A Systems Approach to U.S. Coast Guard Cutter Maintenance

by

Chad Jacoby

B.S. Civil Engineering, U.S. Coast Guard Academy, 1992
M.S. Mechanical Engineering, Old Dominion University, 2002

Submitted to the System Design and Management Program
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management

at the
Massachusetts Institute of Technology
September 2015

Signature of Author Signature redacted
Chad L. Jacoby
System Design and Management Program
30 July 2015

Certified by Signature redacted
Dr. Qi Hommes Ph.D.
Thesis Supervisor
Engineering Systems Division

Accepted by Signature redacted
Patrick Hale
Director
System Design and Management Program

A Systems Approach to U.S. Coast Guard Patrol Boat Maintenance

By

Chad Jacoby

Submitted to the System Design and Management Program in August, 2015
in Partial Fulfillment of the Requirements for the Degree of Master of Science in Engineering and Management

ABSTRACT

The United States Coast Guard (USCG) has entered a unique period in its history marked by the aging of its legacy cutter fleet, the construction and integration of replacement cutters, tight fiscal constraints and the recent modernization of its logistics support organization. The achievement of maritime missions is dependent on the proper allocation of agency resources across the operation, maintenance and repair of Coast Guard cutters. Interdependencies caused by the shared resources of time, funding and inventory parts create complex interactions between the components that make up the Coast Guard's cutter operations and maintenance system.

This thesis uses System Dynamics modeling and simulation techniques to analyze the Coast Guard's cutter operations and maintenance system to identify system constraints, evaluate policy and resource alternatives, and recommend policy changes to improve the operational availability of the fleet.

The application of System Dynamics modeling and simulation tools identify several high leverage variables in the operations and maintenance system structure. Small changes to these variables capitalize on the reinforcing feedback mechanisms already present in the system structure to produce significant improvements in the operational availability of the fleet. Maintenance and repair part inventory levels and operational policies governing cutter standby status are identified as key drivers of system performance, and specific recommendations are provided to increase operational patrol hours by up to 15% and decrease cutter casualty hours by up to 25%. Other recommendations include the revision of command performance metrics to drive behaviors that influence these high leverage variables, application of System Dynamics principles to new cutter sustainment strategies, and expansion of the use of real-time operations and engineering data in engineering and scheduling policy decisions.

Thesis Supervisor: Dr. D. Van Eikema Hommes, Ph.D.
Title: Lecturer, Engineering Systems Division

--THIS PAGE INTENTIONALLY BLANK--

Acknowledgements

I am very grateful for the challenging opportunities the Coast Guard has provided to me and my family over the course of my career. I have been surrounded by great people doing amazing and important work for the protection of the people and interests of the nation. The extraordinary level of responsibility that the Coast Guard entrusts to its members has helped me grow and contribute at a rate beyond what I could have imagined. The opportunity to attend MIT, dedicate time to the analysis of difficult problems, and expand my vision of the world will benefit the Coast Guard in my future assignments. It has also enriched my life; for that, I will always thank the Coast Guard.

I would like to thank the staff of the MIT Systems Design and Management (SDM) program, my Sloan Professors and the rest of the SDM cohort for their instruction and support. Completing the SDM program in 12 months has simultaneously been one of the most inspiring and most challenging things I have ever done. Working alongside the smart, fun and professional people at MIT made the long hours enjoyable and led to an experience that I don't think could have happened anywhere else.

Completing this thesis required a considerable amount of data collection and interpretation of the Coast Guard's operations, financial, and engineering metrics. I would like to thank the members of the CG Surface Forces Logistics Center's Patrol Boat Product Line for their time and expert recommendations over the past year. They eagerly helped with a wide range of inputs, all while maintaining half of the Coast Guard cutter fleet.

I appreciate the encouragement and flexibility of my family over the past year. Adrienne, Melaina and Jake: without your support, I would not have been able pursue the SDM program, and, without your understanding, I would definitely not have been able to finish it.

Contents

List of Figures

List of Tables

List of Acronyms

ALMIS	Aviation Logistics Management Information System
DHS	Department of Homeland Security
FLS	Fleet Logistics System
FMC	Fully Mission Capable
FRC	Fast Response Cutter
GFE	Government Furnished Equipment
MIT	Massachusetts Institute of Technology
MTBF	Mean Time Between Failure
NESSS	Naval and Electronics Supply Support System
SD	System Dynamics
SDM	System Design and Management
SFLC	Surface Forces Logistics Center
SOP	Standard Operating Procedures
US	United States
USCG	United States Coast Guard

Chapter 1: Introduction

1.1 Thesis Motivation

My Coast Guard career has been focused on the engineering and logistics required to sustain the cutter fleet. Over the past 23 years, I have served in roles of progressively higher responsibility on ships as the engineer officer or on land in charge of the cutter support and logistics organizations. In my most recent assignment, I served as the Surface Forces Logistics Center's Patrol Boat Product Line Manager. In this position I was the single point of accountability for the maintenance, repair, supply support, policy and fiscal support of the Coast Guard's fleet of 122 Patrol Boats stationed around the world. One of the most fulfilling aspects of this job was the ability to make innovative changes to the engineering requirements, processes, or cutter hardware to increase operational availability or reduce maintenance costs. This innovative approach to prioritization and completion of the surface fleet maintenance requirements became increasingly important as the federal, Department of Homeland Security (DHS), and Coast Guard budgets decreased. Limited resources (people, funding, assets, and information) and cultural inertia are two examples of the challenges that United States Coast Guard (USCG) leaders face in their efforts to improve delivery of service to the nation. Through this thesis I use the problem-solving methods and systems modeling and analysis methods I have acquired from the MIT- System Design and Management (SDM) Program to provide insights and recommendations that can be used to improve the USCG's ability and efficiency in conducting its maritime missions.

1.2 Opportunities and Challenges

The Coast Guard's fleet of 244 cutters, home ported across 18 time zones, provides 461,000 patrol hours every year in support of the nation's maritime interests (SFLC 2015).
With $300M dedicated to fleet maintenance each year and maritime missions like drug interdiction, search and rescue, and coastal security all hinging on the reliability of the Coast Guard's ships, it is essential that the causal forces behind unplanned down time due to equipment casualties, maintenance backlogs and inventory shortfalls be understood and managed (SFLC

2015). Traditionally, cutter maintenance requirements, funding policies, and resource decisions have been made based on historical information and rules of thumb. Many of these rules were developed during a period when fleetwide real time information on operations, maintenance, casualties and costs was not readily accessible.

The Coast Guard has made high level organizational and procedural changes over the past six years that have significantly advanced the service's ability to track and manage cutter readiness. These changes included the centralization of all cutter maintenance, supply and repair activities under one command and the implementation of new information technology tools to track operational hours, maintenance, casualties and costs.

The first class of cutters to transition to this integrated logistics model was the 87 foot patrol boat fleet. After several years of operations under these updated processes, the 87 foot patrol boat fleet has produced the data necessary to support the quantitative analysis performed in this thesis. Conclusions drawn from this analysis could be directly applied to management of the 87 foot patrol boat fleet. It can also be used to shape the policies that govern operation and maintenance of the remainder of the Coast Guard patrol boat fleet because all of the patrol boats have transitioned to the same integrated logistics model and are scheduled using the business rules that are modeled in this study. In addition, the current acquisition of a new fleet of 154-foot Fast Response Cutters (FRC) provides a unique opportunity to influence the sustainment strategy that will be used to support these newly constructed cutters. Maintenance savings and operational efficiencies identified by this study and incorporated into the sustainment strategy for the 58 cutter FRC fleet could result in substantial long term benefits throughout the 30 year projected service life of the fleet.

1.3 Research Question:

One of the widespread and accepted notions in life is that if you don't maintain something, it will break. Whether the item is a house, a car, a bicycle or a ship, the concept that maintenance leads to reliability is almost universally accepted. Yet as the complexity of the system being maintained increases, the relationship between maintenance and reliability becomes less linear and harder to quantify. In addition, operations and maintenance have a contradictory relationship. The more an asset is operated, the more maintenance it requires. The additional maintenance however takes time away from conducting operations.

With the service motto "Semper Paratus," meaning Always Ready, the USCG clearly embodies the principles of preparation and care in anticipation of answering the call. How can the USCG uphold this central ideology and increase the readiness of its cutter fleet? The question has been asked by engineers, budget managers and operational commanders, but the analysis to date has focused on process and component reliability improvements inside each individual discipline, such as engine monitoring and supply chain management. This study expands the search space for improvements by leveraging both engineering and business principles to analyze the operations and maintenance of a geographically distributed cutter fleet constrained by both operational and logistics policies.

As the entire Coast Guard fleet transitions to a common integrated logistics support model, it is important to leverage the information that the new model provides to validate and update the business rules that govern the fleet. Using data model of the operations and maintenance system, traditional policies can be tested, resource allocation changes can be explored and the system's sensitivity to inputs can be quantified. Accordingly, I propose the following three research questions:

Table 1: List of Thesis Research Questions

Number	Thesis Research Questions
1	How does the structure of the Coast Guard cutter operations and maintenance system affect the management and reaction of the system?
2	What resource decisions and policy levers have the largest impact on operational availability of the Coast Guard fleet?
3	What combination of policies and resources provide a high level of fleetwide operational availability while balancing maintenance, supply, and casualty repair costs?

The research conducted in this study will focus on the application of system analysis to identify previously undocumented interactions between system elements. The analysis will identify the key levers to influence system outcomes and recommend appropriate policy changes to lock these practices into the organizational culture.

1.4 Thesis Overview

Chapter 2 provides a general overview of the Coast Guard's traditional cutter sustainment practices and details the recent centralization of maintenance responsibilities. It includes a high level description of the metrics used to assess the health of the Coast Guard fleet and the effectiveness of maintenance efforts, along with an overview of the USCG's process for allocation of maintenance funding. This chapter also describes the scope of the research and the boundary limits of the system that will be analyzed for the thesis.

Chapter 3 conducts a review of published works that contributes to the subject of this thesis. The areas of reliability engineering, complexity management, systems theory, cognitive science and system dynamics are evaluated.

Chapter 4 applies system dynamics tools to represent and simulate the Coast Guard's cutter operations and maintenance system. The system dynamics model is constructed in phases using the structure and policies of the real life system. The model is then used to evaluate seven policy scenarios.

Chapter 5 provides conclusions and recommendations for improvement of the Coast Guard's operations and maintenance system based on the observations and results in previous chapters.

1.5 Proviso

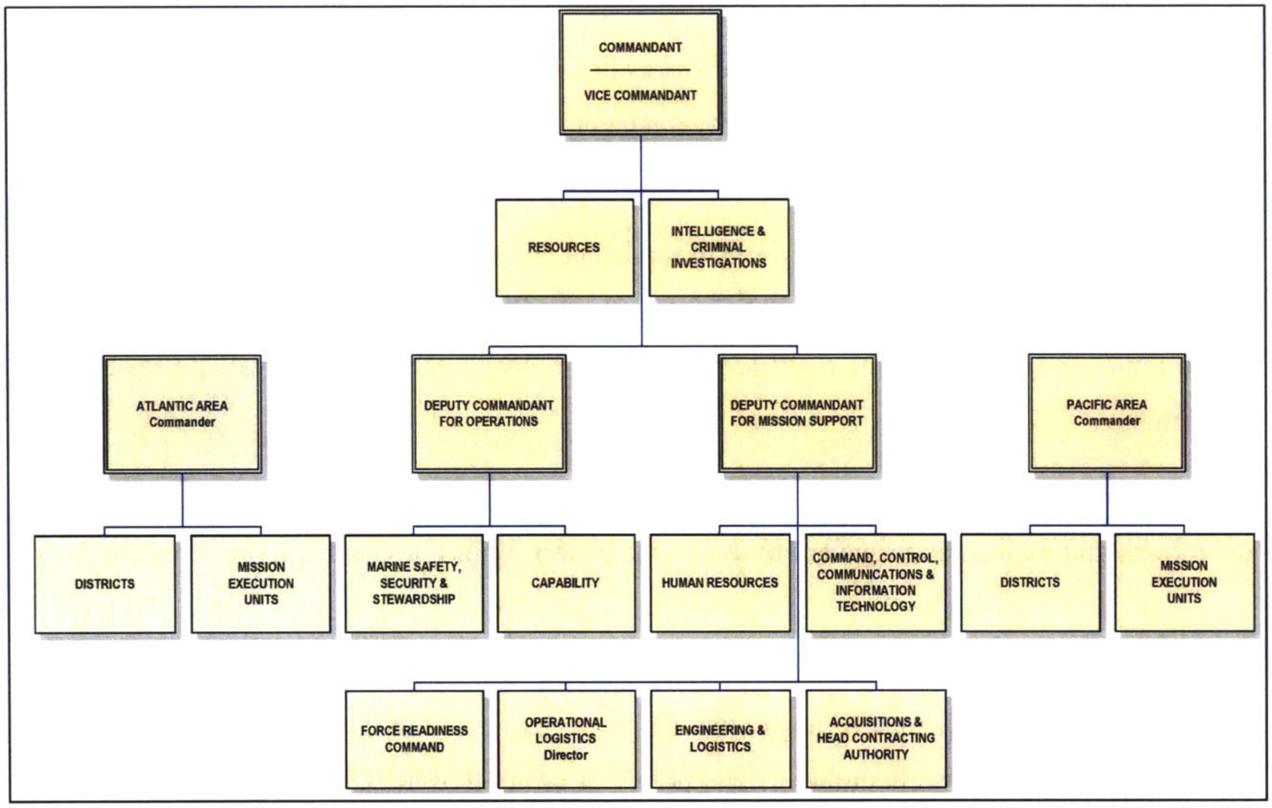
The reader of this thesis must be aware that the views expressed in this academic paper are those of the author and do not reflect the official policy or position of the US government, DHS or the USCG. The system models presented in this thesis are simplified to facilitate easier understanding of the key mechanisms. One of the main benefits of documenting a complex system is that it can reveal differences in people's mental model of the system. Identification and discussion of these differences will improve the Coast Guard's ability to form balanced fiscal, engineering and operational policies.

Chapter 2: Background

2.1 Overview of the Coast Guard

The USCG operates within the DHS. The organization of the USCG is represented in Figure 1 below (xlibrary 2011). The Coast Guard organizational structure includes elements to accomplish all of its eleven statutory missions. This study will focus primarily on the operation and maintenance of Coast Guard cutters which will require a detailed view of the organizational elements shaded in grey.

Figure 1: Organizational Structure of the USCG



The Commandant, Vice Commandant and their Deputy Commandant for Mission Support (DCMS) and Deputy Commandant for Operations (DCO) represent the senior headquarters strategy and policy-making authorities for the USCG. These offices develop the governing policies that allocate resources to CG mission support units (elements of the CG that provide logistical support for operations) and operational units (elements of the CG that perform the missions).

2.2 Cutter Operations and Maintenance

The Coast Guard's organizational structure establishes an operational chain of command and a mission support chain of command. The operational chain of command is focused on "employing Coast Guard forces to meet mission requirements" (Butt 2013). The mission support chain of command "develops, deploys and maintains the resources necessary to sustain the capabilities to meet operational requirements" (Haycock 2014).

Operational units, such as the 87 foot patrol boats which are the subject of this study, are divided geographically and controlled by separate Atlantic Area and Pacific Area Operational Commanders. The Atlantic Area Commander is located in Portsmouth, VA. The Pacific Area Commander is located in Alameda, CA. Each operational commander further divides the geographic regions into "districts" and "sectors" as shown in Figure 2 below. The Surface Forces Logistics Center (SFLC) is located in Baltimore, MD and is responsible for engineering and logistics support for the entire CG fleet, regardless of geographic region.

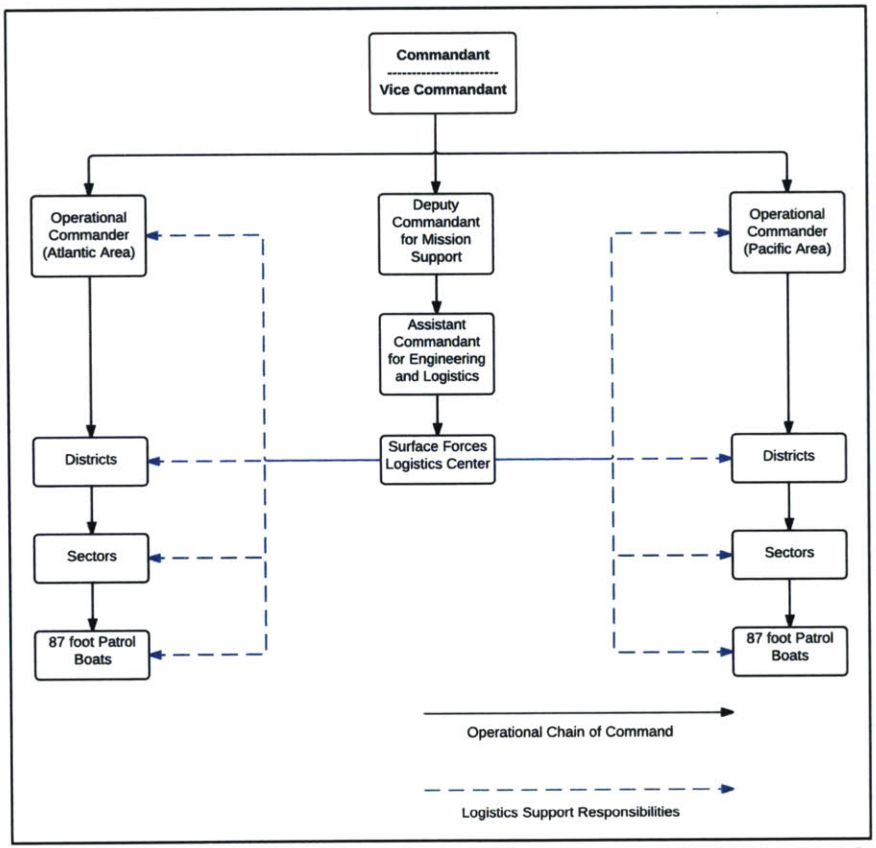


Figure 2: Coast Guard Logistics and Operational Chain of Command

The 87 foot patrol boats are managed at the district and sector levels of the organizational structure. Each district is assigned a certain number of patrol boats based on the operational activity in their area of responsibility. Each year the district is authorized to utilize the patrol boat for a set number of operational hours to execute Coast Guard missions.

