason for the ineffective implementation of new technologies. It fails to adequately plan for the technology's life cycle that includes development, integration on existing platforms, operations and disposal.

The objective of this research is to develop a system dynamics modeling framework that will allow for the evaluation of the technology development process as an integral part of the technology implementation process. The fundamental dynamic behaviors will be explored given that cost overruns are a very important control mechanism within the technology development process. As part of this modeling effort the effects of workforce training, complexity and maturity of the new technology, and rework will be addressed.

Key Words and Phrases: technology development, predictive cost modeling

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1.0 Introduction

In this age of constant influx of new technologies, organizations must continually adopt and exploit new technologies to ensure that the systems they procure and use meet changing performance requirements and long-term cost goals. Unfortunately, adopting new technologies may bring unexpected consequences for the systems the organization procures and for the provision of the necessary services required for the organization's long-term sustainability. The introduction of new technologies can lead to increases in costs due to unforeseen system performance degradation, rework, and increased maintenance over a system's life cycle. Performance refers to the specific measures related to the technical or operational capability of the technology. It can be thought of as the degree to which the system reflects (meets or exceeds) the expected operational requirements. Cost overruns form part of one of the important control mechanisms in the technology implementation process, wherein cost overruns are sometimes traded off against technical performance realizations. These cost overruns translate into increases of system life cycle costs. As a consequence many organizations never realize the full potential of the new technologies they choose to adopt.

The traditional systems engineering implementation process can then be thought of as the chief reason for the ineffective development of new technologies that fails to adequately plan for the technology's life cycle that includes development, integration on existing platforms, operations, support and disposal. Furthermore, during the life cycle issues related to workforce training, complexity, maturity and risk of the new technology, and rework need to be bought to the forefront and assessed. Nevertheless, prior to the development of a complex technology these issues need to be addressed and their effect be predicted and evaluated.

In this paper, the technology development process of the technology implementation life cycle (Vaneman and Triantis, 1999) will be studied and presented. In the traditional implementation of the systems engineering process as far as the management of the research and development is concerned, emphasis is always 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 processes really work, wherein the different stages in technology development actually "talk" to each other on a continuous basis. The technology development process consists of upfront research, design, engineering & development, prototype development (or procurement), testing of prototypes (development and non-development), and adaptability studies (impact on interfacing systems and operations). These different pieces of the technology development process are closely interrelated among themselves with some of the activities occurring later providing a control feedback to earlier occurring activities; thus giving a dynamic nature to the whole process.

We propose a predictive cost modeling approach to make future cost evaluations during the technology development process. Predictive cost modeling techniques are essential elements of Total Ownership Cost (TOC) reduction. The challenges in cost modeling are many and include among others the following. First, a static look at cost modeling and analysis is often not as valuable as studying the structure of the processes that generate the cost data and their performance as they change dynamically with regard to key criteria. Second, the question arises as to exactly which data are relevant to a particular technological system---and whether or not data that represents under-performing historical instances should be used to plan for and model future expenditures. Third, determining the appropriate level of aggregation associated with the various activities is key to effective decision-making. The system dynamics modeling approach proposed in this research can address these challenges and issues.

The objective of this research is to develop a system dynamics model that will allow for the evaluation of the technology development process for ship systems within the technology implementation life cycle. The technology integration and operations support/disposal phases of the technology implementation life cycle are documented elsewhere (Damle, 2002 and Scott, 2002). The system dynamics model will be illustrated for a selected technology and ship system. The fundamental dynamic behaviors will be explored given that cost overruns are a very important control mechanism. As part of this modeling effort the effect of workforce training, complexity and maturity of the new technology, and rework will be addressed. The user-defined parameters for this model pertain to a specific technology that will be integrated in future ship systems. We were not authorized to disclose the technology.

In order to effectively meet the research objective the following tasks have been pursued. These are depicted graphically in Figure 1. *1) Task 1*: The first task of the research involved two critical activities. First, the performance measurement team was established. The research required input from and close collaboration with a government organization that makes affordability evaluations and with a vendor who builds complex ship systems. A series of group modeling sessions were conducted throughout to accomplish each of the modeling tasks. This collaboration is intended to facilitate the accomplishment of another important objective, i.e., ensuring that the model developed meets specific government and industrial needs and will be easily transitioned for industrial use. Second, the system, the technology that requires evaluation, and the problem in hand were defined. Furthermore as part of this activity, the time horizon of the problem was established. *2) Task 2*: Once the problem was identified in Task 1, theories or dynamic hypotheses about the cause of the problem were developed (Sterman, 2000). *3) Task 3*: The third task of the research was the system conceptualization where the technology development system was represented by causal-loop diagrams (Roberts, N., et al., 1983). *4) Task 4*: Model formulation was the next task in this research. During this task, the model generated during the system conceptualization phase was input into system dynamics computer software for simulation (Roberts, N. et. al., 1983). The software selected for this research is the VENTANA Simulation Environment (VENSIM). *5) Task 5*: The model behavior and validation task was conducted during this task under the premise that all models of the real world are inaccurate to some extent. 6*) Task 6:* At this point, policies for the development of new technologies were identified and recommended.

The problem of adopting and implementing new technologies has obvious consequences for the technology's affordability. In order to address the issue of system affordability the following questions were addressed as part of the modeling efforts proposed in this research. What is the effect of the new technology on the life cycle cost of the system and will projected congressional budgets sustain such costs? What is the impact of technology maturity and complexity on development risk? What is the impact of rework and training on new technology development? What are the improvements (re-engineering efforts) that will improve the systems engineering process that is responsible for the development of new technologies?

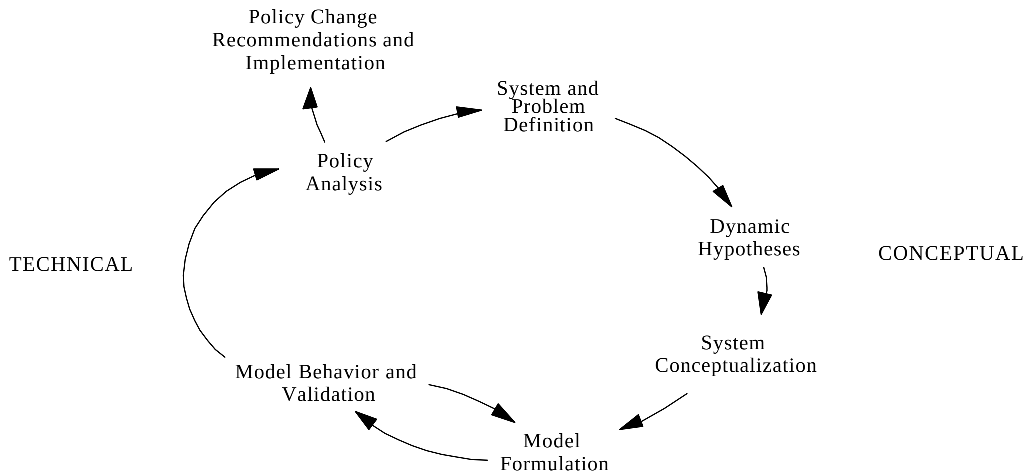

Figure 1. Overview of the Research Tasks

The rest of the paper is organized as follows. Section 2 provides some background on previous work on technology development and project management as it pertains to ship building operations. Sections 3 and 4 provide a description of the problem and the qualitative/quantitative models respectively. The model results are described in Section 5. Finally, the policy recommendations and conclusions are provided in Section 6.

2.0 Background

Effective incorporation and implementation of a new technology poses a formidable challenge in almost all industries and organizations. Many a times, 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 literature 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 are various research and development (R&D) activities, and usually include 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 structure and dynamics of the technology development process, both from management and process perspectives.

There are some references in literature on work done in the area of the System Dynamics approach applied to project management issues that relate to shipbuilding operations. The System Dynamics 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 System Dynamics 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.

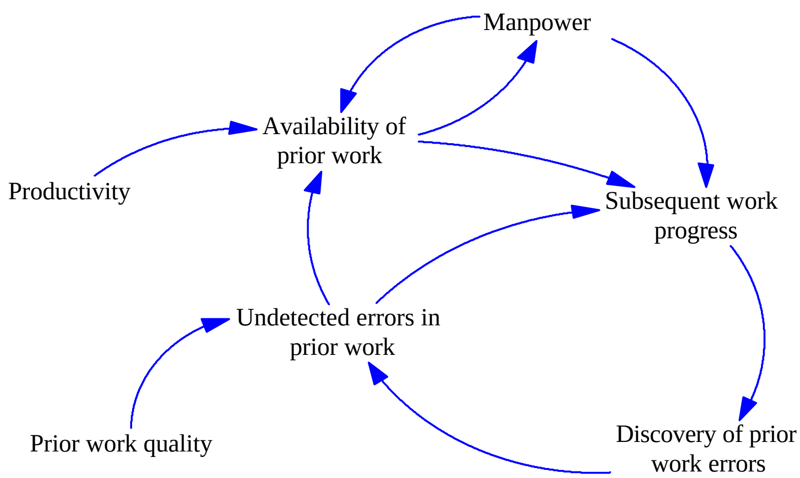

Figure 2 Conceptual Structure of Cooper's (1980) Model

One of the key relationship structures of Cooper's (1980) model is shown in Figure 2. 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 (1980) 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. The concept of cost overrun will be used in this research to capture the basic controlling mechanism in the technology development process.

