System Dynamic Modeling as Applied to Coast Guard Cutter Home Porting Decisions:
Innovating Systems Engineering Processes in Federal Agencies to Engage Stakeholders, Stimulate Local Economies and Benefit the Public Good

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Abstract

System Dynamic Modeling as Applied to Coast Guard Cutter Home Porting Decisions: Expanding Systems Engineering Processes in Federal Decision Making Could Engage Stakeholders, Stimulate Local Economies and Benefit the Public Good

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The U.S Coast Guard uses a codified Systems Engineering process to determine the best location for new Coast Guard cutters. This process, called the Cutter Homeport Decision Process (CHDP), quantifies stakeholder input and evaluations of potential ports to make the best homeporting decision. The goal of this study is to use System Dynamic (SD) modeling, specifically using Causal Loop Diagrams and Stock and Flow Diagrams, as a tool to conduct a port-to-port comparison of Coast Guard Cutter home porting. In doing so this study strives to support the Coast Guard in making even more informed, quantifiable cutter home porting decisions. The process of SD modeling involves robust stakeholder engagement and alinement of assumptions to bring together a model that provides quantitative information of a dynamic system's behavior over time. In this case, a SD model is designed to show the difference between final Coast Guard Cutter operational days given a home port co-located with a maintenance hub versus a remotely located home port. The model is specifically applied to Fast Response Cutter, the Coast Guard's newest surface asset. The model behavior and design were verified by subject matter experts; the results were validated by SME's and also comparted to limited real world data. The study then looks at the economic benefit brought to these different home ports by Coast Guard personnel stationed there. Ultimately this study finds that there is a statistically significant difference between the operational days achieved by a cutter co-located with its maintenance hub versus one that is remote. The co-located maintenance hub has more operational days per year than the remote cutter. Also, in the case of the home ports analyzed by this study, the difference in economic impact is minimal. This study recommends co-location of the cutter with its maintenance hub to maximize operational effectiveness. This study also recommends use of SD modeling for analyzing this decision, and similar decisions, as a powerful tool for stakeholder engagement and alignment. Using SD modeling in this context can support better financial decisions, better use of resources and better support of the American public. This research strives to expand SD modeling into the federal arena and in doing so, support the public good.

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DEDICATION

To Oliver River – That you may always stand in awe of the beautiful complexity of this world.

To Brent – Thank you, with my whole heart

Chapter 1. INTRODUCTION

System Dynamic (SD) modeling is a tool used in systems engineering and systems thinking to quantitatively model complex systems and predict the behavior of those systems over time. This modeling tool is used across a wide range of disciplines, including organizational learning, public policy, academic research and designing better infrastructure. SD modeling is a powerful way to visualize the behavior of a system over time and test theories on different interventions to change a systems behavior. Effective SD modeling also involves robust stakeholder engagement and alignment of assumptions to achieve the best outcomes. This thesis applies SD modeling the Coast Guard Cutter home porting decision process.

1.1 RESEARCH MOTIVATION

The United States Coast Guard (USCG) is a dynamic organization tasked with a diverse array of missions along the coast of the United States and internationally. Those missions include: Port and Waterway Security, Drug Interdiction, Aids to Navigation, Search and Rescue, Living Marine Resources, Marine Safety, Defense Readiness, Migrant Interdiction, Marine Environmental Protection, Ice Operations and Other Law Enforcement (USCG: A Multi-Mission Force). To execute these missions effectively, the USCG has a variety of assets stationed along the coast of the United States. These assets include aircraft, ships (called Coast Guard cutters) and small boats. Each asset has specific capabilities and is tasked based on the area in which it operates and the priorities of the Operational Commander.

The USCG is constantly balancing several factors when deciding where to base assets. First, the assets have to be in locations where they can effectively execute the mission to which they are assigned. Second, the assets also have to be maintainable, so they are operationally ready to execute the mission. The current Cutter Homeport Decision Process strives to balance these two priorities. The third component is the economic boost provided to communities in which Coast Guard assets are stationed where Coast Guard personnel and their families can live and thrive. This is an important political consideration and an important consideration for ensuring Coast Guard personnel are ready and able to execute the mission. This component is generally added to the conversation after the internal CHDP is complete, and these external stakeholders have less opportunity for early engagement in the process.