Until 2010, the Coast Guard mission support chain of command used a geographic hierarchy similar to the operational chain of command to deliver logistics support to operational units. Mission support responsibilities were divided into Atlantic and Pacific regions and further broken down into regional commands close to each operational sector around the country. In 2010, the Coast Guard centralized all engineering and logistics support for the cutter fleet under the Surface Forces Logistics Center (SFLC) in Baltimore, MD. The transition from a distributed organization that closely mirrored the operational chain of command to a centralized organization that focused on fleet wide support required the establishment of new maintenance policies, centralization of maintenance funding, and designation of a single point of accountability for all cutter support functions. This centralized approach to mission support was designated as the Coast Guard Integrated Logistics Support model.

2.3 Coast Guard Integrated Logistics Support

In 2010, the Coast Guard implemented a logistics modernization initiative that consolidated responsibility for all maintenance, repair, policy, finance, and supply requirements under one command, the Coast Guard Surface Forces Logistics Center. The Surface Forces Logistics Center provides all inclusive support through five product lines that encompass all of the cutters and boats that comprise the Coast Guard fleet. Each of the product lines is headed by a Product Line Manager who is charged as the single point of accountability for providing operational support to execute Coast Guard missions. The consolidation of all engineering, maintenance, repair and logistics functions under a single command has allowed Product Line Managers to make funding and resource decisions while weighing fleetwide priorities and fleetwide impacts. Establishment of the Surface Forces Logistic Center and the consolidation of resources and authority at the product line level provided, for the first time in the history of the Coast Guard, the ability to optimize fleet support at the system level. Once this capability was established, it was apparent that the existing forms of cutter status tracking, maintenance reporting, and casualty notification were not adequate to support system level decisions.

In October of 2012, the Surface Forces Logistics Center implemented a new asset management tool which automatically captured the operational time, maintenance time, and downtime due to casualties for all of the cutters and boats stationed around the country (Ciaglo 2012). This tool was adapted from an in-house database used to manage Coast Guard aircraft and retained its name as the Aviation Logistics Management Information System (ALMIS), even after it was adapted to the management of cutters.

Now that a system-oriented organizational structure is in place and several years of system-level operational and logistics data have been captured, it is appropriate to look at the policies and processes that drive maintenance decisions, spare parts stocking levels, operational policies, casualty repair prioritization and fiscal decisions, many of which were carried over from the decentralized model, in order to ensure that they leverage the strength of the new centralized model.

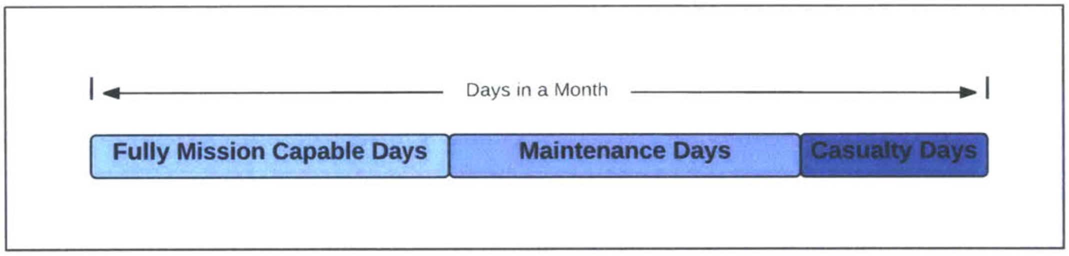
2.4 System Boundary and Assumptions

The USCG's operations and mission support structure is a large and complex socio-technical system which encompasses much of the Coast Guard's infrastructure, personnel, and funding. Modeling the entire system would add unnecessary complexity and make it difficult to focus on the causal relationships. The analysis in this study is focused on the interactions and emergent system characteristics between operations, maintenance, supply support, and casualty repair. The 87 foot patrol boat fleet was used to construct the system model because the 87 foot patrol boat fleet has operated under the integrated logistics model for the longest period of time (more than two and a half years). With 69 ships in the middle of their service life, the 87 foot patrol boat fleet is the Coast Guard's largest class of cutters, has the most robust level of data and has adequate remaining service life to justify identification of policy improvements.

For modeling purposes, operational and scheduling decisions are aggregated at the district level. In practice, some of these decisions are delegated down to the local sector or cutter level. Modeling operational and scheduling decisions at the district level is appropriate because policies for these delegated sector and cutter actions are dictated by each district. Changes to these policies would be initiated by the district. Modeling at the district level also makes the results of the analysis applicable to a wider range of cutters. For example, the 110 foot patrol boat and 154 foot patrol boat fleets operate under similar business rules, just with less delegation of operational and scheduling decisions to the sectors.

Sustained patrol boat operations are accomplished though iterative loops of maintenance and operations, with periodic interruptions due to engineering casualties. Since the vast majority of maintenance actions require the equipment being serviced to be offline, it is generally true that each day of operations takes away a potential maintenance day, and each day of maintenance takes away a potential operational day. Therefore, the status of a cutter falls into one of three categories: Fully Mission Capable Days, Maintenance Days, or Casualty Days. In any given month, the summation of the three categories accounts for 100% of the cutter's time as represented in Figure 3. The CG ALMIS system uses a fourth category labeled "Partially Mission Capable Days." [1]

Figure 3: Coast Guard Cutter Status Categorization



As discussed in Section 2.2, operational policies and cutter scheduling is carried out by the districts in the operational chain of command. Maintenance policies and casualty response resources are provided by the Surface Forces Logistics Center. The system structure and metrics intended to balance this inherently opposed system construct are the focus of this research. Therefore, establishment of the system of interest boundary around the Surface Forces Logistics Center and the district commands allows a detailed analysis of the interactions between logistics and operational policy.

---

[1] For the purpose of this study, partially mission capable days were included in the fully mission capable days category. Partially mission capable status is used when a cutter can safely carry out its primary mission but has a discrepancy that limits its ability to perform one of its secondary missions.

Chapter 3—Literature Review

A literature review was conducted to determine the most appropriate method to answer the research questions posed above. This was achieved by exploring a wide range of factors that influence operational readiness including: component reliability, principles for analysis of complex systems, human factors in complex decisions, and system modeling and analysis.

3.1 Reliability Engineering

Research in reliability engineering reveals the science behind the formulation of maintenance plans designed to increase the Mean Time Between Failure (MTBF) and maximize the uptime of equipment (Jones 2006). These calculations provide maintenance managers with recommendations for what maintenance actions should be written into policy to achieve the desired level of reliability for a mechanical component. When these components are combined into a complex mechanical system, the calculation of maintenance requirements essential to maximize system uptime is complicated by the interfaces and interactions between the individual components. Similarly, when these complex mechanical systems are managed as elements in the widespread organizational system of fleet operations, maintenance and repair, the level of interaction and complexity multiplies.

3.2 Principles for Studying Complex Problems

3.2.1 Reductionist Thinking

Renè Descartes, a sixteenth century French mathematician, philosopher and scientist published a " Discourse on the Method of Rightly Conducting the Reason, and Seeking Truth in the Sciences" in 1637 (Descartes 1993). In his discourse, he argued that the world was like a machine that, like the mechanisms inside a clock, could be understood by taking the pieces apart, studying them, and putting them back together to see the larger picture (Mastin 2008). This principle of breaking a system down into its elements, studying the actions of those elements, and adding the results to determine the action of the system, became known as reductionist thinking. During the Scientific Revolution of the seventeenth century, reductionist thinking formed the basis for important advancements in chemistry, physics and cell biology. Classic mechanics and thermomechanics also use a reductionist approach to explain macroscopic properties in terms of microscopic components (Mastin 2008). A reductionist approach, following principles outlined by Descartes, has been used extensively for more than 300 years.

It was not until the middle of the twenty first century that the limitations of reductionist thinking were broadly recognized. Advances in technology enabled the design and operation of more complex systems that were difficult to analyze in segments due to the large number of important interactions between system elements.

The application of reductionist thinking to the operation and maintenance of Coast Guard cutters would involve breaking the operational and logistics functions into their subprocesses and analyzing them for efficiencies. For example, one of the logistics functions that affects the time it takes to repair a casualty is the availability of replacement parts. A reductionist approach to improving the operational availability of cutters would be to break the casualty repair process down into its sub-requirements of manpower, funding, information, and parts. The requirements to have parts could be further broken down into parts inventory, commercial procurements, and shipping. A similar process could be used to analyze the subprocesses that enable cutter operations and cutter maintenance. This approach allows for focused improvements at the sub-task level and is the technique used in prior Coast Guard process improvement initiatives. However, this process can only be used to optimize a single subprocess and cannot account for the system level response to these actions. In the example provided, the optimization of the parts inventory process would likely yield recommendations to increase the stocking level of high turnover parts. The optimization of cutter maintenance would likely recommend increasing the time the cutter is available for maintenance and improved training for technicians. Optimization of cutter operations would likely recommend increasing the time the cutter is available for operations and allocation of more funding for fuel. Using this reductionist approach fails to account for the interactions between these tasks and subtasks. A very strong interaction exists between cutter maintenance, cutter operations and cutter casualty repair. Since there are only 365 days in a year and, in general, only one of these tasks can be performed at a time, any increase in one category is going to decrease the other categories. Similarly, the fact that the Coast Guard's overall annual budget is fixed and has to pay for fuel, training, parts and technician travel means that an increase in one area needs to be offset by a decrease in another area.

3.2.2 Systems Theory

Aristotle purported in 320 BC one of the most fundamental principles of systems theory, "The whole is more than the sum of its parts" (Brainyquote 2015). While the idea that systems can have characteristics different from the combination of the characteristics of its elements has existed for thousands of years, the field of systems theory has only gained widespread application in the last 50-100 years. The systems approach focuses on systems taken as a whole, not on the parts taken separately (Leveson 2011). It assumes that some properties of systems can be treated adequately only in their entirety, taking into account all facets relating the social to the technical aspects (Leveson 2011). These system properties derive from the relationships between the parts of systems: how the parts interact and fit together (Ackoff 1971).

3.2.3 Cognitive Science

Research by the Carnegie School acknowledges the psychological and cognitive limitations of human members as decision makers in complex systems (Gavetti, Levinthal, and Ocasio 2007). Pioneering work by Cyert, March and Simon of the Carnegie School showed that organizations manage these limitations through the use of factored decision making, decision processes based on partial information and reliance on standard operating procedures (Cyert and March 1963; Simon 1957). The "principle of bounded rationality" is the cornerstone of Carnegie philosophy which suggests that the performance and success of an organization is governed primarily by the limitations of its members: the amount of information they can acquire and retain and their ability to process information in a meaningful way (Morecroft 1983).

John Morecroft demonstrated the ability of System Dynamics modeling to represent the quantity and quality of information that is amenable to human judgmental processing and the decision rules used in management decisions (Morecroft 1983).

3.3 System Dynamics

System dynamics is a method to enhance learning in complex systems (Sterman 2000). It utilizes simulation models that use empirical research to identify and test high leverage policy changes (MITSloan 2015) In *Business Dynamics*, Sterman states that "Just as an airline uses flight simulators to help pilots learn, system dynamics is, partly, a method for developing management flight simulators, often computer simulation models, to help us learn about dynamic complexity, understand the sources of policy resistance, and design more effective policies" (Sterman 2000). System Dynamics modeling has been used to understand systems as large and controversial as the interactions between human population growth and the Earth's environmental carrying capacity and as finite and well documented as the dynamics of economic supply and demand (Sterman 2000; Sutton 2015).

3.3.1 System Dynamics Graphical Construct

System Dynamics utilizes several graphical symbols to represent stocks, variables, flows and feedbacks in complex systems. A definition of these symbols and a short description of their usage is provided using a model of human population (Zhou 2012).

Two factors that influence the population of humans are births and deaths. The effect of the variables "birth rate" and "death rate" on the stock of "human population" are represented in Figure 4:

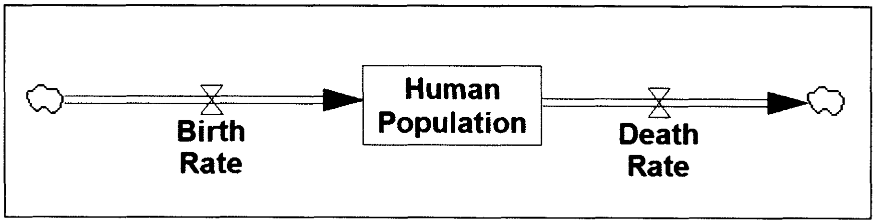


Figure 4: Sample System Dynamics Stock and Flow Diagram

In this very simple model, if the birth rate increases the stock called "human population" fills up with more and more people. If the death rate increases the stock of "human population" is drained at a faster rate. In reality, the birth rate and death rate are not fixed variables, they are dependent on the size of the human population. This form of variable dependency is shown using a blue arrow pointing to the dependant variable. If the human population increases, the birth rate (measured in people/year) will increase. This increase in birth rate will cause a further increase in population creating a reinforcing feedback loop (labeled with a red "R" and a counterclockwise arrow) represented in Figure 5.

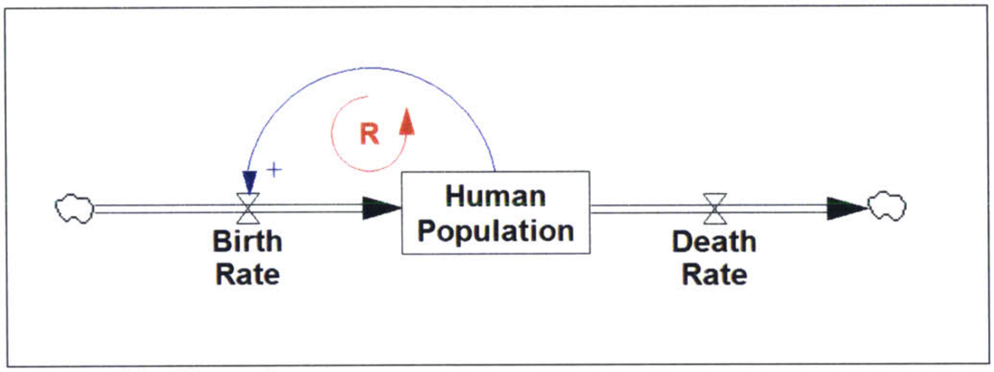


Figure 5: Sample System Dynamics Reinforcing Loop

If this were the only feedback loop in the system, the human population would grow exponentially due to the reinforcing nature of this feedback loop. The death rate is also dependant on the size of the human population, but, as the death rate increases, the human population decreases. This relationship creates a balancing feedback loop (labeled with a red "B" and a clockwise arrow) represented in Figure 6.

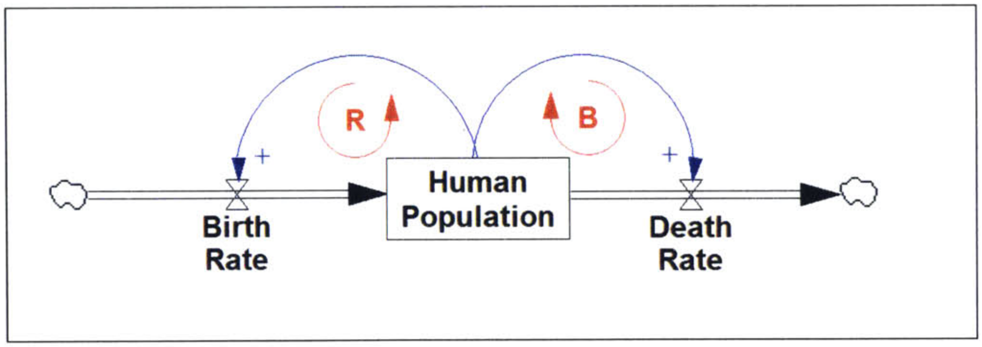


Figure 6: Sample System Dynamics Balancing Loop

This very simplistic model of human population shows the system interactions, the polarity of the relationships, and characterizes the type of system behavior created by the interactions. The human birth rate and death rate can change over time due to external forces like financial prosperity and depression. During some periods, the system output will be dominated by the reinforcing loop (exponential growth of the human population), and during some periods, it will be dominated by the balancing loop (limited growth or decline).

3.3.2 System Dynamics Model Boundary and Scope

System Dynamics modeling techniques can be used to represent any part of a complex system and can be applied at varying levels of abstraction. One of the first steps in developing a System Dynamics model is the establishment of the model boundary and the level of abstraction that will provide the highest level of utility. If one were to model the entire complex system and include all the detail of the real world interactions, the utility of the model would be low because it would be just as hard to understand as the real life system. Conversely, if the System Dynamics model boundary is excessively narrow and the level of detail does not include the dynamics in question, the analysis will be equally limited. The scope and detail of the model should support the desired analysis but not introduce unneeded complexity. For example, the model in Figure 6 would be useful to study the system effect of various birth or death rates but would not have the scope or detail required to study the effect of human population on the ecosystem or the effect of the ecosystem on human population. To evaluate these interactions, the model would have to be expanded to include the carrying capacity of the environment and the degradation of the environment caused by human population.

3.4 Literature Review Summary

All of the methods reviewed have their place in a well-rounded analysis of complex systems. Reliability engineering and reductionist techniques provide valuable tools for the analysis and optimization of mechanical components and subprocesses. These techniques are being used by the Coast Guard to systematically refine maintenance requirements, stocking levels and internal resource allocation. Taking a more holistic view of the challenge, systems theory, control theory and cognitive science incorporate the interactions between system elements and acknowledge the limitations of humans as part of a complex system. This higher level of investigation accounts for the realistic limitations and coupling of resources at the system level to provide a more inclusive representation of how the socio-technical system operates. System dynamics provides a language and structure to represent and simulate the Coast Guard's real world system in order to test the system's reaction over time to variations in system parameters and policy changes.

The readiness level of the Coast Guard fleet is a dynamic function driven by policies and decisions made by managers in both the operational chain of command and the logistics chain of command. These policies and decisions are made by good, well intentioned people at various levels of the organization, but they are made based on segmented information and heuristics. Due to the interconnected nature of these operations and maintenance decisions, a causal modeling approach is suitable for capturing the dynamics and emergent behaviors of the overall system. I use such a method here to display and simulate the Coast Guard operations and maintenance cycles.

Chapter 4: Use of System Dynamics

4.1 Modeling Process

In this section, I present a model of the Coast Guard's current 87 foot Patrol Boat operational scheduling and maintenance process. I utilized the stock and flow diagramming method commonly used in the System Dynamics field and described in Section 3.3 to represent the Coast Guard's operations and maintenance decisions as a set of variables and directional connections that form feedback loops that generate the dynamics of the system (Repenning and Sterman 2002). This model allowed me to vary the policy parameters used by decision makers in the operational scheduling and maintenance process and measure the system impact caused by those changes.