3.0 Problem Definition and Dynamics Hypotheses

As part of the initial group modeling sessions, the system, the problem, the key variables and their reference modes, the time horizon, and dynamic hypotheses were defined. These issues are described subsequently.

3.1 The Technology Development 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 ship systems. The key issue that was decided on up front was to aggregate the technology development activities into three major activities, i.e., technology development (research, requirements definition, specification development, engineering, modeling and simulation, drawing development, hardware and software development, system architecture development), project management, and testing. The justification for this was that at this point in the modeling process that this level of aggregation was adequate given the need to evaluate the overall life cycle of the technology implementation process that included in addition to technology development, technology integration and operations, support and disposal.

3.2 Problem Definition

The development of new technologies leads to increases in ***costs*** due to up-front delays in the process of development. One of the reasons for this increase in cost is that the implementation of the ***traditional systems engineering process does not view technology development as an integrated system*** and fails ***to evaluate cost appropriately*** as an integral element in the ***decision making process*** where technological tradeoffs are evaluated. 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 allocated 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 based on the experiences of the shipbuilder 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).

3.3 Reference Modes

The behavior pattern of certain key variables was elicited from the decision-makers at the outset of the group modeling process (Figure 3). Those variables were as follows.

Cost: It is viewed as the total life cycle costs (LCC) of the technology development. It would include all costs associated with the technology development activities.

Technology Development Activity: It is level of effort (expressed either in man hours or dollars) associated with the technology development activities.

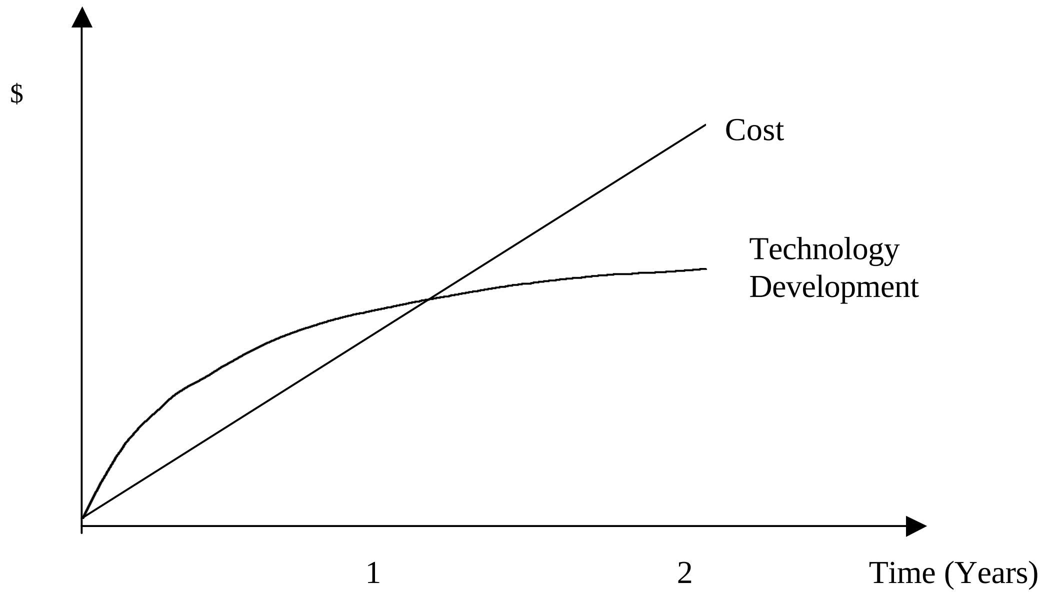

Figure 3 Reference Modes for Key Variables

3.4 Time Horizon:

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).

3.5 Dynamic Hypotheses

The following hypotheses were proposed at the outset of the modeling process.

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.

3) An increase in the complexity 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 of the technology decreases the total costs incurred.

4.0 The Model

4.1 Qualitative Model Description: The Causal Loop Diagram

The feedback structure of the technology development system was qualitatively mapped using causal diagrams. The process of obtaining the causal loop diagram for this system (Figure 4) was obtained by defining key variables (Appendix A: Table 2), finding the causes for these variables, determining the consequences of the key problem variables, identifying the feedback loops that are prevalent, isolating growth loops, and then identifying the balancing loops that limit them. There were a series of assumptions that were made that related to the behavior of the variables (Appendix B). This process was conducted as a series of group modeling sessions.

The main causal loops identified for the technology development system depicted by Figure 4 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
ReTDis-B: Redevelopment-Testing Results-Discrepancy balancing loop

<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. 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.

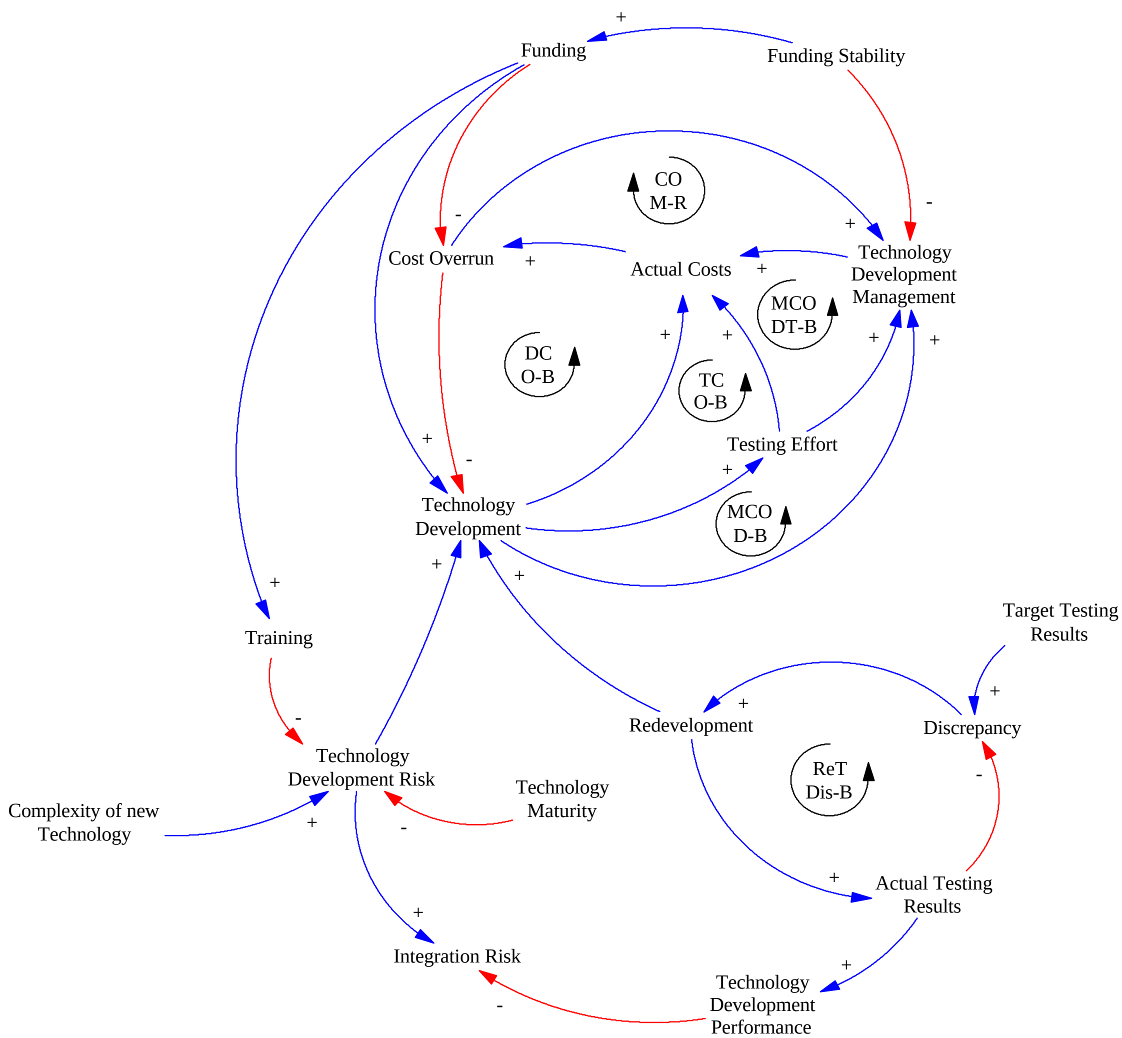

Figure 4 Technology Development Causal Loop Diagram

<u>Development-Cost Overrun Balancing Loop (DCO-B)</u>

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.

<u>Testing-Cost Overrun Balancing Loop (TCO-B)</u>

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 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.

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 need for lower (higher) rate 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.

Furthermore, there were a number of additional interactions that were deemed important as part of the technology development system. 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 first, third and fourth dynamic hypotheses of the model. These hypotheses are imbedded in the relationship defined between training/complexity/maturity and technology development risk. Furthermore, there is no direct linkage between the integration risk and the development effort or any other activity in this subsystem.

An increase (reduction) in training leads to a reduction (increase) of the development risk. 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, 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.

4.2 The Quantitative Model Description: Formulating a Simulation Model

This next step in modeling involves setting up a formal model complete with equations, parameters and initial conditions that represent the system. In the group modeling sessions, the equations describing the relationships between the various variables were elicited from the participants. 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. The user-defined parameters that were elicited from the participants of the group modeling sessions are included in Appendix C Table 3.

Figure 5 represents the technology development stock and flow diagram. 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. 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 one of the most important of which is discussed subsequently. The remaining structures are presented in Appendix D. All of the relationships derived for this model followed Ford and Sterman's (1998) group modeling equation elicitation approach. During these group modeling sessions experts and decision-makers from government and the shipbuilder participated.

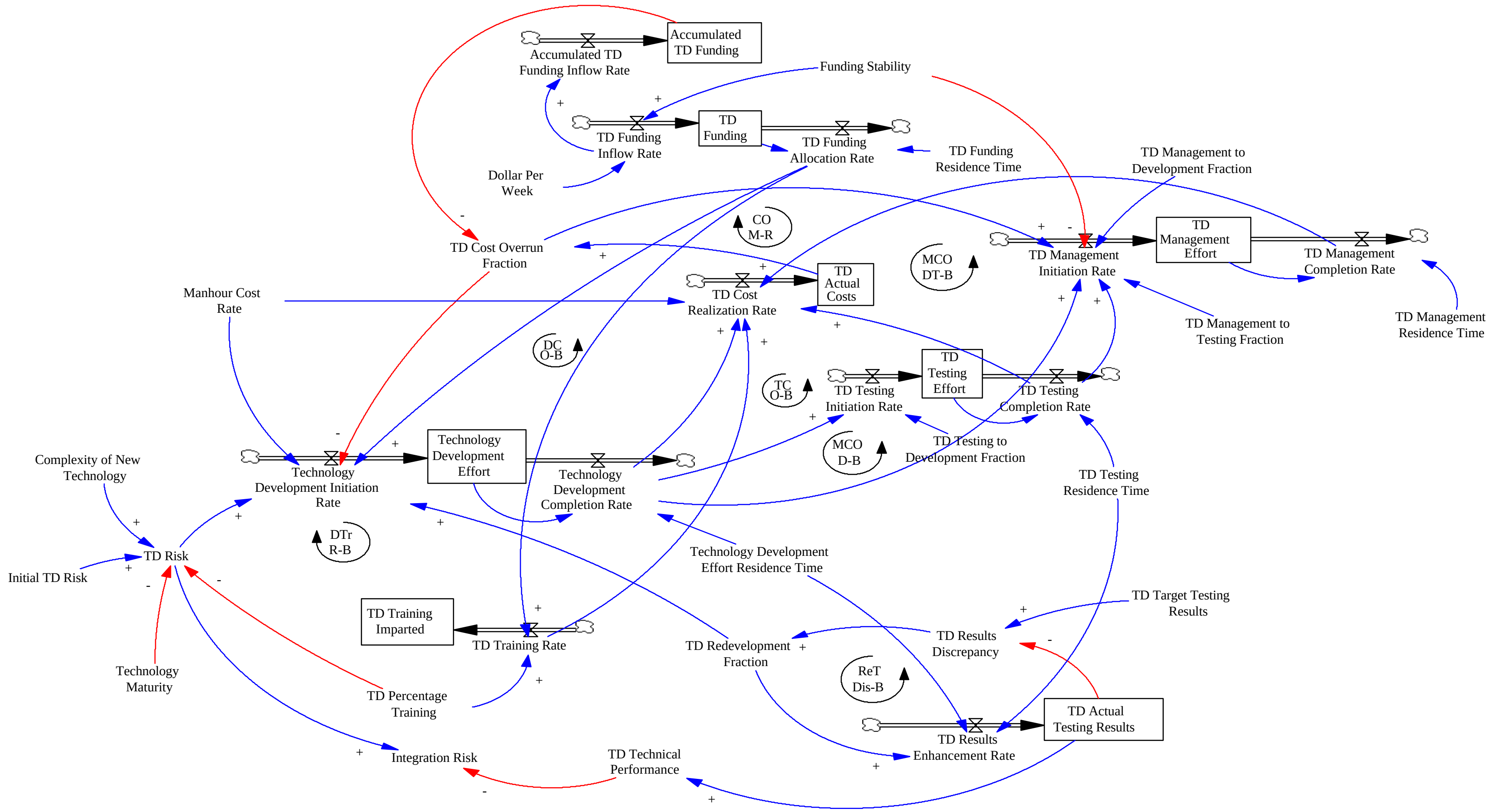

Figure 5 Technology Development Stock and Flow Diagram

4.2.1 TD Risk Structure

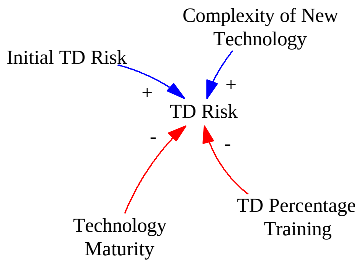

Figure 6 TD Risk Structure

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 (Input received from session modeling experts). The following graphical relationship (Figure 7) between TD Risk and TD Percentage Training at different values of Initial TD Risk (ITDR) was elicited from modeling session participants and experts.

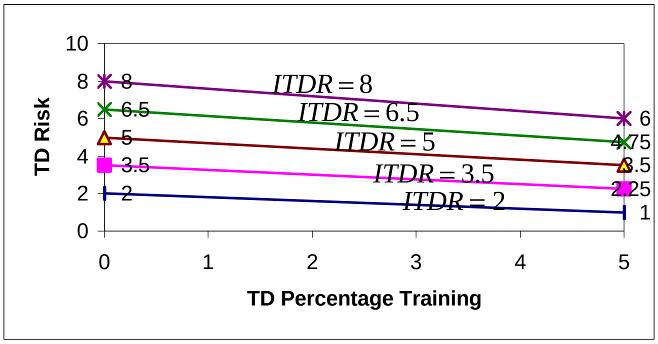

Figure 7 Impact of TD Percentage Training on TD Risk

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 (1)

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) affects 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 graph depicted below (Figure 8) was plotted in MS Excel 2000.

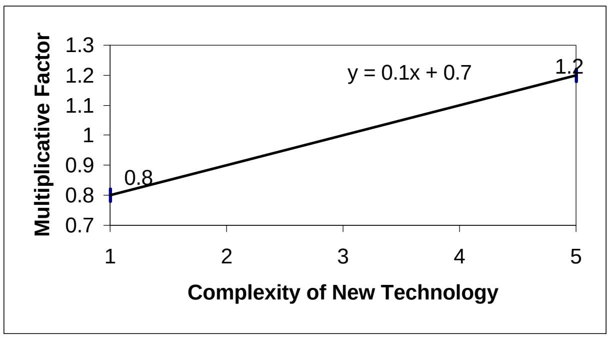

Figure 8 Impact of Complexity of New Technology on TD Risk

An increase (decrease) in Technology Maturity leads to a 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) affects 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 graph depicted below (Figure 9) was plotted in MS Excel 2000.

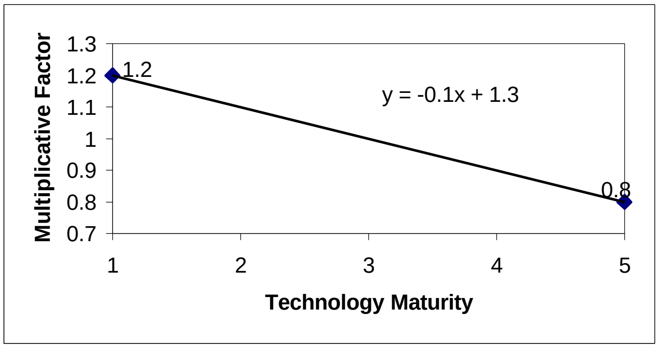

Figure 9 Impact of Technology Maturity on TD Risk

The overall equation 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)* (2)

5.0 Results, Testing, Sensitivity Analysis, Validation and Verification

The model was programmed in VENSIM Professional 4.0 software. The model was simulated for a specific technology whereby the group modeling participants and experts provided the user-input parameters (Appendix C). For a different technology, there would have been a different set of parameters. The results obtained from running the simulation are discussed in this section. The dynamic hypotheses 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.

5.1 Results

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 in Figure 10.

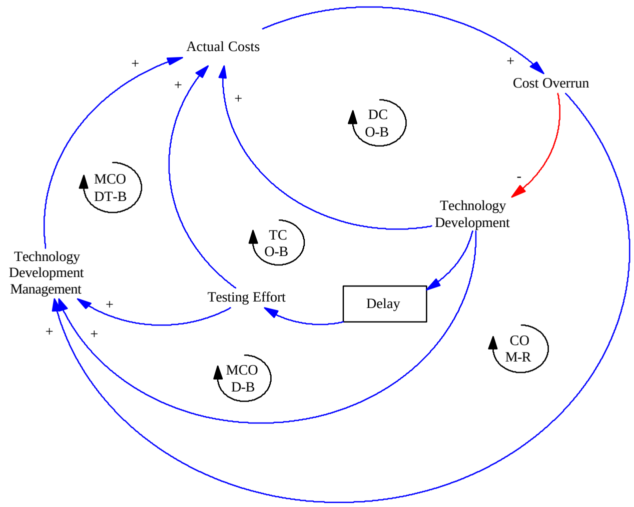

Figure 10 Feedback Structure Causing Damped Oscillation

Oscillation arises due to negative feedback with significant time delays. 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 10. 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 affecting 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.