There are two main subprocesses in the operations and maintenance system. The first subprocess is the scheduling and execution of operations as well as the completion of organizational maintenance (maintenance completed by the cutter crew). It is a localized process that is carried out at seven district offices around the country. The second subprocess is the stocking of parts, depot-level maintenance (maintenance not completed by the crew) execution and casualty support. It is centrally managed by the SFLC in Baltimore. Each of these subprocesses are sufficiently complex on their own and display some non-intuitive interactions between system elements. These subprocesses will first be modeled individually for clarity. The two sub models will then be combined into a system model that represents the complete Coast Guard operations and maintenance system. The system model will be used to evaluate the characteristics of the system and evaluate policy and resource alternatives.

4.2 District Sub Model

Three of the factors that influence the operational availability of Coast Guard cutters are the number of days they are scheduled for operations, the number of days they are scheduled for maintenance, and the number of casualties they have. These three factors can be studied by looking at the decisions and actions that take place at the districts.

The Coast Guard has sixty-nine 87 foot patrol boats home ported around the country and divides the fleet into seven geographic "districts" centered on major cities like Boston, Miami, and Honolulu. The primary mission of the fleet is to provide near shore law enforcement, search and rescue, and port security capability in the form of underway patrols and in port quick response status. Each district is given an approved number of potential operating hours to conduct locally generated missions throughout the fiscal year. At the end of each year, all unused, potential operating hours are lost and a new allotment of potential operating hours are issued to the districts.

The district sub model is constrained by the fact that there are a limited number of days in a year and any increase in maintenance days, operational days or casualty days causes decreases in the other categories. The first section of the sub model shows the operations scheduling process in which the districts plan the underway time and in port maintenance time for their cutters. This process is driven by the importance of the operational missions and each district's desire to provide the highest level of service possible with the assets that are assigned to them. The process starts with the district comparing its accumulated operating hours for the year to a calculated target to assess whether their operational hour burn rate is too high (it will run out of potential hours before the end of the year), too low (it will not be able to use all of their potential hours by the end of the year), or on target (they will utilize all of their hours as the year ends). The results of this comparison influence how many days each cutter is scheduled to be "fully mission capable" each month (either underway or in a standby status ready to get underway). Since the majority of required cutter maintenance cannot be done when the cutter is underway or in a quick response, standby status, the allocation of fully mission capable days automatically dictates the number of days that each cutter is scheduled for maintenance. The number of days that each cutter spends conducting underway operations each month adds to the district's patrol rate, which increases the accumulated district operational hours. This cycle is repeated constantly throughout the year as districts try to optimize their patrol hours using the cutters that are assigned to them. This sequence of decisions tends to balance the system over time. If a district is below its desired operational hour target, there is pressure to schedule more operations, which raises the patrol rate and brings the operating hours closer to the target. If a district is above the target, it conserves its hours by scheduling fewer operations. The district scheduling loop pictured in Figure 7 is a balancing feedback loop that promotes goal seeking system behavior. In this case, the feedback loop balances maintenance days and fully mission capable days while trying to reach the annual operational hour goal.

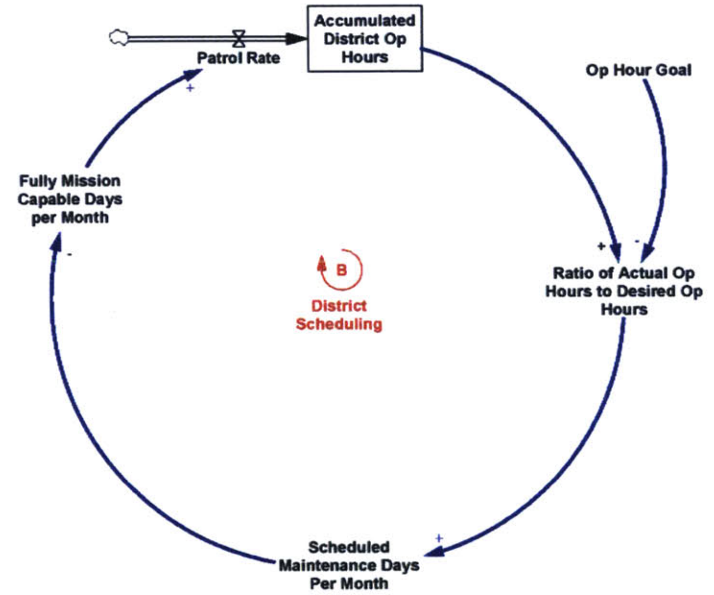


Figure 7: Partial Causal Diagram of District Scheduling Process

The second section of the district sub model shows the maintenance process and the effect that casualties have on the operational readiness of the cutters. The number of maintenance days scheduled by the district directly influences the amount of maintenance completed. If the amount of maintenance completed is less than the amount of maintenance required, a backlog of defects accumulate which, after a delay, increase the frequency of engineering casualties on the cutters. This sequence of decisions and feedback signals tends to reinforce itself over time. For example, a one time reduction in maintenance days would cause a larger backlog of defects, increasing the casualty rate and therefore lowering the district's accumulated operation hours. This reduction in accumulated operating hours would send a signal to decision makers to increase fully mission capable time to close the operating hour gap, further reducing maintenance days. This reinforcing system behavior is a powerful force that has been documented in related organizational systems (Sterman 2000). The maintenance loop shown in Figure 8 is a reinforcing feedback loop. This type of feedback loop tends to reinforce change with even more change, which can lead to rapid growth at an ever increasing rate (Kirkwood 1998). As described in Section 3.3, the behavior of a system that contains both balancing and reinforcing loops can change based on shifts in dominance between the two loops (Kirkwood 1998).

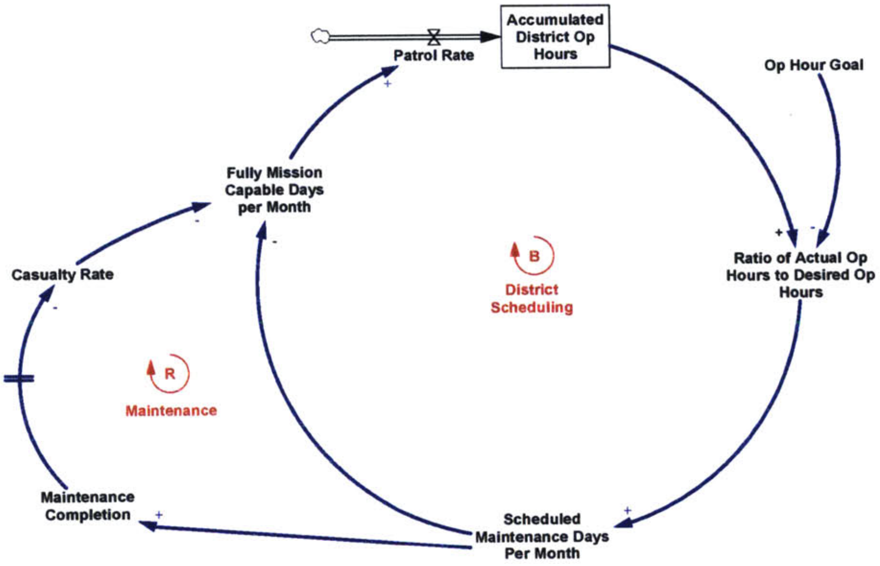


Figure 8: Partial Causal Diagram of District Scheduling and Maintenance Process

4.2.1 District Sub Model Testing

Although the proposed model represents familiar Coast Guard processes and the modeling mechanics have been successfully documented in other industries, no full examination of the relationship between cutter maintenance decisions and operational outcomes has been published (Oliva and Sterman 2001). To test and build confidence in the model as a whole, it is necessary to assess whether the relationships are consistent across a wide range of service settings and if their interactions are capable of replicating the observed behaviors of known service settings (Van Horn 1971).

In 2010, the Coast Guard centralized all engineering and logistics support for the cutter fleet under the Surface Forces Logistics Center (SFLC) in Baltimore, MD. In October of 2012, the SFLC implemented a new asset management tool which automatically captured the operational time, maintenance time, and downtime due to casualties for each of the sixty-nine 87 foot patrol boats stationed around the country. Combining the fleetwide financial data from the SFLC and the time series data for the operations and maintenance of 87 foot patrol boat fleet over the past two and a half years creates a dataset which can be used to test the model across a wide range of system scenarios.

First, the operations scheduling loop of the model was isolated and tested against the actual operational data logged by the 87 foot Patrol Boat fleet over the past two years. In this test, the casualty loop is not active so the model reflects a world where casualties do not happen. In this scenario, with no penalty for not doing maintenance, each district's scheduled maintenance days per month quickly fell to zero which increased their patrol rate and allowed each district to satisfy its annual operational hour goal before the end of the year. For example, District 1 has seven 87 foot patrol boats with an annual operational hour limit of 2,000 hours per cutter, giving them an annual district limit of 14,000 operational hours. Without the casualty loop activated, the model shows that District 1 would complete 100% of its allotted operational hours around the tenth month of each year. The operational hours are reset at the beginning of each year, and the cycle repeats.

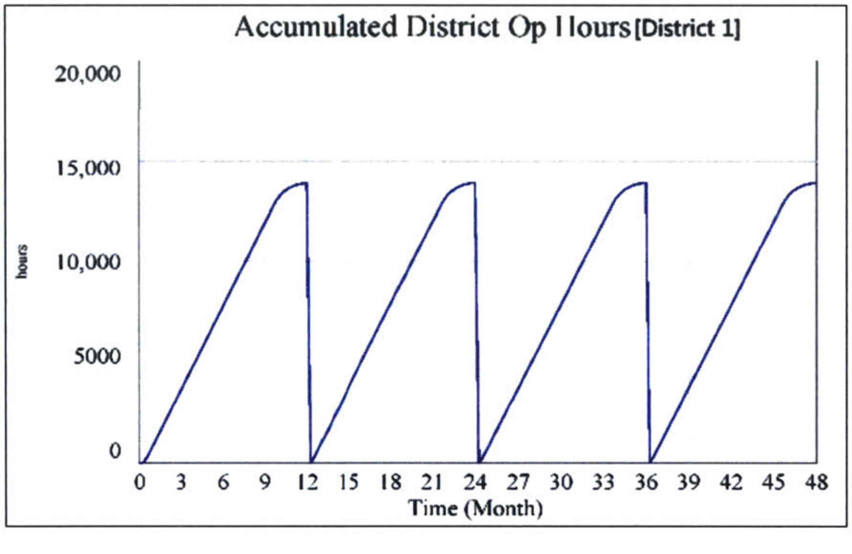


Figure 9: Sample Accumulated District 1 Operational Hours (without casualties)

The actual average maintenance days that each district provided its cutters over the past two years was calculated from the operational data logged by the cutters in ALMIS. Setting the lower limit on minimum maintenance days per cutter, per month, to the actual average maintenance days that each district afforded its cutters over the past two years, provided a test of the accuracy of the model in a realistic range. Since the model reported the number of operational hours that each district would have achieved if casualties did not occur, the model results were compared to the average number of operating hours the districts reported over the last two years, plus the average casualty hours that impacted operations. The model output for each district is within +1% to -2% of the actual values with an aggregated accuracy across the entire fleet of over 99.5%.

Table 2: Comparison of District Sub Model Casualties to ALMIS Data

	Model Op Hours Per Year Without Casualties	Actual Op Hours Per Year Without Casualties*	Difference
District 1	13200	13002	1%
District 5	12940	12920	0%
District 7	20700	21178	-2%
District 8	26730	26897	-1%
District 11	23980	23679	1%
District 13	10970	11109	-1%
District 14	3615	3704	-2%
		Overall Fleet Accuracy	99.68%

* Actual Op Hours per year without casualties was calculated by adding the actual hours lost to casualties to the actual annual Op Hours.

To test the accuracy of the sub model, I set the district policy on minimum maintenance days to the actual number of days that each district provided their cutters over the past two years. With the actual number of maintenance days as an input, the model provided outputs for the number of accumulated operating hours that each district would achieve under those conditions. Since the model conditions are the same as the actual conditions at each district over the past two years, comparing the model results to the actual operational hours recorded by the 87 foot patrol boat fleet over the past two years, provided a good test of accuracy. Table 2 shows that the model results were within 1.6% of the actual fleet operating hours over the past two years

Table 3: Comparison of District Sub Model Operational Hours to ALMIS Data

	Model Op Hours Per Year	Actual Op Hours Per Year	Difference
District 1	11270	11330	99.5%
District 5	11170	11780	94.8%
District 7	17660	18330	96.3%
District 8	23910	22460	106.5%
District 11	21120	21390	98.7%
District 13	9249	9814	94.2%
District 14	3014	3044	99.0%
		Overall Fleet Accuracy	98.4%

4.2.2 District Sub Model Analysis

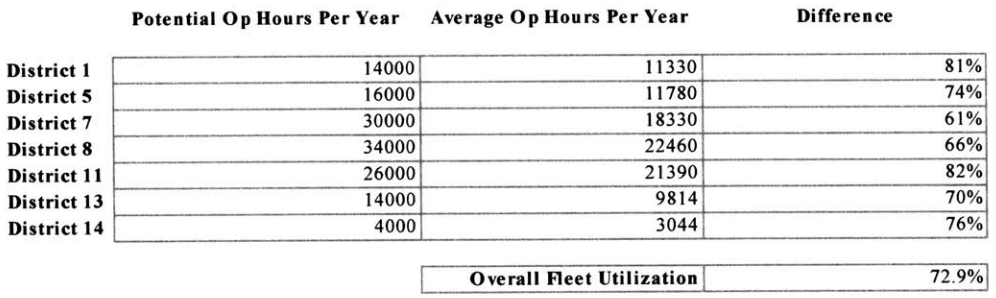
The simulation results fit the actual data quite well, increasing my confidence in the utility of the proposed model to accurately respond to changes in system parameters. The first analysis that I performed with the model was the measurement of the effect that local cutter scheduling has on the 87 foot patrol boat fleet's ability to meet operational hour goals over time.

In the complex system of cutter scheduling and maintenance, some elements are visible to select groups of people, and some are almost invisible. The patrol rate, number of operational hours, maintenance days and fully mission capable days are observed and carefully managed by each district around the country. The number of fully mission capable days and the aggregated casualty rate for the fleet is centrally monitored by the SFLC in Baltimore. The defects that accumulated inside the mechanical systems were not visible to either the district or the Logistics Center until, after a delay, they manifested themselves as an increase in casualties. Decisions that were made during the scheduling and maintenance process were made with the information that each subset of the organization had access to at the time.

Those local decisions were generally made based on heuristics, rules of thumb or standard operating procedures, which were developed to translate the available data into decision criteria.

ALMIS data for the 87 foot patrol boat in Table 4 shows that each of the seven districts only utilized between 61% and 82% of their potential operating hours each year.

Table 4: Comparison of Potential and Actual Operational Hours



	Potential Op Hours Per Year	Average Op Hours Per Year	Difference
District 1	14000	11330	81%
District 5	16000	11780	74%
District 7	30000	18330	61%
District 8	34000	22460	66%
District 11	26000	21390	82%
District 13	14000	9814	70%
District 14	4000	3044	76%
		Overall Fleet Utilization	72.9%

The dynamics of the Coast Guard's fleet operations and maintenance process create a dangerous short term and long term system response. When a district feels pressure to meet an annual operational hour goal, the only policy lever they have available to them is the decision of how many maintenance days to schedule per month. A decision to reduce the number of maintenance days per month provided a short term increase in the amount of operational hours that the district could achieve. This increase in operating hours is easily observable through the metrics that the district already tracks. The decision to decrease the number of maintenance days per month can have a long term, negative effect that is much greater than the short term, positive effect. In contrast to the highly visible nature of the short term effect, the equipment degradation that leads to the long term, negative effect is not observable by any of the metrics currently used by the Coast Guard. In addition, the delay time between a decision to reduce maintenance and the manifestation of the negative effect, in the form of increased cutter casualty days per month, could cause decision makers to lose sight of the causal relationship.

To illustrate the time delay between action and observation of a negative effect, I compared the simulation for a scenario where all districts completed 100% of mandated maintenance, to a scenario where all districts completed 100% of mandated maintenance except for the period from six months to 12 months, where they completed 60% of the mandated maintenance. The results in Figure 10 show that there was approximately a one and one half year delay between the end of the period of reduced maintenance and the point where negative effects would be seen in fleet operational hour metrics.

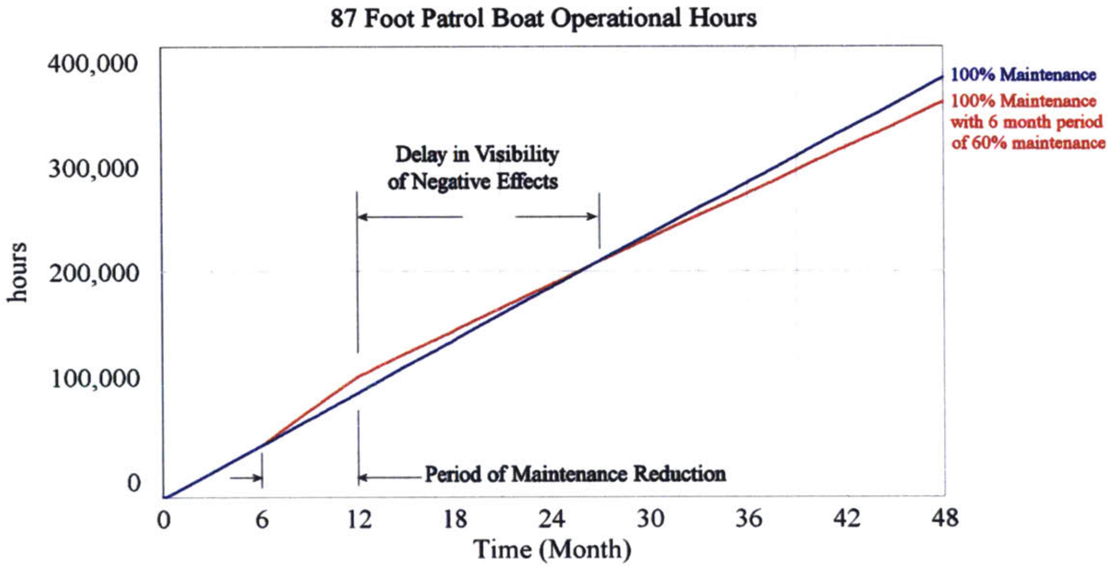


Figure 10: Delay in Visibility of Negative Effects Due to Reduced Maintenance

4.3 Surface Forces Logistics Center Sub Model Structure

Additional factors that influence the availability rate of Coast Guard cutters include completion of depot level maintenance, availability of parts for maintenance and availability of parts for casualty repairs. These variables are centrally managed by the Surface Forces Logistics Center (SFLC) in Baltimore.