5.1.1 Technology Development Effort

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 continues to week 32. The equilibrium value of the rate at which technology development needs to be done appears to be 652 man-hours/week. Figure 11 shows the damped oscillatory behavior.

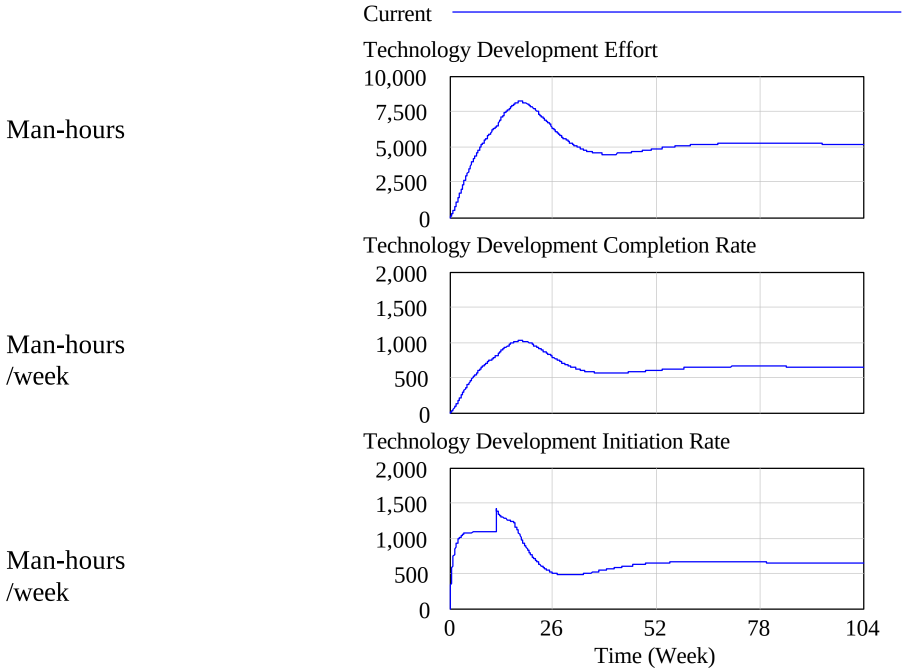

Figure 11 Technology Development Behavior

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.

5.1.2 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. Figure 12 below shows the damped oscillatory behavior.

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 in Figure 13. *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.

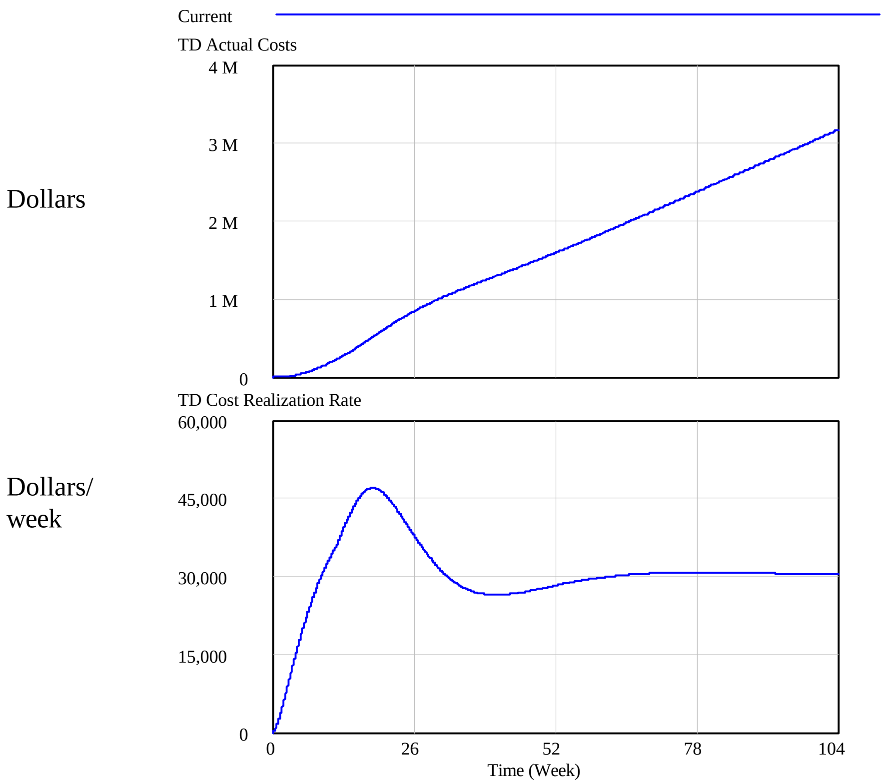

Figure 12 TD Actual Costs and Cost Realization Rate

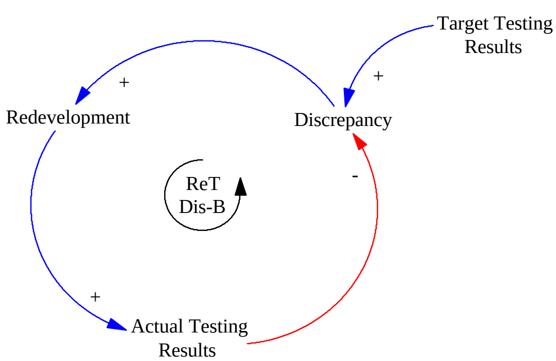

Figure 13 Feedback Structure Causing Goal Seeking

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

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. Figures 14 and 15 show the goal seeking behavior observed on running the simulation.

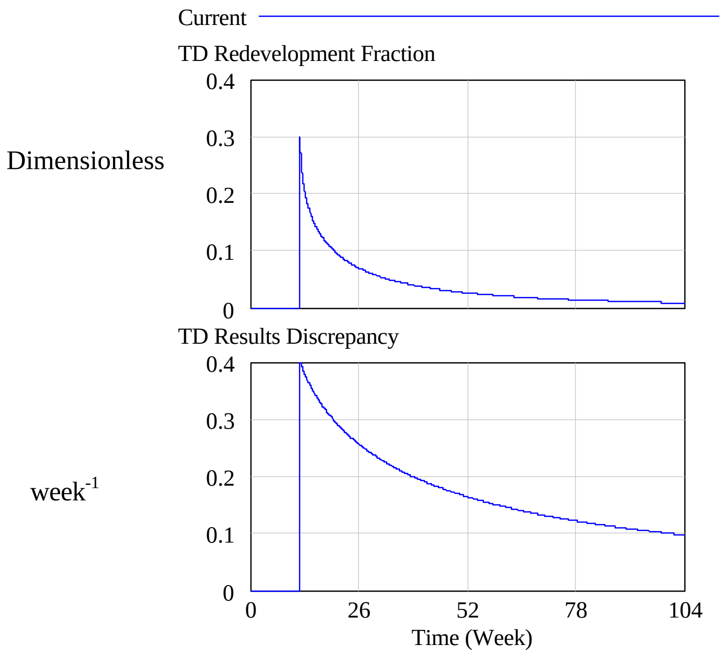

Figure 14 TD Redevelopment Fraction and Results Discrepancy

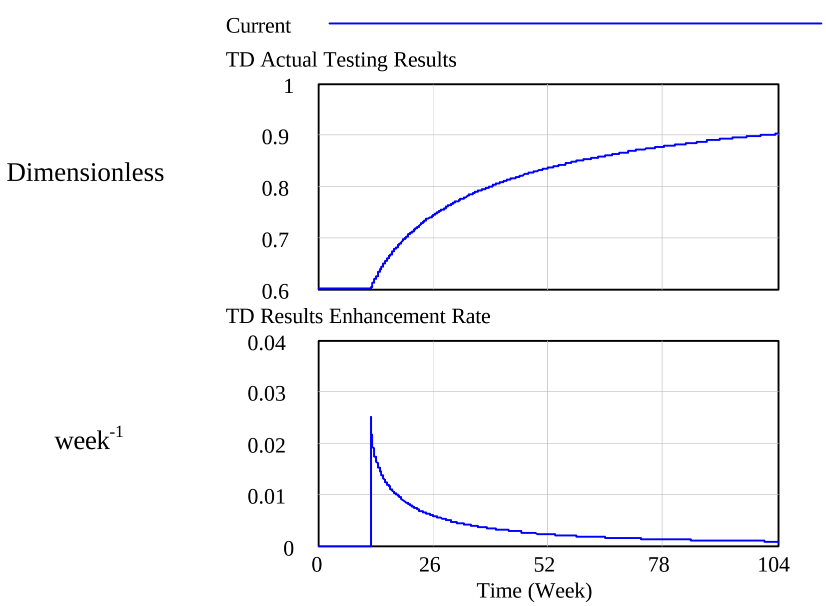

Figure 15 TD Results Enhancement Rate and Actual Testing Results

5.2 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 Figures 16 and 17. 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.

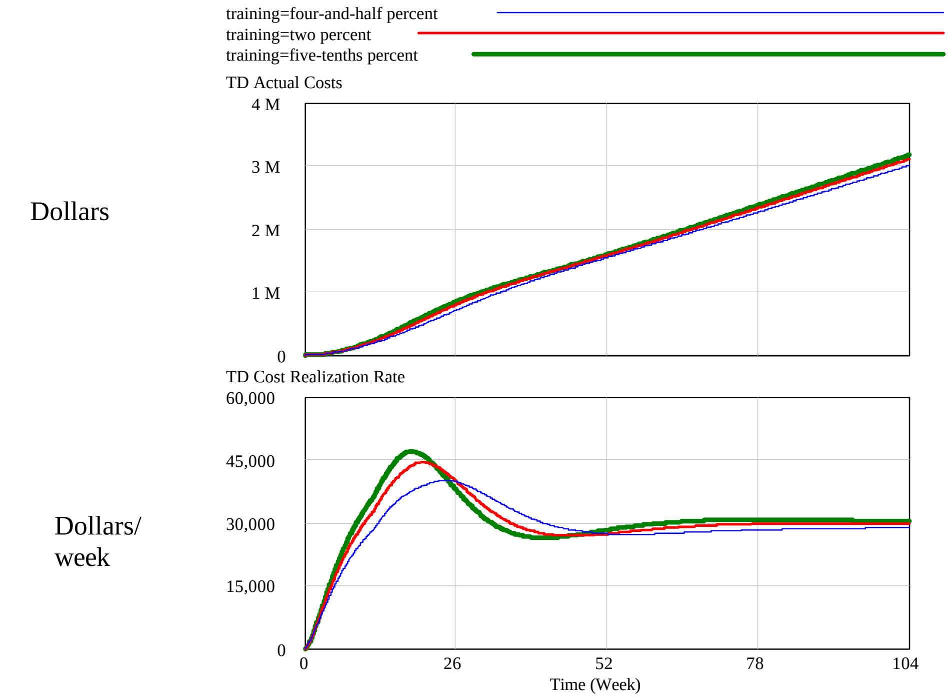

Figure 16 TD Costs at Three Training Levels

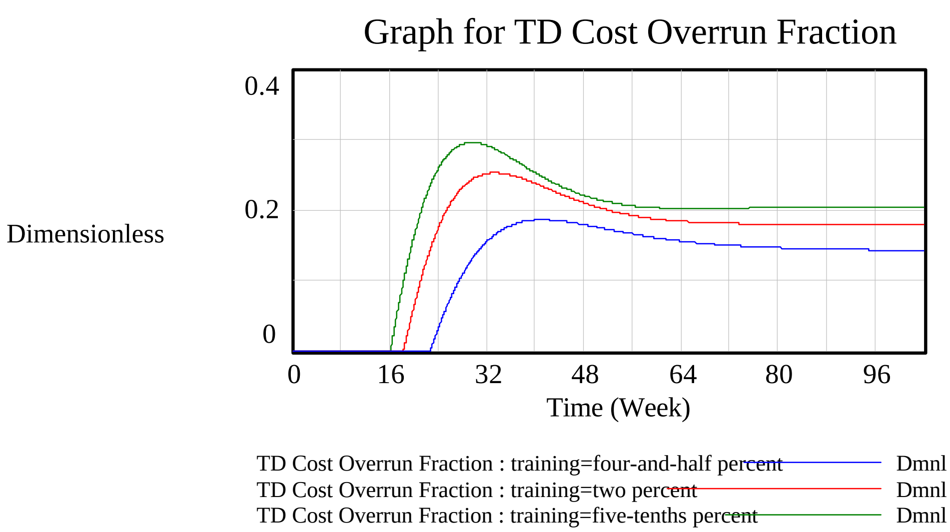

Figure 17 TD Cost Overrun Fraction at Three Training Levels

Hypothesis 2: 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 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 show that this hypothesis is true.

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 18. 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 increases from 1 (very simple) to 5 (very complex).

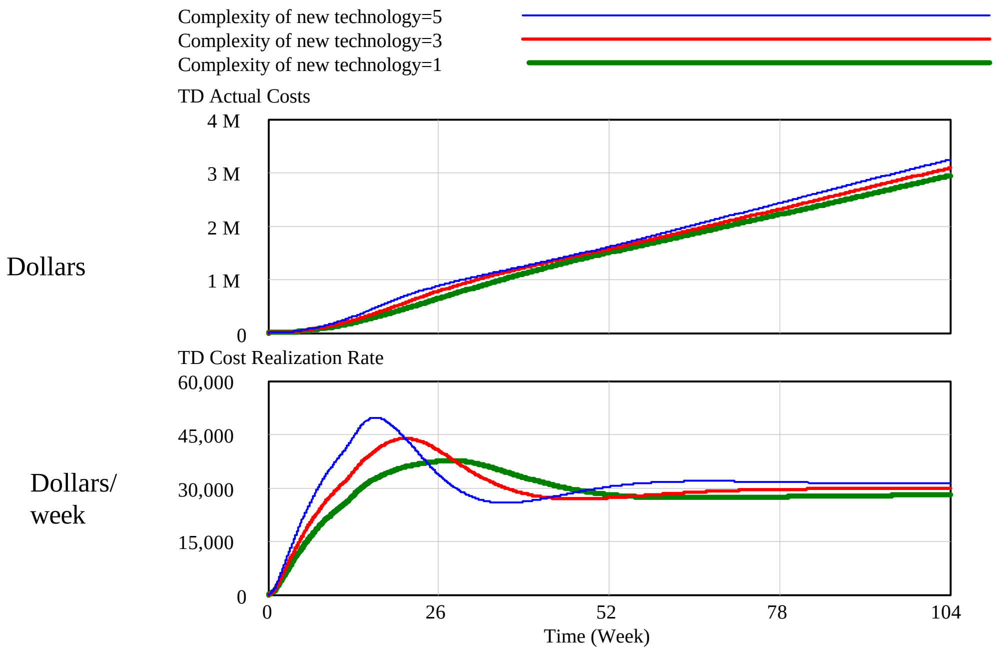

Figure 18 TD Costs at Three Levels of Complexity

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 19. 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).

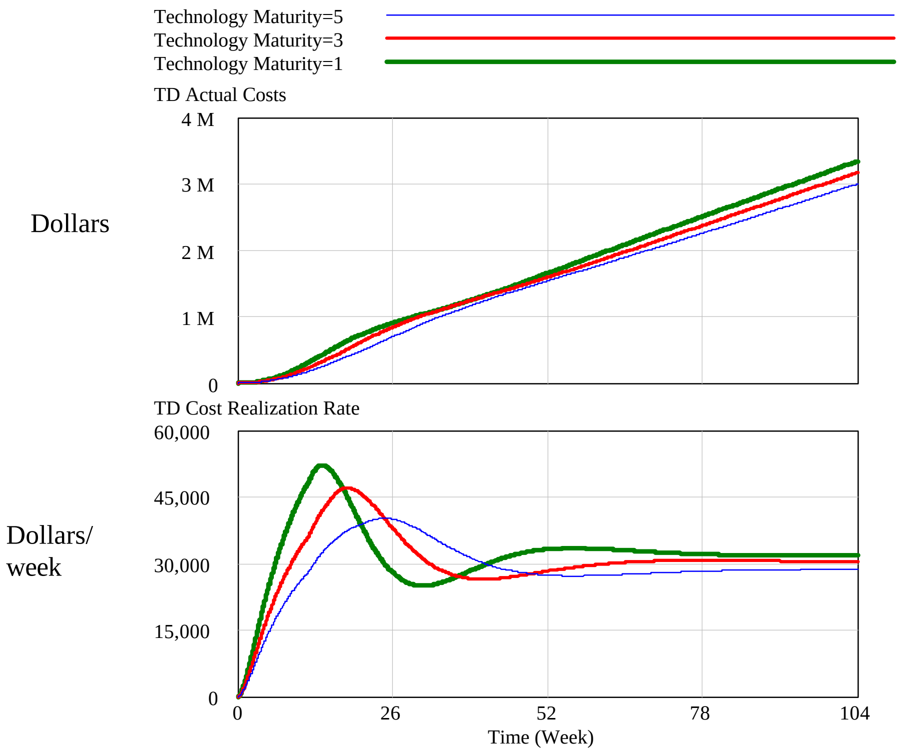

Figure 19 TD Costs at Three Levels of Technology Maturity

5.3 Sensitivity Analysis

The model was simulated with three sets of key parameter combinations that 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 in Figures 20 and 21.

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 had an average maturity, it had an average complexity, 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 the least 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.