4.3.1 SFLC Budget

While the district sub model was primarily constrained by the limited number of days available, the SFLC sub model is constrained by the limited number of maintenance dollars available. The SLFC receives an annual allotment of funding that must fund the completion of depot level maintenance, purchase of maintenance parts, purchase of casualty repair parts and the execution of casualty repairs. Similar to the dynamics observed in the district sub model, an increase in any one category of spending causes decreases in the amount available in the other categories (Figure 11).

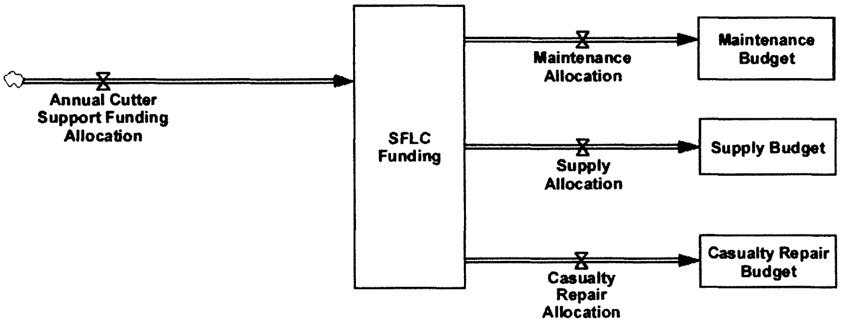


Figure 11: SFLC Budget Allocation Diagram

Analysis of SFLC financial data for fiscal years 2013 and 2014 indicate that, at the beginning of the fiscal year, an average of 51% of available 87 foot patrol boat funding is allocated to fund depot level maintenance, 40% is allocated to fund supply inventory purchases, and 9% is allocated to fund casualty repairs (Table 5).

Table 5: SFLC 87 foot Patrol Boat Budget Allocation

	Average Annual Budget	Percentage
Depot Level Maintenance Budget	$14,187,457	51%
Supply Budget	$11,086,533	40%
Casualty Repair Budget	$2,545,979	9%

Total	$27,819,969

Based on interviews with SFLC staff, reallocations of funding are possible during the fiscal year if one of the three budgets runs out of funding. Due to the high visibility and operational urgency of casualty repairs and the long planning process that goes into awarding depot level maintenance contracts, the supply budget is often used to supplement the other two budgets.

4.3.2 SFLC Depot Level Maintenance

One of the primary responsibilities of the SFLC is the completion of depot level maintenance for the cutter fleet. This process is driven by the need to complete major maintenance including engine overhauls, hull plate renewal, propeller replacement, and the overhaul of major mechanical systems based on an approved schedule defined as the Coast Guard's Depot Level Maintenance Requirements. These maintenance requirements were established to maintain the safety and reliability of Coast Guard cutters. The vast majority of depot level maintenance requirements are time based and recur every one to four years. These requirements can be readily forecasted, and, due to the regulations surrounding formal government contracting, require up to six months of planning prior to completion. A simplified view of the depot level maintenance process (without links to other processes, which are addressed in Section 4.5) is provided in Figure 12 below.

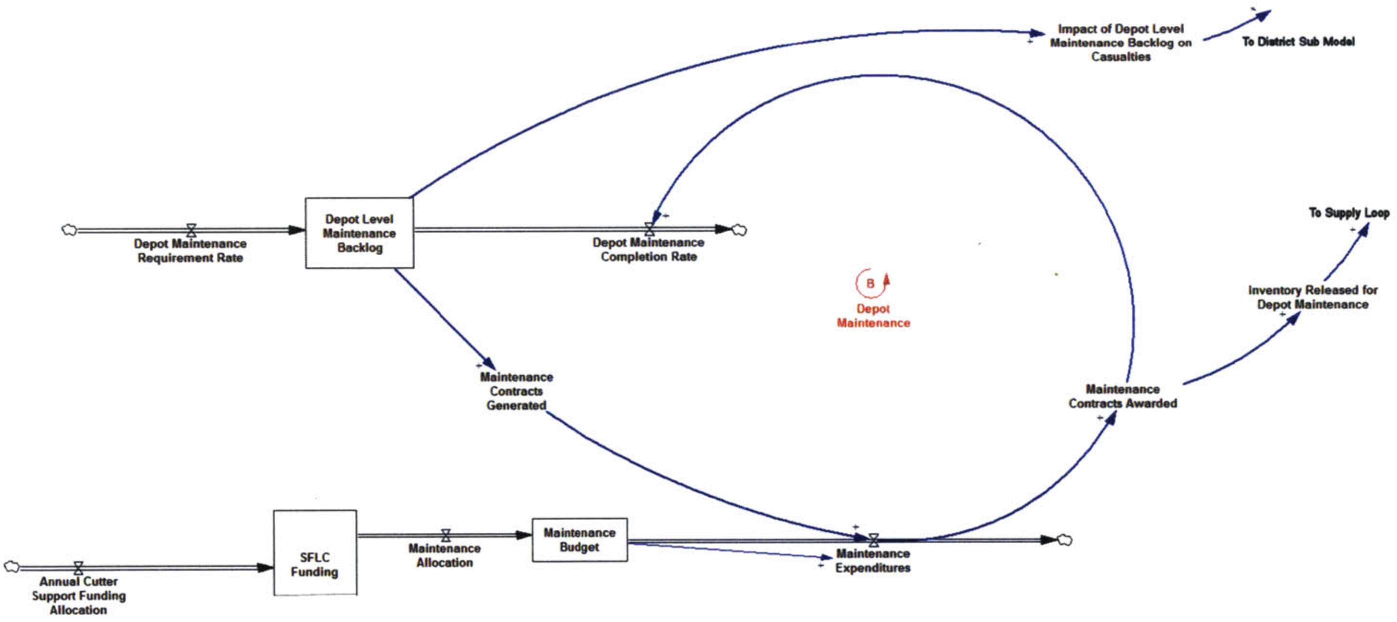


Figure 12: SFLC Depot Maintenance Feedback Loop

In this process, depot maintenance requirements drive the creation of maintenance contracts which require funding from the maintenance budget prior to award. Once the contracts are awarded, the maintenance is completed, and the stock of depot maintenance backlog is reduced. If maintenance contracts are not awarded, the depot maintenance backlog increases.

In addition to expending funds from the maintenance budget, the award and completion of depot level maintenance influences the casualty rate of the cutters and requires the release of supply inventory in the form of government furnished equipment (GFE). The influence of the depot level maintenance backlog on the casualty rate is accounted for in Section 4.5. The influence of depot level maintenance on the supply budget is accounted for in section 4.3.4.

4.3.3 SFLC Casualty Repair

Another central function that SFLC provides to the cutter fleet is the repair of engineering casualties. When a cutter breaks, SFLC is responsible for funding and coordinating the repair. The frequency and magnitude of casualties across a fleet of cutters is difficult to predict. Therefore, historical estimates are used as a basis for the casualty repair budget and reallocations are made throughout the year to adjust the budget.

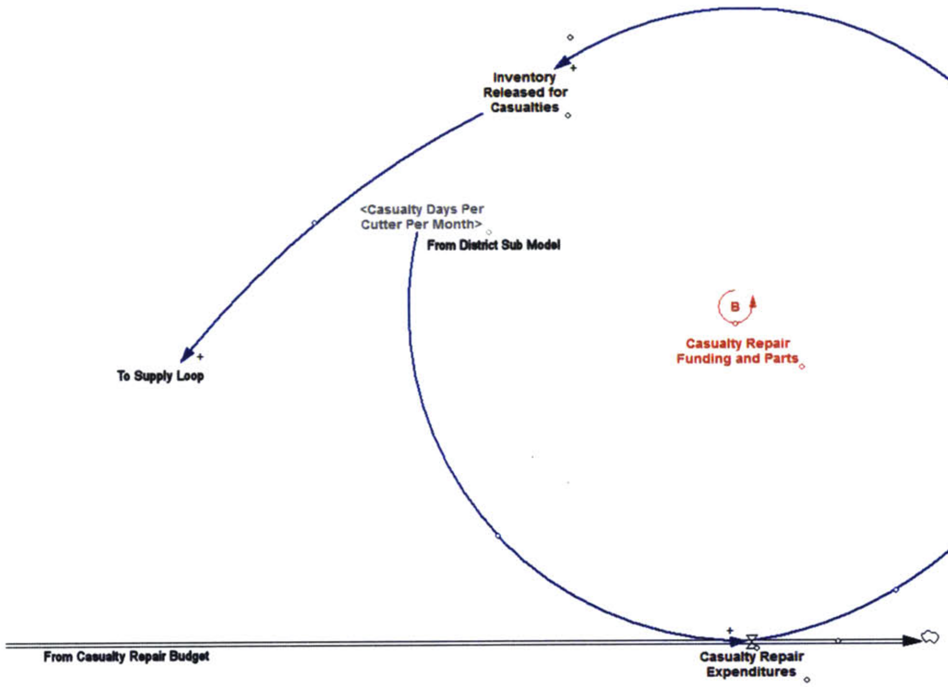


Figure 13: SFLC Casualty Repair Feedback Loop

The number of casualties that occur directly influences the rate of casualty repair expenditures through the establishment of repair contracts for technical services or commercial repair actions. The number of casualties per month also influences how many inventory parts are released for casualties, addressed in Section 4.3.4 below.

4.3.4 SFLC Supply Inventory

The SFLC supply budget is intended to maintain the inventory of parts required to support the completion of depot level maintenance, organizational level maintenance, and casualty repairs. A desired inventory level is established given how much government furnished equipment will be needed for depot level maintenance, how many parts the fleet will require to complete organizational level maintenance, and a historical data-based estimate of how many casualty repair parts will be required. Purchase decisions are made by comparing the current inventory level to the desired inventory level. The purchase rate is limited by a maximum number of procurements that the contracting staff can process in a one month period, and purchases can only occur when there is funding available in the supply budget.

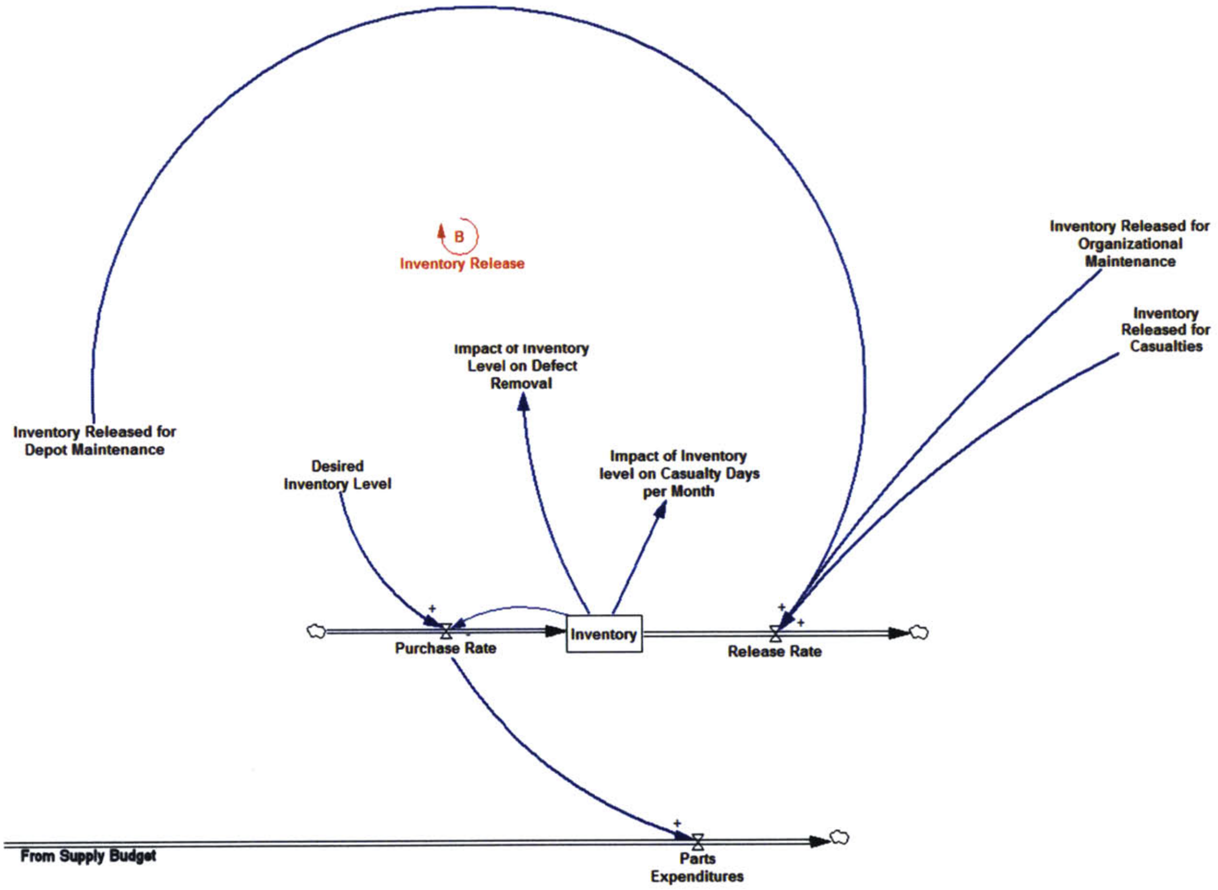


Figure 14: SFLC Inventory Release Feedback Loop

4.4 SFLC Sub Model Analysis

Combining the depot level maintenance, casualty repair, and supply inventory processes displayed in sections 4.3.2 through 4.3.4 into one model provides an accurate representation of the SFLC support system. The support functions that SFLC provides are constrained by the fact that all the functions must be executed using the same funding source, and, by the fact that depot maintenance, organizational maintenance, and casualties all draw from the same inventory of available parts.

Simulating the SFLC sub model using SFLC historical funding levels and fleet average casualty and organizational maintenance rates provides results that are consistent with the expectations expressed during SFLC interviews (Langelier 2015). The depot level maintenance backlog grows each year and the supply inventory fluctuates between \$9.6M and \$11.5M, never reaching the desired inventory level of \$12.4M (Lyons 2015).

4.5 Structure of Integrated System Model

In Sections 4.2.1 and 4.4, pieces of the Coast Guard cutter operations and maintenance system were analyzed using the data and business rules that are in place within the respective organizations. The boundary of each of these subsystems was purposefully chosen to mirror the boundaries of information availability that each of the responsible organizations currently base their policy decisions on. Therefore, the two disconnected sub models presented above closely approximate the current state of the Coast Guard cutter operations and maintenance activities. The Coast Guard districts around the country have an in depth knowledge of the number of maintenance days and operational days each of its cutters is scheduled for and are keenly aware of the number of casualty days experienced by their cutters. However, many districts do not know the maintenance backlog status of their cutters or the inventory level of maintenance and repair parts. The Surface Forces Logistics Center closely monitors inventory and maintenance backlog levels of the fleet but does not know the operational schedule of the individual cutters and does not currently have a formalized method to monitor the organizational level maintenance completion of cutters. Each organization tries to balance their subsystem, but the interactions between the two subsystems are not incorporated into policy decisions.

Analysis of the entire operations and maintenance system requires that interactions between the SFLC decisions and district decisions are acknowledged and accounted for. Examples of these interactions include:

1. SFLC policy decisions that impact the depot level maintenance backlog influence the casualty days per cutter per month in the district sub model (lack of depot maintenance will lead to increased casualties).
2. The number of scheduled organizational maintenance days per month in the district sub model directly influences the inventory released for organizational maintenance in the SFLC sub model. (an increase in maintenance days will cause an increase in parts demand).
3. District policy decisions that impact the number of casualty days per cutter per month in the district sub model dictate the number of casualties per month in the SFLC sub model.
4. The inventory level in the SFLC sub model influences defect removal through maintenance in the district sub model (maintenance cannot be completed if parts are not available).
5. The inventory level in the SFLC sub model influences the casualty days per cutter per month in the district sub model. (casualty repair time is reduced if casualty repair parts are in stock).

The inclusion of these interactions expose additional reinforcing loops that influence the way the system reacts to inputs and changes. For example, when the interactions 4 and 5 above are integrated with the district scheduling and maintenance loops presented in Figure 8, two additional reinforcing loops are created. In Figure 15, the loop labeled "Slower Repairs" shows that an increase in the casualty rate will decrease the SFLC part inventory. A decrease in the SFLC parts inventory will, in turn, increase the casualty rate (because cutters will take longer to repair without in stock parts). Similarly, the "Reduced Maintenance" loop shows that the same decrease in the SFLC parts inventory reduced the district's ability to complete maintenance which will cause increases in the casualty rate.

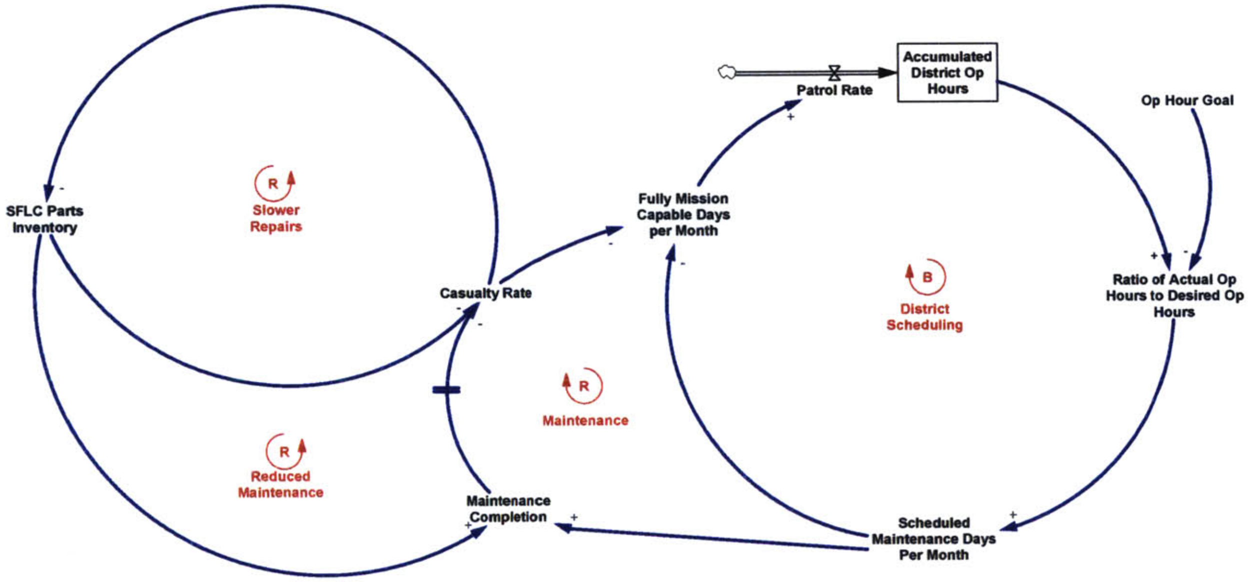


Figure 15: Example of Additional Feedback Loops Caused by Sub Model Interactions

The full system model consists of the combination of the two sub models constructed and tested in Sections 4.2 and 4.3 along with the interactions identified in Section 4.5. This model of the entire operations and maintenance system that can be used to assess the impact of policy decisions across the entire system. The model will be used to evaluate several potential policy changes and the system output will be measured to determine the efficiency or effectiveness of the policy change.