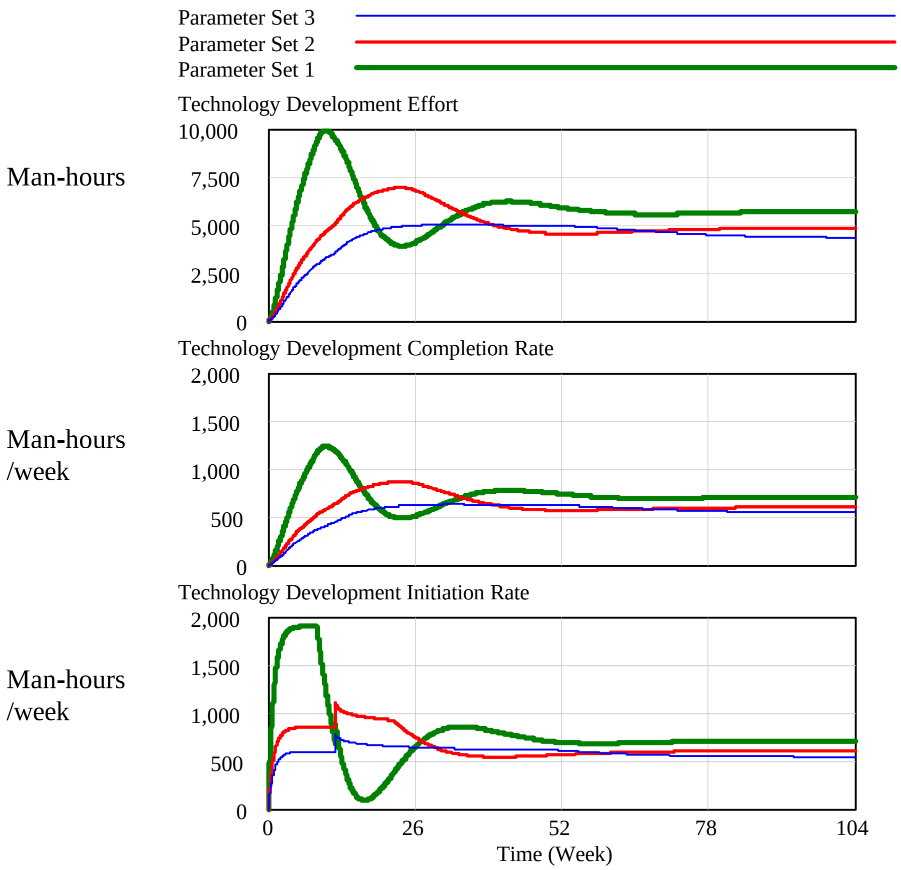

Figure 20 Technology Development at Three Sets of Parameter Inputs

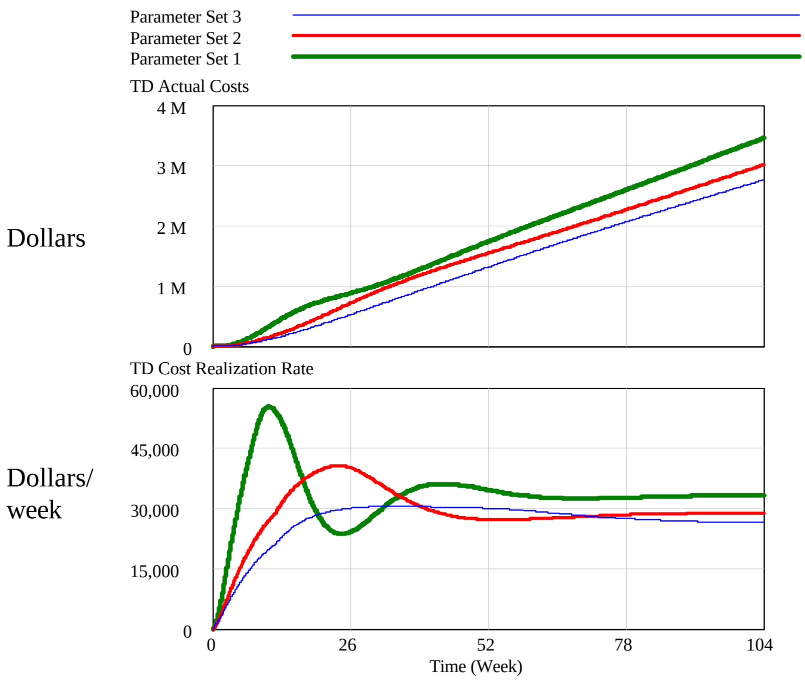

Figure 21 TD Costs at Three Sets of Parameter Inputs

5. 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.

5.4.1. Face Validity

The participants in the group modeling sessions who were also the resident experts 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 the participation of all group-modeling participants. This causal loop diagram was discussed and refined upon in an iterative manner over the course of four modeling sessions. A similar interactive process was followed in developing the stock and flow structure for the model.

5.4.2 Structure Assessment Tests

The experts confirmed the level of aggregation of the variables and concepts in the SD model. The expert team 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.

5.4.3 Dimensional Consistency Tests

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.

5.4.4 Integration Error Tests

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

5.4.5 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 the experts were costs and technical performance or testing results.

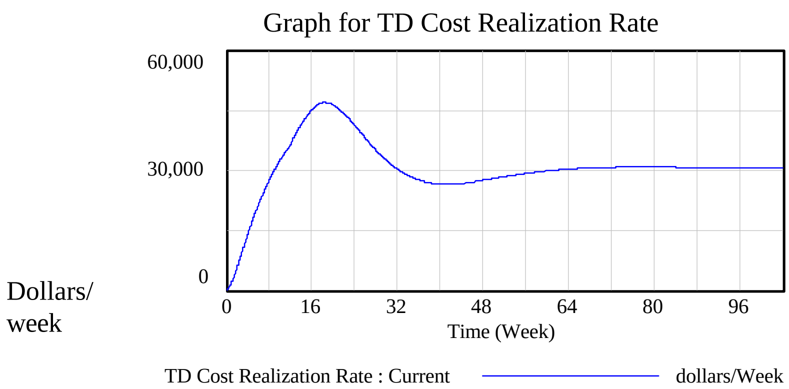

Figure 22 TD Cost Realization Rate

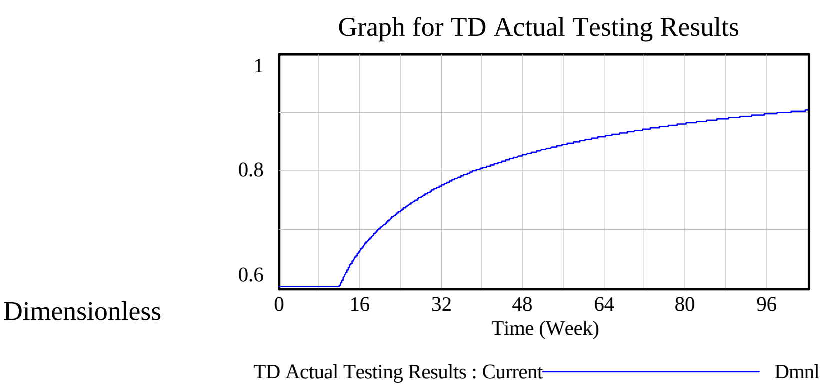

Figure 23 TD Actual Testing Results

Figures 22 and 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 experts.

6.0 Conclusions and Future Research

The System Dynamics Technology Development model was simulated for a specific technology whereby the 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 section. 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, Technology Development Testing Effort, Technology Development Management Effort, and Technology Development 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. The other dynamic behavior observed was the goal seeking observed for the variable Actual Testing results.

Varying parameters and observing the changes in the subsequent results from the simulation tested the dynamic hypotheses. The first hypothesis was that a lack of appropriate training causes cost overruns and higher costs in the technology development process. From the simulation results, it was observed that the Technology Development Actual costs, the Technology Development Cost Realization rate, and the Technology Development Cost Overrun fraction decreased as the amount of training imparted (as a percentage of available funding) was increased. 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 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 show that this hypothesis is true. However, analysis of the effect of the increase in Technology Development redevelopment fractions on the Technology Development 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. 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. 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.

Based on the results and testing done on the System Dynamic model, certain policy suggestions and outcomes were defined by the decision makers. These are summarized in Table 1. The policies would affect some of the initial parameters in the simulation model. For example, 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 technology development process because of the lack of a historical perspective and understanding with respect to the new technology. As seen by the model, 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.

Policies	Outcomes
Re-engineer the process for obtaining initial funding requirements.	Establish the appropriateness of the funding requirements.
Assure that the engineers have adequate knowledge of assessing technology risk.	Define the final risk level that impacts the activities in technology integration, operations, support and disposal.
Re-evaluate the commitment to technology development training.	Establish the need for training.
Evaluate the development of all competing designs.	Identify the actual level of effort and cost realized.
Provide clear articulation of technology development goals.	Understand cost behavior.
Improve the industrial base that supports technology development.	Restructure the current cost management process.
Promote the development of dual use technologies.	Identify the role of management in securing additional funds

Table 1: Identified Policies and Outcomes of the Technology Development Process

Furthermore, by running the model the decision-makers had an appreciation of the actual cost behavior associated with technology development, the level of effort involved, the training required, the risk level reached as a result of the technology development effort and identified the need to restructure the cost management process. All of this information can be used in the future to define and establish future policies that will impact future technology development efforts.

System Dynamics modeling is inherently iterative. One of the main issues in System Dynamics 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 analysis for the Technology Development subsystem. Breaking down the Technology Development effort into more detailed activities and studying their dynamics individually could add further insights into understanding its cost behavior.

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. The current structure of the model formulation assumes a steady constant 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.

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Appendix A: Table 2: Variable Definitions

Variable Name	Variable Description
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 2002 dollars).
Technology Maturity	It is defined as the state of development of a new technology. Increased technology maturity implies reduced development or procurement risk. It is a dimensionless variable measured using a relative scale (varying from 1 to 5; 1=very immature, 2=immature, 3=medium mature, 4=mature, and 5=very mature).
Technology Development	It is the effort (including both labor and materials) required to develop the new technology. It includes all activities except testing. It is measured using human effort time (units are man-hours)
Actual Testing Results	These are the actual results produced from testing the technology being developed. These testing results are mainly 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).
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 varying from 0 to 1; 0 corresponds to total failure and 1 corresponds to total success.
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. 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).
Technology Development Technical Performance	It 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).
Technology Development Risk	It is defined as a measure of the risk involved in developing the new technology. 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).
Complexity of New Technology	It 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).
Technology Development Management	It 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).
Technology Development Redevelopment Fraction	It 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.
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.
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 2002 dollars).
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)
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 2002 dollars)
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.
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).

Appendix B: Model Assumptions

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.

Appendix C

Table 3: User Defined Parameters

Parameter	**Range**	**Value**	**Unit**
Time horizon		204	Week
Initial time		0	Week
Time step		0.03125	Week
Initial TD risk	1-10	6.5	-
Man-Hour cost rate		70	$/Man-Hr
Technology maturity	1-5	3	-
Complexity of new technology	1-5	4	-
Funding stability	1-10	8	-
TD Management to development fraction		0.15	-
Technology development effort residence time		8	Week
TD Funding residence time		1	Week
TD Percentage training		0.005	-
TD Testing to development fraction		1/6	-
TD Management residence time		1	Week
TD Management to testing fraction		0.1	-
TD Initial testing results	0-1	0.6	-
TD Target testing results	0-1	1.0	-
TD Testing residence time		4	Week

Appendix D

Key Model Stock and Flow Structures

TD Funding Stock and Flow Structure

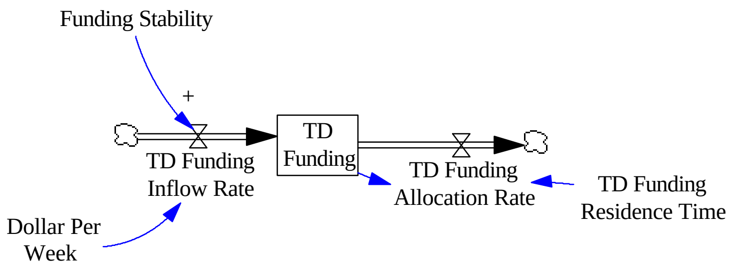

Figure 24 TD Funding Stock and Flow Structure

$$\text{TD Funding}(t) = \text{TD Funding}(0) + \int [\text{TD Funding Inflow Rate} - \text{TD Funding Allocation Rate}]\, dt \text{ where}$$
$$\text{TD Funding}(0) = 0 \qquad (3)$$

The TD Funding Inflow Rate was assumed to have a base value of $25000/week 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 affects the base value of TD Funding Inflow Rate by a divisive factor. At Funding Stability equals 10, the divisive factor is 1. At Funding Stability equals 4, the divisive factor is 1.1. At Funding Stability equals 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. The graph depicted in Figure 25 was plotted in MS Excel 2000.

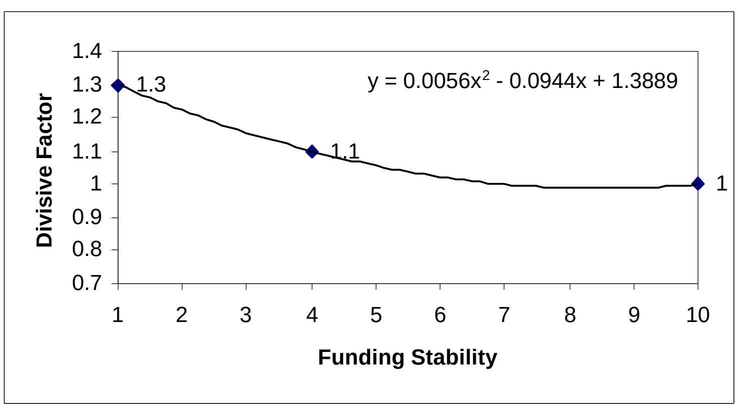

Figure 25 Impact of Funding Stability on TD Funding Inflow Rate

The overall equation to describe the relationship is:

$$\text{TD Funding Inflow Rate} = 25000 / (0.0056 * \text{Funding Stability}^2 - 0.0944 * \text{Funding Stability} + 1.3889) * \text{Dollar Per Week} \qquad (4)$$

The TD Funding Allocation Rate is a first order delay of the TD Funding stock. The TD Funding Residence Time is the average time the incoming funding stays in the stock before being allocated.

TD Funding Allocation Rate = TD Funding / TD Funding Residence Time (5)

Technology Development Effort Stock and Flow Structure

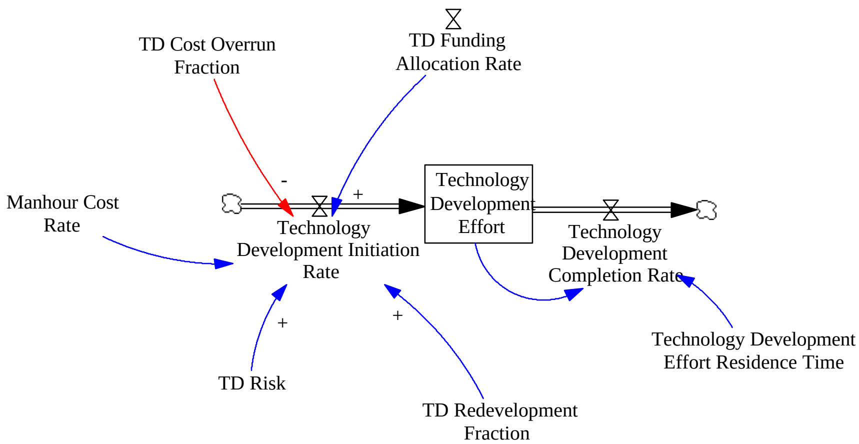

Figure 26 Technology Development Effort Stock and Flow Structure

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).

Technology Development Effort (t) = Technology Development Effort (0) + ò [Technology Development Initiation Rate – TD Funding Allocation Rate] dt where Technology Development Effort (0) = 0 (6)

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 Man-hour 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 affects 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. The graph depicted in Figure 27 was plotted in MS Excel 2000.

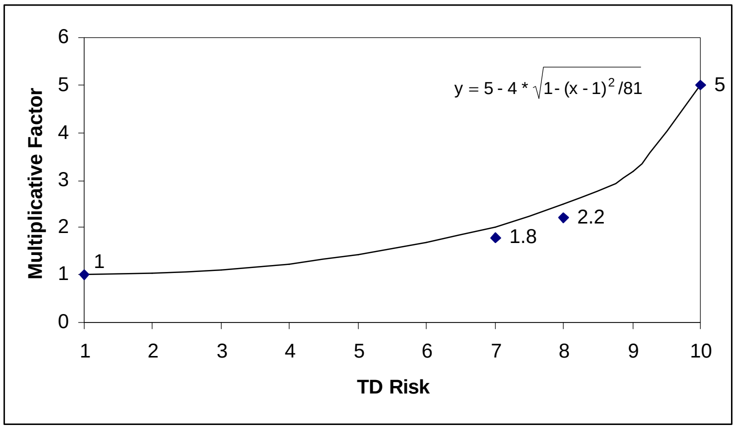

Figure 27 The Impact of TD Risk on the rate of Technology Development

The overall equation to describe the relationship is:

*Technology Development = TD Funding Allocation Rate / Man-hour Cost Rate * 0.75 Initiation Rate * (1+TD Redevelopment Fraction) * (1-2*TD Cost Overrun Fraction) * (5-4** $\sqrt{1-(TDRisk-1)^2/81}$ *)* (7)

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

Technology Development = Technology Development Effort /Completion Rate Technology Development Effort Residence Time (8)

TD Testing Effort Stock and Flow Structure

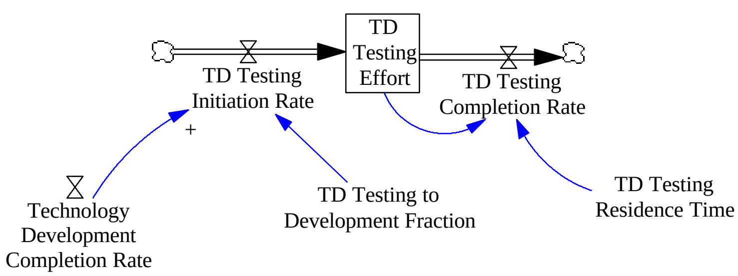

Figure 28 TD Testing Effort Stock and Flow Structure

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) + $\int$ *[TD Testing Initiation Rate – TD Testing Completion Rate] dt where TD Testing Effort (0) = 0* (9)

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* (10)

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 (11)

TD Actual Testing Results Stock and Flow Structure

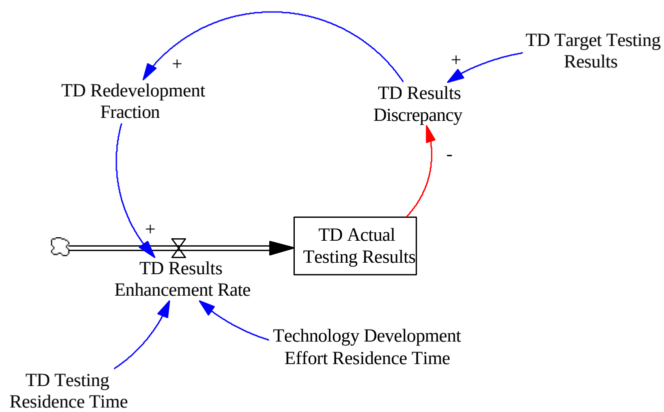

Figure 29 TD Actual Testing Results Stock and Flow Structure

The TD Actual Testing Results stock (dimensionless) is fed into by a TD Results Enhancement Rate (week^{-1}).