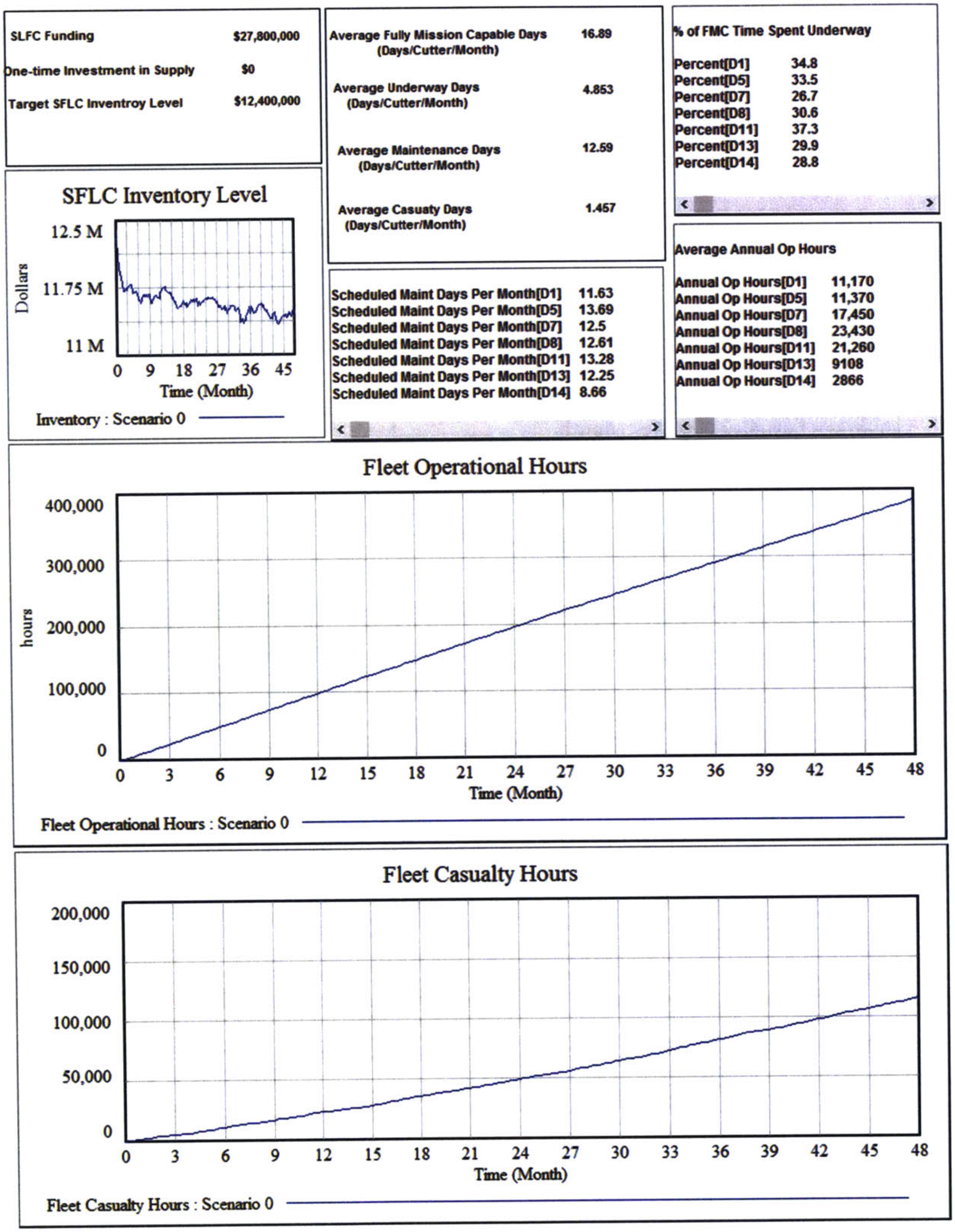
4.6 Analysis of Coast Guard Operations and Maintenance System

The Coast Guard cutter operations and maintenance system exists to conduct maritime Coast Guard missions. All of the existing policies were established with a focus toward providing the highest level of operational availability and reliability possible by optimizing available resources. To analyze the system, resources levels and existing policies will be changed in the system dynamics model to observe the impact that these changes have on other system parameters. The analyzed scenarios will then be evaluated for their benefit in terms of operational availability and reliability compared to their cost.

4.6.1 Scenario 0: Baseline Case

A baseline case will be used as a reference to compare various policy scenarios. The baseline case represents current district and SFLC policies and key input parameters such as SFLC funding level, funding allocation percentages, district scheduled maintenance days per month, and the percentage of fully mission capable time cutters spend underway. In the baseline case, these values are set to match the historical averages documented in the Coast Guard logistics management and information system. For example, the SFLC support funding level is $27.8M (the average level for the past two years) and the SFLC target inventory level is $12.4M (the current target stocking level). Operational parameters such as the average scheduled maintenance days per month and the percent of fully mission capable time spent underway reflect the current average values in the Coast Guard ALMIS database. A summary of model inputs and outputs is provided in Figure 16.

Scenario 0: Baseline Case



SLFC Funding	$27,800,000
One-time Investment in Supply	$0
Target SFLC Inventroy Level	$12,400,000

Average Fully Mission Capable Days (Days/Cutter/Month)	16.89
Average Underway Days (Days/Cutter/Month)	4.853
Average Maintenance Days (Days/Cutter/Month)	12.59
Average Casuaty Days (Days/Cutter/Month)	1.457

% of FMC Time Spent Underway

Percent[D1]	34.8
Percent[D5]	33.5
Percent[D7]	26.7
Percent[D8]	30.6
Percent[D11]	37.3
Percent[D13]	29.9
Percent[D14]	28.8

Scheduled Maint Days Per Month[D1]	11.63
Scheduled Maint Days Per Month[D5]	13.69
Scheduled Maint Days Per Month[D7]	12.5
Scheduled Maint Days Per Month[D8]	12.61
Scheduled Maint Days Per Month[D11]	13.28
Scheduled Maint Days Per Month[D13]	12.25
Scheduled Maint Days Per Month[D14]	8.66

Average Annual Op Hours

Annual Op Hours[D1]	11,170
Annual Op Hours[D5]	11,370
Annual Op Hours[D7]	17,450
Annual Op Hours[D8]	23,430
Annual Op Hours[D11]	21,260
Annual Op Hours[D13]	9108
Annual Op Hours[D14]	2866

Figure 16: System Model Simulation Results: Scenario 0

The baseline case reflects a simulation of the current funding levels and policies of the Coast Guard operations and maintenance system over a four year time horizon. The results of the baseline case compared to a current snapshot of fleet parameters are provided in Table 6.

Table 6: Comparison of Model Results to Actual Data

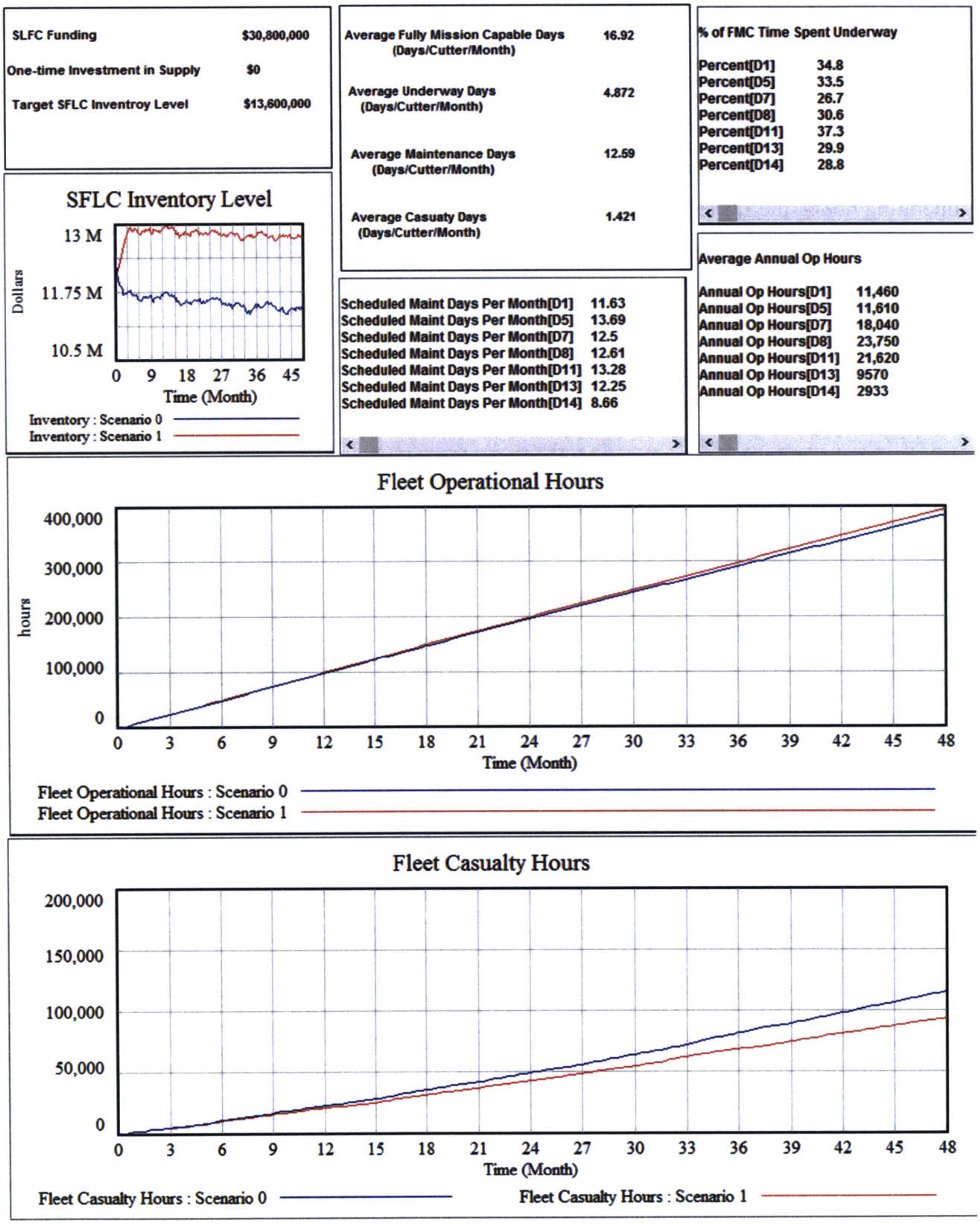
	Baseline Case Model Results	Actual Data from ALMIS, NESSS, and FLS*
SFLC Funding Level	$27,800,000	$27,819,969
Average Maintenance Days Per Month	12.59	12.57
Average Fully Mission Capable Days Per Month	16.89	15.64
Average Underway Days Per Month	4.853	4.94
Average Casualty Days Per Month	1.457	2.15

4.6.2 Scenario 1: Increased Support Funding

For years, Coast Guard engineers have proffered that the best way to increase the availability and reliability of cutters is to increase the funding provided to the maintenance and repair organization. Increased funding would allow a reduction in the maintenance backlog, increase the stocking level of parts and increase the funding available for casualty repairs, all of which help to increase maintenance completion and decrease the casualty rate which leads to increased operational availability and reliability. The argument that increased support funding would benefit the cutters is easy to make, but the magnitude of the funding required and what the return on that investment would be in the form of increased operations has been difficult to quantify.

In Scenario 1, the funding provided to SFLC to support the 87 foot patrol boat fleet is increased by $3M per year (a 10.8% increase over current levels), and all other policies and resource levels are kept the same as the baseline case.

Scenario 1: Increased Support Funding



SLFC Funding	$30,800,000
One-time Investment in Supply	$0
Target SFLC Inventroy Level	$13,600,000

Average Fully Mission Capable Days (Days/Cutter/Month)	16.92
Average Underway Days (Days/Cutter/Month)	4.872
Average Maintenance Days (Days/Cutter/Month)	12.59
Average Casuaty Days (Days/Cutter/Month)	1.421

% of FMC Time Spent Underway

Percent[D1]	34.8
Percent[D5]	33.5
Percent[D7]	26.7
Percent[D8]	30.6
Percent[D11]	37.3
Percent[D13]	29.9
Percent[D14]	28.8

Scheduled Maint Days Per Month[D1]	11.63
Scheduled Maint Days Per Month[D5]	13.69
Scheduled Maint Days Per Month[D7]	12.5
Scheduled Maint Days Per Month[D8]	12.61
Scheduled Maint Days Per Month[D11]	13.28
Scheduled Maint Days Per Month[D13]	12.25
Scheduled Maint Days Per Month[D14]	8.66

Average Annual Op Hours

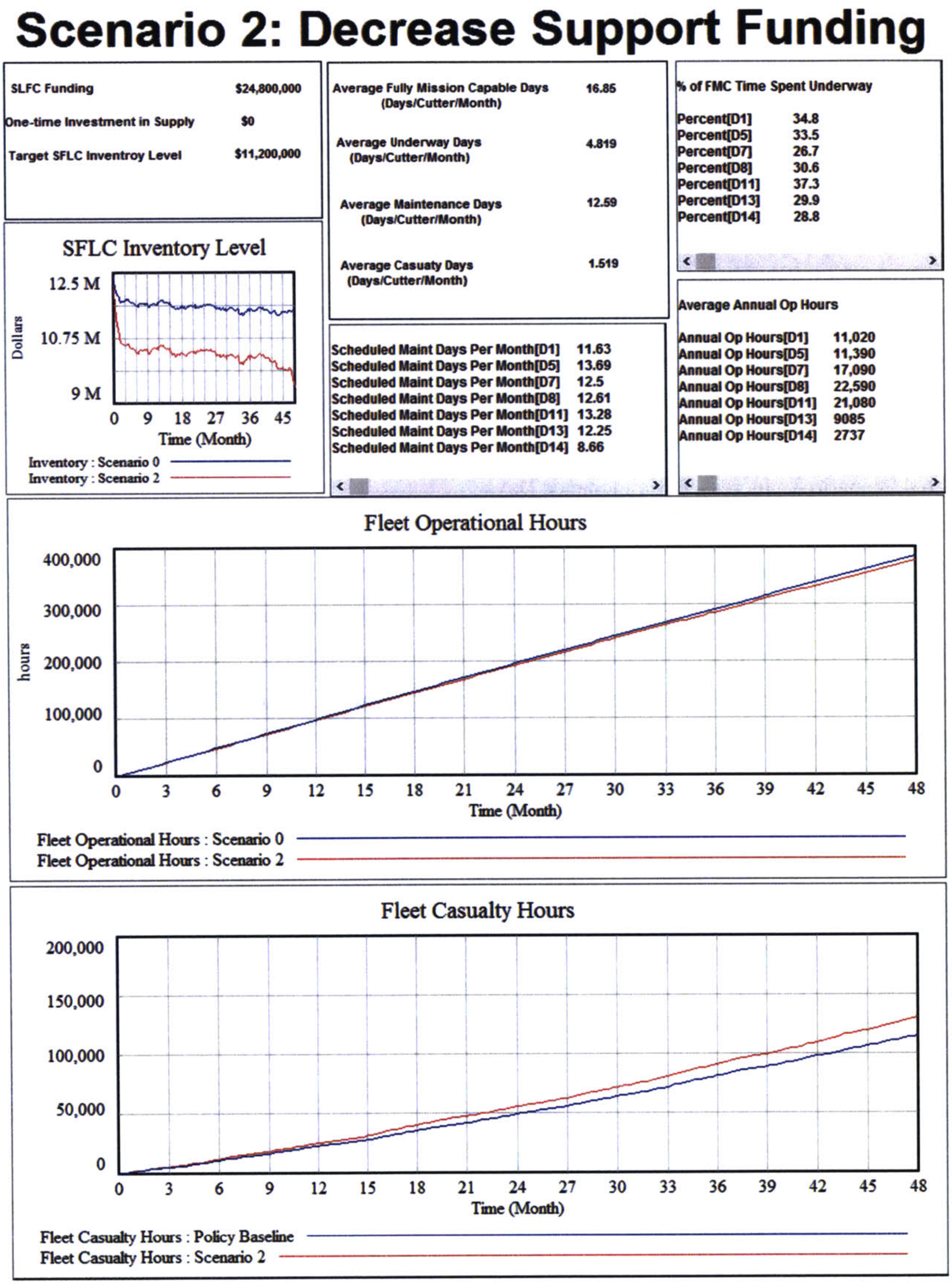
Annual Op Hours[D1]	11,460
Annual Op Hours[D5]	11,610
Annual Op Hours[D7]	18,040
Annual Op Hours[D8]	23,750
Annual Op Hours[D11]	21,620
Annual Op Hours[D13]	9570
Annual Op Hours[D14]	2933

Figure 17: System Model Simulation Results: Scenario 1

Adding $3M to the 87 foot annual support budget increases the fleet's average fully mission capable time by .18 days per month (equal to each cutter in the fleet being FMC for an additional 4.3 hours each month). Average underway days increase by .15 days per month (equal to 3.5 hours of additional underway time). Average casualty days drop by .28 days per cutter per month (equal to 6.6 less casualty hour per cutter per month). Over a period of four years, the addition of $3M to the 87 foot annual support budget would allow the fleet to provide 11,000 more operating hours, the fleet would experience 21,000 fewer casualty hours, and SLFC parts inventory would end the four year period with an inventory value $1.3M higher than at the end of the baseline case.