TD Actual Testing Results (t) = TD Actual Testing Results (0) + $\int$ *[TD Results Enhancement Rate] dt* (12)

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. 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. So, 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. The overall equation to describe the relationship is:

TD Results Enhancement Rate = TD Redevelopment Fraction /(Technology Development Effort Residence Time +TD Testing Residence Time) (13)

The TD Results Discrepancy (dimensionless) is the difference between the TD Target Testing Results and the TD Actual Testing Results.

TD Results Discrepancy = TD Target Testing Results-TD Actual Testing Results (14)

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 TD Results Discrepancy affects it. 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. 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. The graph depicted in Figure 30 was plotted in MS Excel 2000.

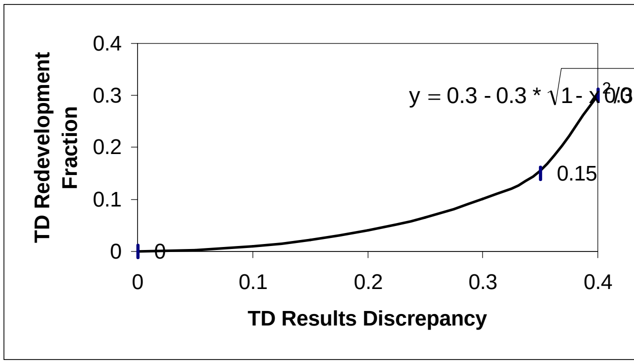

Figure 30 Impact of TD Results Discrepancy on TD Redevelopment Fraction

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

$$TD\ Redevelopment\ Fraction = 0.3 - 0.3 * \sqrt{1 - TDResultsDiscrepancy^2 / 0.16} \qquad (15)$$

TD Management Effort Stock and Flow Structure

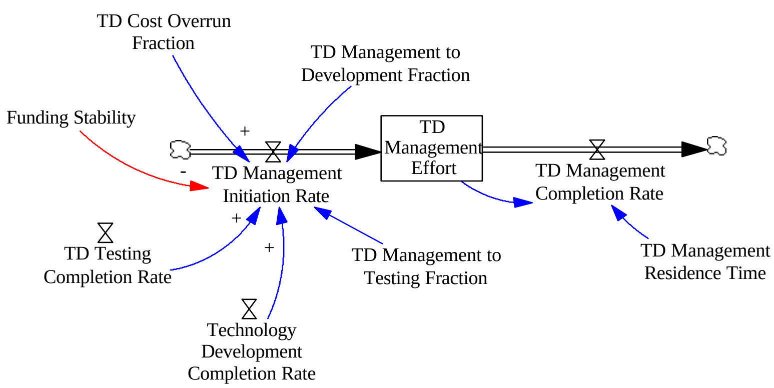

Figure 31 TD Management Effort Stock and Flow Structure

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).

$$TD\ Management\ Effort\ (t) = TD\ Management\ Effort\ (0) + \int [TD\ Management\ Initiation\ Rate - TD\ Management\ Completion\ Rate]\ dt \quad where\ TD\ Management\ Effort\ (0) = 0 \qquad (16)$$

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). The TD Management Initiation Rate increases at ten percent of the rate of increase in cost overruns. An increase (decrease) in Funding Stability leads to a decrease (increase) in the TD Management

Initiation Rate. Funding Stability affects 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.

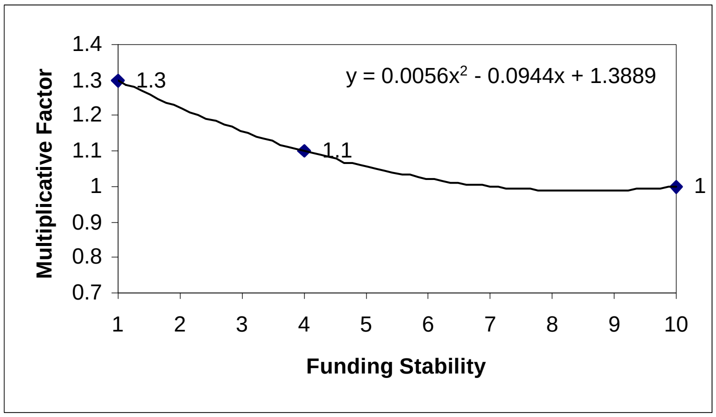

Figure 32 Impact of Funding Stability on Management Initiation Rate

The overall equation 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 Stability² - 0.0944 * Funding Stability + 1.3889)* (17)

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 (18)

TD Actual Costs Stock and Flow Structure

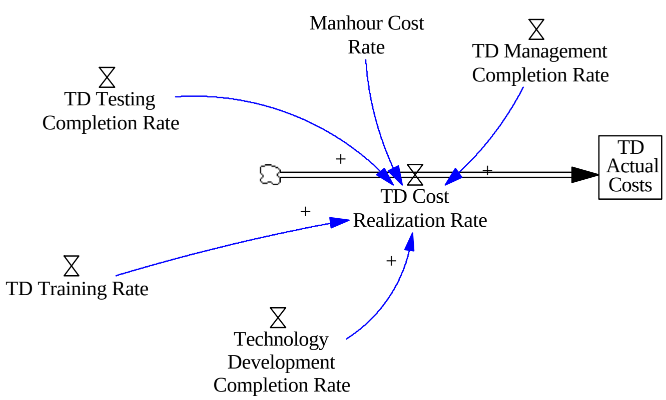

Figure 33 TD Actual Costs Stock and Flow Structure

The TD Actual Costs stock (dollars) is fed into by a TD Cost Realization Rate (dollars/week).

TD Actual Costs (t) = TD Actual Costs (0) + ∫ [TD Cost Realization Rate] dt,
where TD Actual Costs (0) = 0 (19)

The TD Cost Realization Rate is driven by the man-hour rates of technology development, testing, and management activities. The Man-hour 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* (20)

TD Cost Overrun Fraction Structure

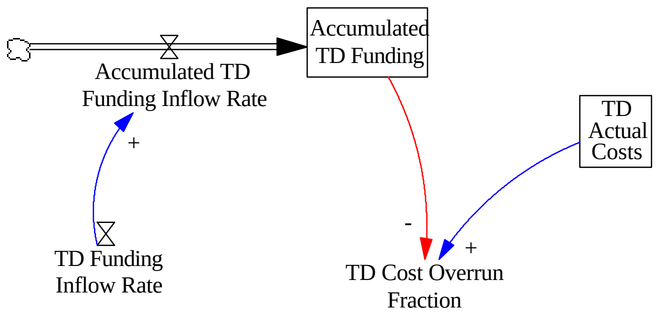

Figure 34 TD Cost Overrun Fraction Structure

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

Accumulated TD Funding (t) = Accumulated TD Funding (0) + ∫ [Accumulated TD Funding Inflow Rate] dt, where Accumulated TD Funding (0) = 0 (21)

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

Accumulated TD Funding Inflow Rate = TD Funding Inflow Rate (22)

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 is realized. This cost overrun is captured in the TD Cost Overrun Fraction variable as a fraction of the Accumulated TD Funding.

TD Cost Overrun Fraction = MAX ((TD Actual Costs-Accumulated TD Funding)/ Accumulated TD Funding, 0) (23)

TD Training Imparted Stock and Flow Structure

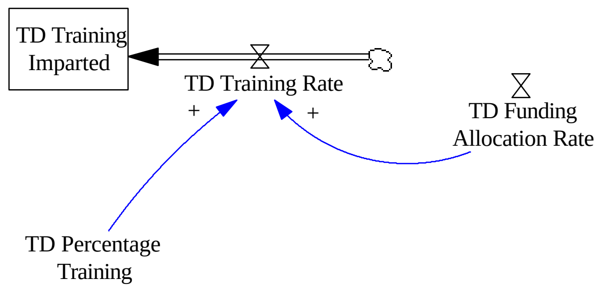

Figure 35 TD Training Imparted Stock and Flow Structure

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

TD Training Imparted (t) = TD Training Imparted (0) + $\int$ *[TD Training Rate] dt, where TD Training Imparted (0) = 0* (24)

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* (25)

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