4.6.3 Scenario 2: Decreased Support Funding

Observing that a $3M increase in support funding produces a substantial increase in fully mission capable hours and underway hours along with a significant decrease in casualty hours begs the question: what would happen if funding were reduced by the same amount? Scenario 2 reduces the annual SFLC funding level for 87 foot patrol boat support from $27.8M to $24.8M which would reduce the allocation of funding for depot maintenance, supply inventory and casualty support. The reduction of supply inventory funding would also reduce the SFLC target 87 foot patrol boat inventory level from $12.4M to $11.2M. All other policies and resources remain the same as the baseline case.



Scenario 2: Decrease Support Funding

SLFC Funding	$24,800,000
One-time Investment in Supply	$0
Target SFLC Inventroy Level	$11,200,000

Average Fully Mission Capable Days (Days/Cutter/Month)	16.85
Average Underway Days (Days/Cutter/Month)	4.819
Average Maintenance Days (Days/Cutter/Month)	12.59
Average Casuaty Days (Days/Cutter/Month)	1.519

% of FMC Time Spent Underway

Percent[D1]	34.8
Percent[D5]	33.5
Percent[D7]	26.7
Percent[D8]	30.6
Percent[D11]	37.3
Percent[D13]	29.9
Percent[D14]	28.8

Scheduled Maint Days Per Month[D1]	11.63
Scheduled Maint Days Per Month[D5]	13.69
Scheduled Maint Days Per Month[D7]	12.5
Scheduled Maint Days Per Month[D8]	12.61
Scheduled Maint Days Per Month[D11]	13.28
Scheduled Maint Days Per Month[D13]	12.25
Scheduled Maint Days Per Month[D14]	8.66

Average Annual Op Hours

Annual Op Hours[D1]	11,020
Annual Op Hours[D5]	11,390
Annual Op Hours[D7]	17,090
Annual Op Hours[D8]	22,590
Annual Op Hours[D11]	21,080
Annual Op Hours[D13]	9085
Annual Op Hours[D14]	2737

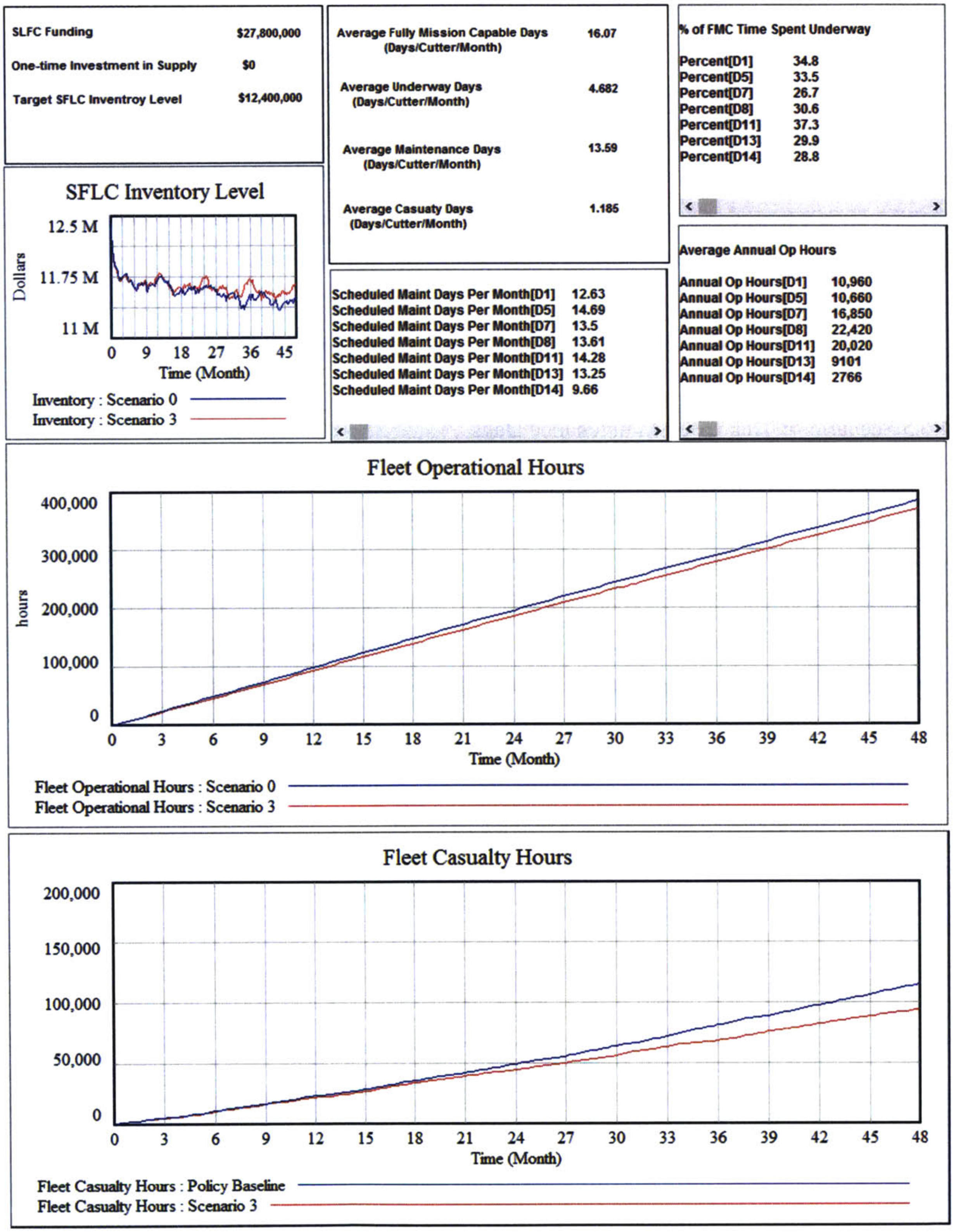
Figure 18: System Model Simulation Results: Scenario 2

The results of Scenario 2 show that a reduction in support funding has a significant negative effect on the operational availability of the 87 foot patrol boat fleet. A $3M reduction in funding results in a reduction in average fully mission capable days of .12 days per cutter per month (equal to each cutter in the fleet being fully mission capable 2.9 hour less each month). Additionally, average underway days decrease by .1 days per month (equal to 2.4 less underway hour per cutter per month). Average casualty days rise by .19 days per cutter per month (equal to about 4.5 more casualty hours per cutter per month). Over a period of four years, the removal of $3M to the 87 foot annual support budget would cause the fleet to produce 7,800 fewer operating hours; the fleet would experience 14,500 more casualty hours, and SLFC parts inventory would end the four year period with an inventory value $2M lower than at the end of the baseline case.

4.6.4 Scenario 3: Increased Maintenance Days

Another intuitive suggestion to increase operational availability and reliability of cutters might be to increase the time that they are available for maintenance. It would stand to reason that increasing the scheduled maintenance days per month would reduce the casualty rate of the cutters, therefore increasing the operational availability. However, due to the constraints on the system, increasing maintenance days directly decreases the number of fully mission capable days. Using simple linear reasoning, it is difficult to determine which one of these effects will have a larger influence on the system outcome. Scenario 3 increases the fleet average maintenance days from 12.59 days per month per cutter to 13.59 days per month per cutter (accomplished by adding one additional maintenance day to each of the district's scheduled maintenance day averages) while keeping all other policies and resources consistent with the baseline case.

Scenario 3: Increased Maintenance Days



SLFC Funding	$27,800,000
One-time Investment in Supply	$0
Target SFLC Inventroy Level	$12,400,000

Average Fully Mission Capable Days (Days/Cutter/Month)	16.07
Average Underway Days (Days/Cutter/Month)	4.682
Average Maintenance Days (Days/Cutter/Month)	13.59
Average Casuaty Days (Days/Cutter/Month)	1.185

% of FMC Time Spent Underway

Percent[D1]	34.8
Percent[D5]	33.5
Percent[D7]	26.7
Percent[D8]	30.6
Percent[D11]	37.3
Percent[D13]	29.9
Percent[D14]	28.8

Scheduled Maint Days Per Month[D1]	12.63
Scheduled Maint Days Per Month[D5]	14.69
Scheduled Maint Days Per Month[D7]	13.5
Scheduled Maint Days Per Month[D8]	13.61
Scheduled Maint Days Per Month[D11]	14.28
Scheduled Maint Days Per Month[D13]	13.25
Scheduled Maint Days Per Month[D14]	9.66

Average Annual Op Hours

Annual Op Hours[D1]	10,960
Annual Op Hours[D5]	10,660
Annual Op Hours[D7]	16,850
Annual Op Hours[D8]	22,420
Annual Op Hours[D11]	20,020
Annual Op Hours[D13]	9101
Annual Op Hours[D14]	2766

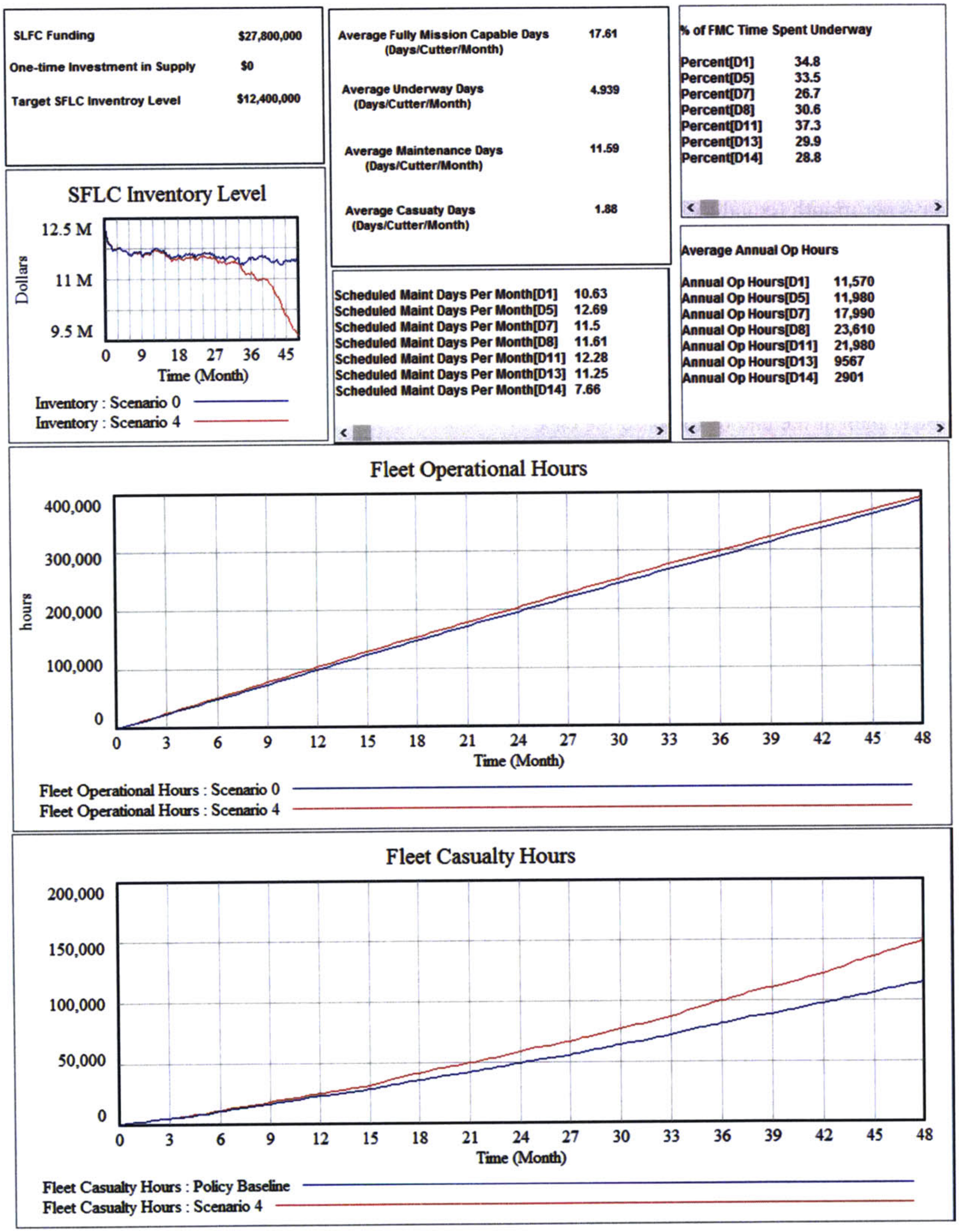
Figure 19: System Model Simulation Results: Scenario 3

Increasing the number of maintenance days that are provided to the 87 foot patrol boat fleet by one day per month , while making no other changes, actually decreases the fleet's average fully mission capable time by .82 days per month (equal to each cutter in the fleet being fully mission capable for 20 fewer hours each month). Average underway days decreased by .1 days per month (equal to 2.4 fewer hours underway time per cutter per month). Average casualty days drop a substantial .27 days per cutter per month (equal to 6.5 fewer casualty hours per cutter per month). Over a period of four years, adding one more maintenance day per month to the 87 foot maintenance schedule would reduce fleet operating hours by 13,500 hours; the fleet would experience 21,440 fewer casualty hours, and SLFC parts inventory would end the four year period with an inventory value $170K higher than at the end of the baseline case.

4.6.5 Scenario 4: Decreased Maintenance Days

Since the input parameters in Scenario 3 provided a positive response in the form of decreased casualty hours but a negative response in the form of decreased operational hours, it would be informative to document the system response to a decrease in maintenance days. Scenario 4 decreases the fleet average maintenance days from 12.59 days per month per cutter to 11.59 days per month per cutter (accomplished by subtracting one maintenance day from each of the district's scheduled maintenance day averages) while keeping all other policies and resources consistent with the baseline case.

Scenario 4: Decreased Maintenance Days



SLFC Funding	$27,800,000
One-time Investment in Supply	$0
Target SFLC Inventroy Level	$12,400,000

Average Fully Mission Capable Days (Days/Cutter/Month)	17.61
Average Underway Days (Days/Cutter/Month)	4.939
Average Maintenance Days (Days/Cutter/Month)	11.59
Average Casuaty Days (Days/Cutter/Month)	1.88

% of FMC Time Spent Underway

Percent[D1]	34.8
Percent[D5]	33.5
Percent[D7]	26.7
Percent[D8]	30.6
Percent[D11]	37.3
Percent[D13]	29.9
Percent[D14]	28.8

Scheduled Maint Days Per Month[D1]	10.63
Scheduled Maint Days Per Month[D5]	12.69
Scheduled Maint Days Per Month[D7]	11.5
Scheduled Maint Days Per Month[D8]	11.61
Scheduled Maint Days Per Month[D11]	12.28
Scheduled Maint Days Per Month[D13]	11.25
Scheduled Maint Days Per Month[D14]	7.66

Average Annual Op Hours

Annual Op Hours[D1]	11,570
Annual Op Hours[D5]	11,980
Annual Op Hours[D7]	17,990
Annual Op Hours[D8]	23,610
Annual Op Hours[D11]	21,980
Annual Op Hours[D13]	9567
Annual Op Hours[D14]	2901

Figure 20: System Model Simulation Results: Scenario 4

The results of Scenario 4 show that a reduction in scheduled maintenance days by one day per month increases fleet operating hours over a four year period while significantly increasing fleet casualty hours and decreasing the SFLC inventory level. A one day reduction in scheduled maintenance days per month from 12.59 days per cutter per month to 11.59 days per cutter per month increases the average fully mission capable days by .72 days per month (equal to each cutter in the fleet being FMC 17 hour more each month). Average underway days increase by .09 days per month (equal to 2 more underway hours per cutter per month). Average casualty days rise by .42 days per cutter per month (equal to about 10 more casualty hours per cutter per month). Over a period of four years, a decrease of one maintenance day per month would cause the fleet to produce 6,600 more operating hours; the fleet would experience 33,700 more casualty hours, and SLFC parts inventory would end the four year period with an inventory value $1.9M lower than at the end of the baseline case.

Extending the timeline of system model an additional eight months shows that Scenario 4 would not be sustainable over a long time period. By month 52 fleet casualty hours rise exponentially as the SFLC inventory level falls exponentially. This causes a halt in fleet operations which brings total fleet operating hours below those of the baseline case.

4.6.6 Scenario 5: Modification of Standby Cutter Policy

One of the benefits of the development of a system model is that the process of building the model often illuminates relationships or policies that may not receive a large amount of organizational attention but have significant leverage over the response of the system. One factor that appears to have a strong influence over the number of operational hours achieved by the 87 foot fleet is the percentage of fully mission capable time spent underway. Some of the time that a cutter is in fully mission capable status is spent at the pier in a standby cutter status and some of the time is spent underway on patrol.

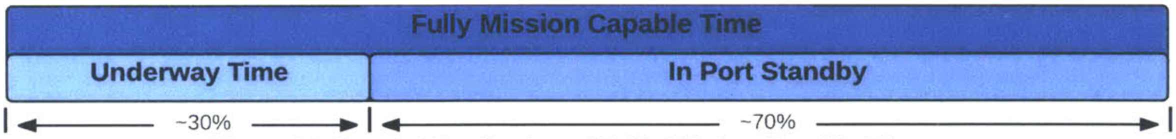


Figure 21: Sample Distribution of Fully Mission Capable Time

According to the operational data recorded by the 87 foot patrol boat fleet over the past two years (Table 7), the percentage of fully mission capable time that a cutter spends underway varies by district from a low of 26.7% to a high of 34.8%.

Table 7: Percent of Fully Mission Capable Time Spent Underway

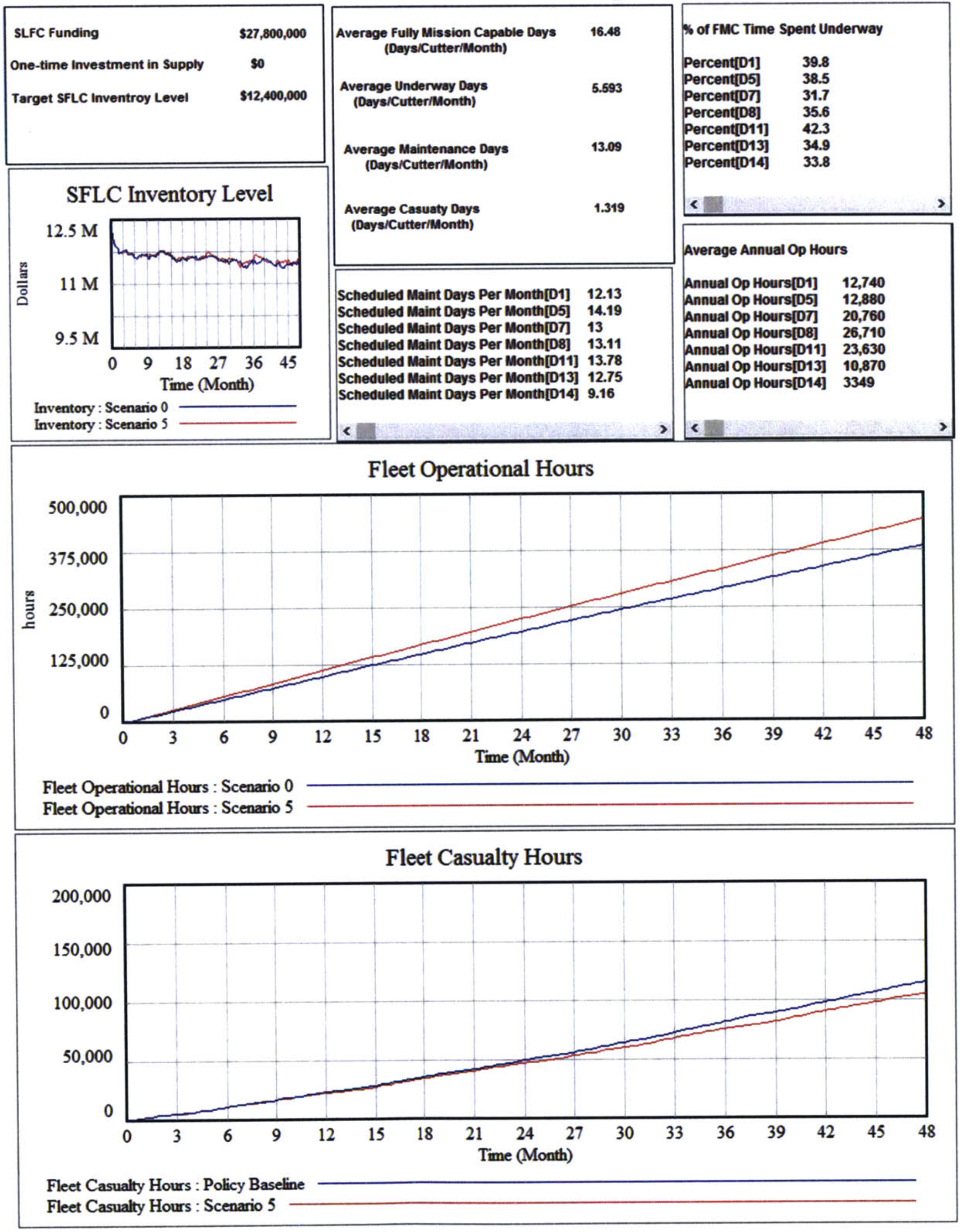
	Fiscal Year	Total Operating Hours	Average Operating Hours	Average Operating Hours per Cutter	Average Fully Mission Capable Hours	Percent of Fully Mission Capable Time Spent Underway
District 1	2013	10603	11326	1618	4646	34.8%
	2014	12049				
District 5	2013	12512	11781	1473	4398	33.5%
	2014	11050				
District 7	2013	20022	20768	1385	4572	26.7%
	2014	21514				
District 8	2013	21804	22461	1321	4311	30.6%
	2014	23119				
District 11	2013	21560	21379	1645	4414	37.3%
	2014	21198				
District 13	2013	12904	12617	1802	4686	29.9%
	2014	12331				
District 14	2013	3386	3044	1522	5284	28.8%
	2014	2702				

Based on input from district patrol boat schedulers, this standby time is intended to provide a ready response cutter of search and rescue, surge capacity for district operations and as redundancy in case an operational cutter suffers a casualty (Langelier 2015). Scheduling a cutter to enter standby status also forces the cutter to stop doing major maintenance and repairs and transition to a fully mission capable status. Geographical differences, frequency of search and rescue case load, and the location of cutters in each district will necessitate different standby policies in each district. This thesis does not evaluate the operational needs that drive the standby status requirements of individual districts. This thesis does, however, strive to identify high leverage policy opportunities to increase operational availability.

Based on the system structure, small changes in the amount of time that cutters spend in fully mission capable status but not underway could have a large effect on the fleet's ability to reach operating hour targets. Because the scheduling of fully mission capable days is inversely related to the scheduling of maintenance days, which in turn influences the number of casualty days, scheduling fewer fully mission capable days while increasing the percentage of fully mission capable time that a cutter spends underway could have the effect of increasing both operating hours and reliability.

Scenario 5 adds one half of one day to the average 87 foot patrol boat scheduled maintenance days per month and increases the percentage of each districts fully mission capable time spent underway by 5% while keeping all other policies and resources consistent with the baseline case. The parameters in this scenario effectively test what would happen if, through a policy change, 0.5 days per month of standby time could be converted to maintenance time.

Scenario 5: Modification of Standby Cutter Policy



SLFC Funding	$27,800,000
One-time Investment in Supply	$0
Target SFLC Inventroy Level	$12,400,000

Average Fully Mission Capable Days (Days/Cutter/Month)	16.48
Average Underway Days (Days/Cutter/Month)	5.593
Average Maintenance Days (Days/Cutter/Month)	13.09
Average Casuaty Days (Days/Cutter/Month)	1.319

% of FMC Time Spent Underway

Percent[D1]	39.8
Percent[D5]	38.5
Percent[D7]	31.7
Percent[D8]	35.6
Percent[D11]	42.3
Percent[D13]	34.9
Percent[D14]	33.8

Scheduled Maint Days Per Month[D1]	12.13
Scheduled Maint Days Per Month[D5]	14.19
Scheduled Maint Days Per Month[D7]	13
Scheduled Maint Days Per Month[D8]	13.11
Scheduled Maint Days Per Month[D11]	13.78
Scheduled Maint Days Per Month[D13]	12.75
Scheduled Maint Days Per Month[D14]	9.16

Average Annual Op Hours

Annual Op Hours[D1]	12,740
Annual Op Hours[D5]	12,880
Annual Op Hours[D7]	20,760
Annual Op Hours[D8]	26,710
Annual Op Hours[D11]	23,630
Annual Op Hours[D13]	10,870
Annual Op Hours[D14]	3349

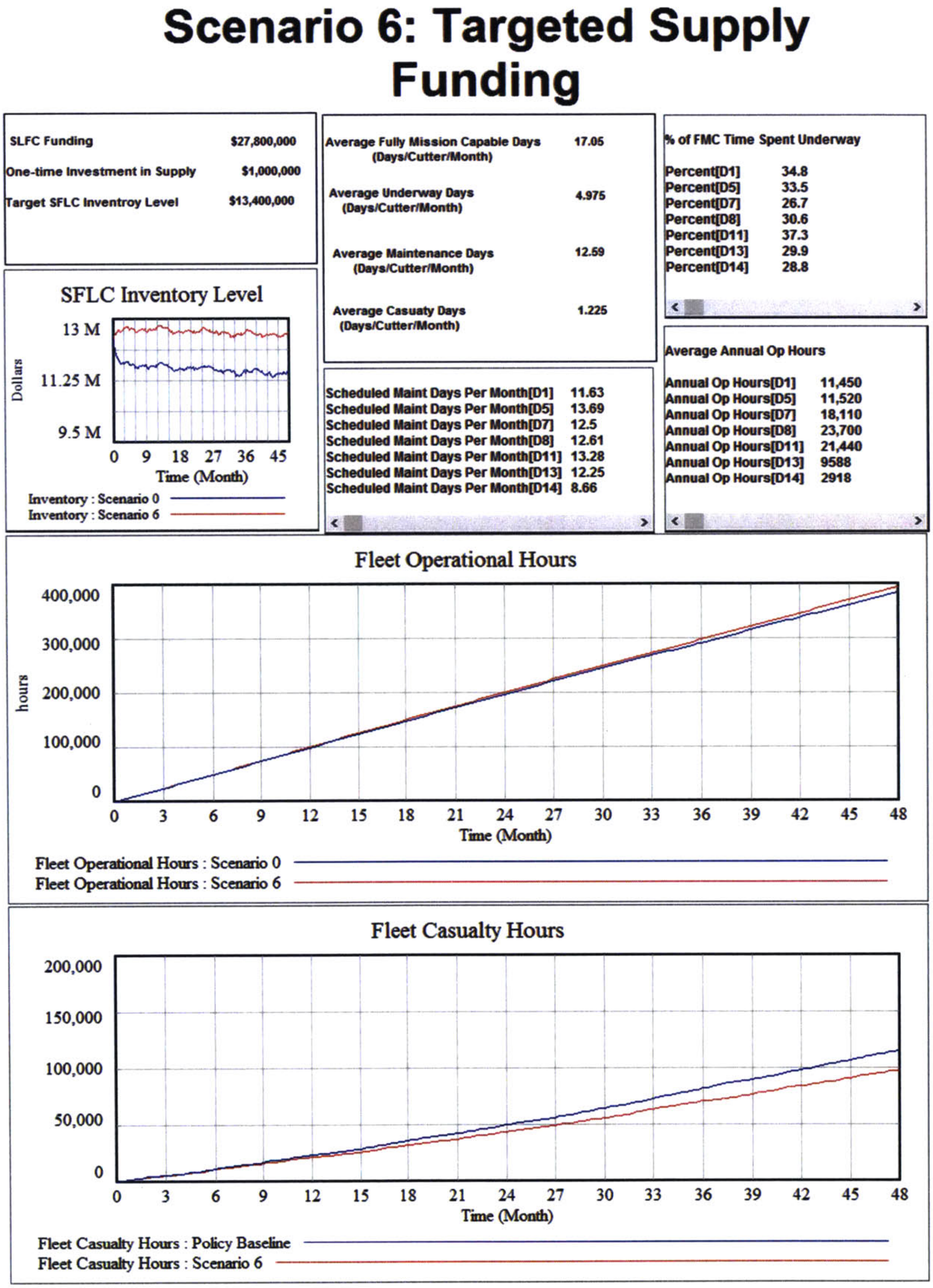
Figure 22: System Model Simulation Results: Scenario 5

Converting one half of a day per month from standby time to scheduled maintenance time has the positive effect of simultaneously increasing fleet operational hours, decreasing fleet casualty hours, and increasing the SFLC inventory level. If the system consisted solely of the simple "District Scheduling" loop presented in figure 2, the 5% increase fully mission capable time spent underway and the .5 day increase in maintenance days would tend to cancel each other out, but the presence of feedback loops that influence the fleet casualty rate and SFLC inventory level, drive positive results in all three system parameters. Increasing the percentage of fully mission capable time spent underway by 5% and increasing the number of maintenance days per month by .5 days decreases the fleet's average fully mission capable time by .41 days per month (equal to each cutter in the fleet being FMC for 10 hours less each month). Average underway days increased by .74 days per month (equal to 18 more underway hours per cutter per month). Average casualty days drop by .14 days per cutter per month (equal to 3 fewer casualty hours per cutter per month). Over a period of four years, converting one half of a day per month from standby time to scheduled maintenance time would increase fleet operating hours by 58,500 hours; the fleet would experience 10,900 fewer casualty hours, and SLFC parts inventory would end the four year period with an inventory value $150K higher than the end of the baseline case.

4.6.7 Scenario 6: Modification of SFLC Funding Policy

The availability of parts influences almost all of the processes that make up the Coast Guard cutter operations and maintenance system. Depot maintenance completion is dependent on the availability of government furnished equipment from the SFLC inventory. Casualty repair time is increased or decreased based on the availability of in stock repair parts. A sufficient inventory of planned maintenance parts are required to enable organizational level maintenance completion.

The fact that the SFLC parts inventory is part of multiple system feedback loops that drive the overall system goal of fleet operational hours indicates that small changes in the SLFC inventory level policy could have a large impact of the system outcome. Scenario 6 adds a one time allocation of $1M and changes the SFLC target inventory level policy to include the purchase of additional 87 foot patrol boat maintenance and repair parts. All other policies and resources remain consistent with the baseline case.



Scenario 6: Targeted Supply Funding

SLFC Funding	$27,800,000
One-time Investment in Supply	$1,000,000
Target SFLC Inventroy Level	$13,400,000

Average Fully Mission Capable Days (Days/Cutter/Month)	17.05
Average Underway Days (Days/Cutter/Month)	4.975
Average Maintenance Days (Days/Cutter/Month)	12.59
Average Casuaty Days (Days/Cutter/Month)	1.225

% of FMC Time Spent Underway	
Percent[D1]	34.8
Percent[D5]	33.5
Percent[D7]	26.7
Percent[D8]	30.6
Percent[D11]	37.3
Percent[D13]	29.9
Percent[D14]	28.8

Scheduled Maint Days Per Month[D1]	11.63
Scheduled Maint Days Per Month[D5]	13.69
Scheduled Maint Days Per Month[D7]	12.5
Scheduled Maint Days Per Month[D8]	12.61
Scheduled Maint Days Per Month[D11]	13.28
Scheduled Maint Days Per Month[D13]	12.25
Scheduled Maint Days Per Month[D14]	8.66

Average Annual Op Hours	
Annual Op Hours[D1]	11,450
Annual Op Hours[D5]	11,520
Annual Op Hours[D7]	18,110
Annual Op Hours[D8]	23,700
Annual Op Hours[D11]	21,440
Annual Op Hours[D13]	9588
Annual Op Hours[D14]	2918

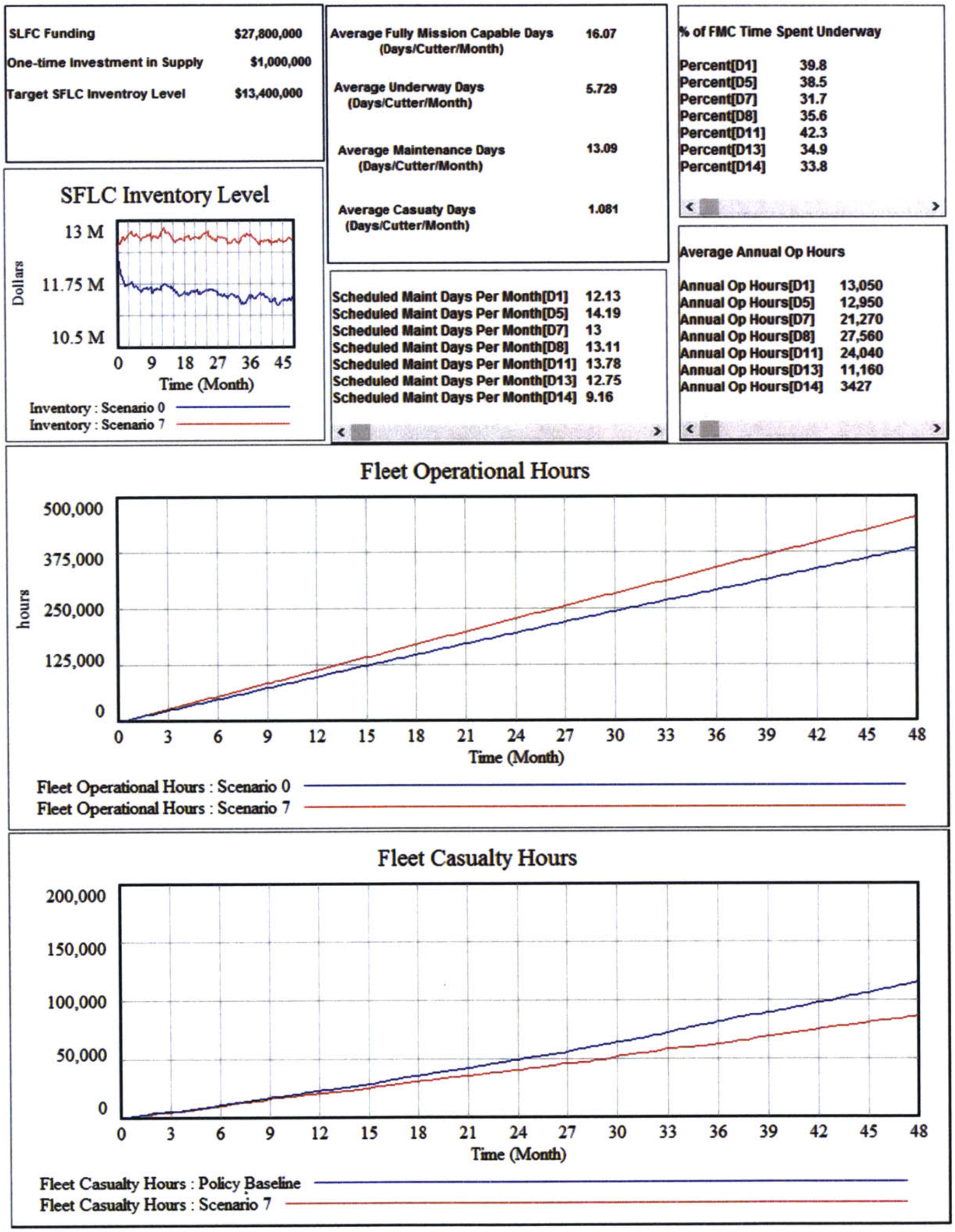
Figure 23: System Model Simulation Results: Scenario 6

A targeted increase of $1M in maintenance and repair parts increases the fleet's average fully mission capable time by .16 days per month (equal to each cutter in the fleet being FMC for 3.8 hours more each month). Average underway days increased by .12 days per month (equal to 2.9 more underway hours per cutter per month). Average casualty days drop by .23 days per cutter per month (equal to 5.6 fewer casualty hours per cutter per month). Over a period of four years, the onetime infusion of $1M would increase fleet operating hours by 9,900 hours; the fleet would experience 18,300 fewer casualty hours, and SLFC parts inventory would end the four year period with an inventory value $1.2M higher than at the end of the baseline case.

4.6.8 Scenario 7: Modification of Standby Cutter and SFLC Funding Policy

Scenario 7 is a combination of Scenario 5 and Scenario 6. The complex and nonlinear nature of the operations and maintenance system means that the results of the two scenarios cannot be simply added together to predict the outcome of the combined case, and a separate simulation needs to be run to account for any positive of negative interactions between the system parameters.

Scenario 7: Targeted Investment in Supply and Modification of Standby Policy



SLFC Funding	$27,800,000
One-time Investment in Supply	$1,000,000
Target SFLC Inventroy Level	$13,400,000

Average Fully Mission Capable Days (Days/Cutter/Month)	16.07
Average Underway Days (Days/Cutter/Month)	5.729
Average Maintenance Days (Days/Cutter/Month)	13.09
Average Casuaty Days (Days/Cutter/Month)	1.081

% of FMC Time Spent Underway

Percent[D1]	39.8
Percent[D5]	38.5
Percent[D7]	31.7
Percent[D8]	35.6
Percent[D11]	42.3
Percent[D13]	34.9
Percent[D14]	33.8

Scheduled Maint Days Per Month[D1]	12.13
Scheduled Maint Days Per Month[D5]	14.19
Scheduled Maint Days Per Month[D7]	13
Scheduled Maint Days Per Month[D8]	13.11
Scheduled Maint Days Per Month[D11]	13.78
Scheduled Maint Days Per Month[D13]	12.75
Scheduled Maint Days Per Month[D14]	9.16

Average Annual Op Hours

Annual Op Hours[D1]	13,050
Annual Op Hours[D5]	12,950
Annual Op Hours[D7]	21,270
Annual Op Hours[D8]	27,560
Annual Op Hours[D11]	24,040
Annual Op Hours[D13]	11,160
Annual Op Hours[D14]	3427

Figure 24: System Model Simulation Results: Scenario 7

The combined effect of converting one half of a day per month from standby time to scheduled maintenance time (Scenario 5) and a one time allocation of $1M and a change to the SFLC target inventory level policy for the purchase of 87 foot patrol boat maintenance and repair parts (scenario 6) decreases the fleet's average fully mission capable time by .22 days per month (equal to each cutter in the fleet being fully mission capable for 5.3 fewer hours each month). Average underway days increased by .88 days per month (equal to 21 more underway hours per cutter per month). Average casualty days drop by .38 days per cutter per month (equal to 9 fewer casualty hours per cutter per month). Over a period of four years, the modification of the stand-by cutter policy and the onetime infusion of $1M to the 87 foot patrol boat parts inventory would increase fleet operating hours by 69,100 hours; the fleet would experience 29,500 less casualty hours, and SLFC parts inventory would end the four year period with an inventory value $1.2M higher than at the end of the baseline case.

4.7 System Analysis Summary

A summary of simulation results is provided in Table 8.

Table 8: Summary of Simulation Results

	Scenario							
	0	1	2	3	4	5	6	7
	Current "Baseline" Policies	Increase Maintenance Funding	Decrease Maintenance Funding	Increase Maintenance Time	Decrease Maintenance Time	Convert 5% of Standby Time to Maintenance Time	Increase Target Inventory and One Time $1M Increase	Combination of Scenario 6 and 7
SFLC Funding Level	$27,800,000	$30,800,000	$24,800,000	$27,800,000	$27,800,000	$27,800,000	$27,800,000	$27,800,000
Non-recurring Funding							$1,000,000	$1,000,000
Target SFLC Inventory Level	$12,400,000	$13,600,000	$11,200,000	$12,400,000	$12,400,000	$12,400,000	$13,400,000	$13,400,000
Average Maintenance Days Per Month	12.59	12.59	12.59	13.59	11.59	13.09	12.59	13.09
Average Fully Mission Capable Days Per Month	16.89	17.07	16.77	16.07	17.61	16.48	17.05	16.67
Average Underway Days Per Month	4.853	5.001	4.751	4.682	4.939	5.593	4.975	5.729
Average Casualty Days Per Month	1.457	1.182	1.645	1.185	1.88	1.319	1.225	1.081
Total Fleet Operating Hours (at end of 4 years)	383,700	395,500	375,900	370,200	390,300	442,200	393,600	452,800
Total Fleet Casualty Hours (at end of 4 years)	115,500	93,640	130,000	94,060	149,200	104,600	97,160	86,000
Total SFLC Inventory (at end of 4 years)	$11,460,000	$12,770,000	$9,383,000	$11,630,000	$9,560,000	$11,610,000	$12,640,000	$12,640,000

Model Inputs are shaded

Model Outputs are not shaded

Scenario 0 represents the Coast Guard's current policies and funding levels and is used as a baseline for the relative change observed in the remaining scenarios.

Scenario 1 explores the effect of an increase in SFLC funding and shows a relative rise in average fully mission capable days and underway days along with a relative decrease in casualty days. This scenario achieves the goal of increasing fleet operational hours and decreasing casualties but would cost an additional $12M over the course of four years. This means that the additional 11, 800 operational hours accomplished under this scenario would come at a cost of $1,017 per gained operational hour.

Scenario 2 examines the effect of a decrease in SFLC funding and shows a relative decrease in average fully mission capable days and underway days along with a relative rise in casualty days. This scenario shows the magnitude of operational decline caused by a decreased support funding. Interestingly, the removal of $12M over four years decreases operations by 7,800 hours which results in a value of $1,538 per lost operational hour.

Scenario 3 analyzes the impact of the addition of one maintenance day per cutter per month and shows a relative decrease in average fully mission capable days and underway days along with a relative decrease in casualty days. This scenario returns a mixed result: the operational commander would benefit from a decrease in casualty days but the magnitude of that benefit is not large enough to overcome the accompanying reduction in fully mission capable days.

Scenario 4 looks at the fleet impact of a one day reduction in maintenance day per cutter per month and shows a relative increase in average fully mission capable days and underway days over a four year period along with a relative increase in casualty days. This scenario displays the system response caused by reinforcing feedback loops described in section 5.1.1. During the first several years of the simulation, the balancing "District Scheduling" feedback loop dominated the system behavior and provided an increase in underway days per month. During this time, the maintenance backlog grew, the SFLC inventory level decreased, and the number of casualty days per month grew. By month 48, the reinforcing behavior of the "maintenance" feedback loop dominates the system behavior when, fueled by large maintenance backlogs and a lack of parts, fleet casualty hours start to rise at an ever increasing rate and underway days per month fall at an ever increasing rate. Extending the analysis out to a total of 72 months shows the rapid rise in casualty hours (Figure 25) and subsequent decrease of fleet operating hours (Figure 26) triggered by the accumulation of maintenance backlogs.

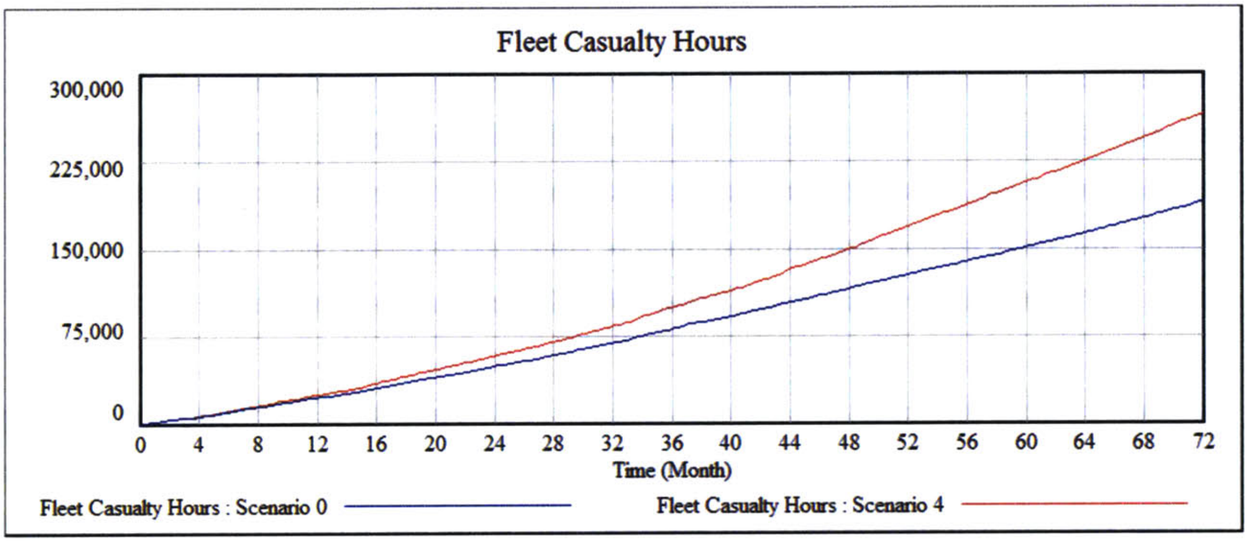


Figure 25: Scenario 4 Fleet Casualty Hours Over 72 Month Timeline

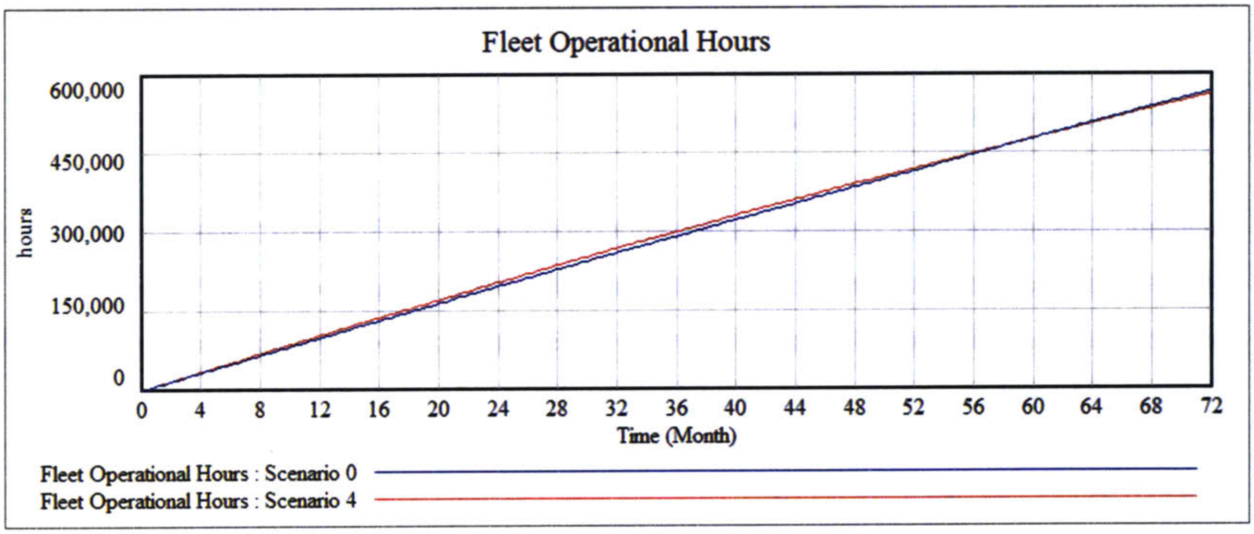


Figure 26: Scenario 4 Fleet Operational Hours Over 56 Month Timeline

If not identified and managed, this type of complex system behavior can lead organizations to adopt policies that focus on the short term system reaction without accounting for the long term ramifications of those actions.

Scenario 5 explores an operational policy change that effectively converts one half of one day per month from fully mission capable standby time to maintenance time and shows a relative decrease in average fully mission capable days, a relative increase in underway days, and a relative decrease in casualty days. The structure of the Coast Guard's operations and maintenance systems makes the system outcome very sensitive to small changes in the level of cutter standby time. The vast majority of cutter standby time is needed to provide search and rescue response and redundancy in operational coverage but if, through an operational policy change, just 5% of current standby time could be converted to maintenance time, the 87 foot patrol boat fleet could produce an additional 100,000 operating hours per year.

Scenario 6 studies the impact of a one time infusion of $1M into the SFLC supply budget along with a corresponding change to the SFLC target inventory level and shows a relative increase in average fully mission capable days and underway days along with a relative decrease in casualty days. This scenario uses the reinforcing characteristics of the "maintenance" feedback loop to create a positive and self sustaining system outcome. By changing the 87 foot target inventory level and funding the purchase of additional parts with a non recurring $1M supplement, the same reinforcing behavior that dragged the system down in Scenario 4 can be used to increase operating hours and decrease casualties.

Scenario 7 simultaneously implements the input parameters from Scenario 5 and Scenario 6 and shows a slight decline in average fully mission capable days, a large increase in average underway days, and a large decrease in casualty days. Based on the simulation results presented in Figure 24 combination of an operational policy change (Scenario 5) and a logistics policy change (Scenario 6) would provide 15% increase in underway days per month and a 25% decrease in casualty days per month.

Chapter 5: Conclusions, Recommendations and Future Research

5.1 Conclusions

A detailed study of the structure and behavior of the Coast Guard's cutter operations and maintenance system resulted in the development of a system dynamics model which was used to evaluate policy and resource scenarios. The first four scenarios were based on traditional approaches to influence the system outcome through funding or scheduling changes. These actions resulted in either negative long term effects to the operational availability of the fleet or were very costly and are not recommended for implementation. The fifth, sixth, and seventh scenarios targeted high leverage variables in the operations and maintenance system where small changes could result in significant improvements in operational availability.

5.2 Summary of Research Questions

Question 1: How does the structure of the Coast Guard cutter operations and maintenance system effect the management and reaction of the system?

The structure of the operation and maintenance system is driven by the organizational structure of Coast Guard, the authorities granted to various organizational branches, and the policies established by each office. Logistics support for the cutter fleet is centralized. Operational authority is distributed to districts around the country. This asymmetric organizational structure could lead policy makers in the respective organizations to treat operations and maintenance as two separate systems, similar to the sub models presented in sections 4.2 and 4.3. Analysis of the complete operations and maintenance systems conducted in section 4.6 showed that the complex interactions between operations, maintenance, supply inventory and casualties must be understood and leveraged to implement policies that drive positive system behavior.

Questions 2: What resource decisions and policy levers have the largest impact on operational availability of the Coast Guard fleet?

Scenario 5 and Scenario 6 demonstrate two high return resource and policy levers. Both scenarios use to amplifying effect of the system interactions to create a large change in system behavior using a small change in policy or resources. A small reduction in standby time has the benefit of increasing maintenance without decreasing operations. An increase in supply parts inventory simultaneously improves organizational maintenance completion, depot level maintenance completion, and casualty repair rate, leading to a compounded positive system impact.

Question 3: What combination of policies and resources provide a high level of fleet-wide operational availability while balancing maintenance, supply, and casualty repair costs?

After documenting the Coast Guard operations and maintenance system, constructing a model that reacts similar to the real-life system, and simulating multiple scenarios that varied the allocation of resources and the establishment of policies, I recommend the following actions.

5.3 Recommendations

1. I recommend that the Coast Guard review district standby cutter policies and conduct an analysis to determine if 5% of current patrol boat standby time could be converted to maintenance time.
2. I recommend that the Coast Guard establish a dashboard metric in the ALMIS system to allow districts to incorporate cutter standby averages statistics in scheduling decisions.
3. I recommend that SFLC increase the 87 foot parts inventory target level by $1M investigate the availability of non recurring supplemental funding for the purchase of additional parts.
4. I recommend that SFLC establish a command metric to monitor the supply inventory level (as a percentage of the required inventory level) of each product line as a leading indicator of the product line's ability to support maintenance and repair of the fleet.

5.4 Future Research

The dynamics observed in this study are not limited to the 87 foot patrol boat fleet. Future research should be completed to adapt the outcomes of this study to improvements in the 110 foot patrol boat fleet and the 154 foot patrol boat fleet. Additionally, the fields of system theory and system dynamics have widespread applicability in the complex systems that the Coast Guard manages. Future studies of operational, acquisition and engineering systems should leverage system analysis tools whenever applicable.

References

Ackoff, Russell L. 1971. "Towards a System of Systems Concepts." *Management Science* 17 (11): 661–71. doi:10.1287/mnsc.17.11.661.

Brainyquote. 2015. "Aristotle Quotes." BrainyQuote.com Xplore Inc. http://www.brainyquote.com/quotes/quotes/a/aristotle377766.html.

Butt, Mark. 2013. "CG-7 Mission:" December 12. http://www.uscg.mil/hq/cg7/.

Ciaglo, Mike. 2012. "Patrol Boat Product Line ALMIS Buisness Rules Message."

Cyert, R.M., and J.G. March. 1963. *A Behvioral Theory of the Firm*. Prentice Hall.

Descartes, René. 1993. *Discourse on the Method of Rightly Conducting One's Reason and of Seeking Truth in the Sciences*. http://www.gutenberg.org/ebooks/59.

Gavetti, Giovanni, Daniel Levinthal, and William Ocasio. 2007. "Neo-Carnegie: The Carnegie School's Past, Present, and Reconstructing for the Future." *Organization Science* Vol. 18 (No. 3): 523–36.

Haycock, Mike. 2014. "Engineering and Logistics Directorate (CG-4)." July 22. http://www.uscg.mil/hq/cg4/.

Jones, James. 2006. *Integrated Logistics Support Handbook*. McGraw–Hill Professional.

Kirkwood, Craig. 1998. *System Dynamics Methods: A Quick Introduction*. http://www.public.asu.edu/~kirkwood/sysdyn/SDIntro/preface.pdf.

Langelier, Mike. 2015. Phone Interview with LT Lagelier, USCGPhone.

Leveson, Nancy. 2011. *Engineering a Safer World: Systems Thinking Applied to Safety*. MIT Press.

Lyons, Kevin. 2015. Meeting with Mr LyonsIn Person.

Mastin, Luke. 2008. "Reductionism." http://www.philosophybasics.com/branch_reductionism.html.

MITSloan. 2015. "MIT Sloan System Dynamics Web Page." http://mitsloan.mit.edu/group/system-dynamics/.

Morecroft, John. 1983. "System Dynamics: Portraying Bounded Rationality." *Jornal of Management Science* Vol 11 (No. 2): 131–42.

Oliva, Rogelio, and John D. Sterman. 2001. "Cutting Corners and Working Overtime: Quality Erosion in the Service Industry." *Management Science* 47 (7): 894–914. doi:10.1287/mnsc.47.7.894.9807.

Repenning, N, and J.D. Sterman. 2002. "A Simulation-Based Approach to Undertsanding the Dynamics of Innovation Implimentation." *Organization Science* 13: 109–27.

SFLC. 2015. "About SFLC Overview.v1." Accessed July 20. http://www.uscg.mil/SFLC/About_SFLC_Overview.v1.pdf.

Simon, HA. 1957. "Rationality and Decision Making." *Models of Man*.

Sterman, J.D. 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. McGraw-Hill/Irwin.

Sutton, Paul C. 2015. "The Limits to Growth (book)." *Salem Press Encyclopedia of Science*.

Van Horn, Richard L. 1971. "Validation of Simulation Results." *Management Science* 17 (5): 247–58. doi:10.1287/mnsc.17.5.247.

xlibrary. 2011. "US Coast Guard Org Chart." June 7. http://www.dhs.gov/xlibrary/assets/org-chart-uscg.pdf.

Zhou, Jenny. 2012. "Learn to Read Causal Loop Diagrams." http://systemsandus.com/2012/08/15/learn-to-read-clds/.