Balancing these three considerations when deciding where to base USCG assets is challenging. Different stakeholders both in and outside of the USCG have strong interests and values around the three topics. Sometimes competing priorities regarding where assets should be located. Coast Guard leadership needs to make the best possible decisions to support operational readiness, ensure area coverage for missions, ensure the maintainability of assets and keep political good will for the Coast Guard in the region. In 2015, Coast Guard leadership codified the decision process for home porting Coast Guard Cutters. This document, Commandant Instruction Manual M3111.1, The Cutter Homeporting Decision Process (CHDP), is a codified instruction manual that describes, step by step, the detailed process for determining where to home-port cutters, starting with the approval of a new cutter. It lays out a comprehensive systems engineering approach to determining where cutters should be located to best serve the needs of the USCG (Cutter Homeporting Decision Process, 2015). This approach includes interviewing diverse stakeholders within the organization, assessing the physical and geographic considerations of different home porting options, looking at the logistics support and infrastructure available in different areas, and applying quantifiable metrics to different USCG priorities throughout the process. The CHDP also provides a transparent, repeatable process tool to ensure consistency.

The motivation of this study is to take the current systems engineering-based process to cutter home porting and apply SD modeling. In general, SD modeling can provide a new way to visualize the interplay between different elements in the system. Applying SD modeling to the USCG's CHDP will potentially open new learnings and insights and allow for better decision making in support of Coast Guard mission execution by providing quantifiable trade-offs between two potential home ports, and by making the stakeholder engagement process more robust. Another critical component, and benefit, of SD modeling is the robust stakeholder engagement process. Working closely with stakeholders to align assumptions and accurately code them into an SD model has the additional benefit of improved communication and understanding across the entire decision process. This study asks: "Can System Dynamic Modeling be used to analyze a port-to-port comparison of Coast Guard Cutter home porting and in doing so, support the Coast Guard in making rational, quantifiable cutter home porting decisions?"

1.2 Research Contribution

This study specifically looks at applying SD modeling as a tool for comparing two potential home port alternatives for the Coast Guard's newest surface asset, the Fast Response Cutter (FRC). The sample model used in this study looks at the Area of Responsibility (AOR) of Southeast Alaska. The model generates specific metrics around the number of operational days per year for the cutter, depending on the home port in which it is located. The model generates additional metrics including maintenance days per year and deferred (or postponed) maintenance days per year. This model can be further modified for different AOR's and different asset types.

Modeling home port decision making in Southeast Alaska is relevant, as new FRC's will be placed in Alaska over the next several years, and also serves as a proof of concept to determine if the SD modeling process adds value and insight to the CHPD.

This study also contributes to the wider body of academic knowledge by applying SD modeling and other formal systems engineering tools to internal federal decision making at an organizational level. While SD modeling is applied across a broad range of topics and disciplines, there is no published public research on using SD models for this purpose. It should be noted that SD processes are certainly used internally in the Federal Government; the New York Times famously published a systems level diagram of the U.S Department of Defense's strategy in Afghanistan (Bumiller, 2010), which was widely misunderstood in the media. However, published academic research in this area is lacking. Broadening the use of SD modeling to make better, more informed decisions which have the intended impact (and avoid unintended consequences) is important for the effectiveness of federal agencies. Using SD modeling in this context can support better financial decisions, better use of resources and better support of the American public. This research strives to expand SD modeling into the federal arena and in doing so, support the public good.

1.3 ORGANIZATION

This paper is organized into five sections. Chapter 2 discusses the background Coast Guard Cutter home port decision making, the history of Systems Thinking and System Dynamic modeling (including the broad range of applications of these methods) and the concept of emergence (behavior of complex systems not obvious from the system structure alone). This section also discusses existing research and applications of these topics. Chapter 3 discusses the design process for the specific SD model comparing two home port options for FRC's in

Southeast Alaska. This chapter walks through the systems engineering process of interviewing stakeholders, identifying and analyzing potential system elements, and designing the SD model. It also includes the final SD model and the quantitative coding associated with it. Chapter 4 is a deep dive into the use of the model, including a side by side comparison of the two home port options for the FRC and a sensitivity analysis on the model elements. This chapter also serves as a guideline for applying the model to different home port comparisons, or even expanding the model to different asset types. Chapter 5 is a summary of findings including discussion of the effectiveness of using SD modeling for this application, the feasibility of capturing the nature of this decision process, and a discussion on model validation. This chapter also includes future work and research areas.

Chapter 2. LITERATURE REVIEW

The Coast Guard Homeporting Decision Process is codified and published, making it the natural starting point for understanding this problem from inside the organization. Understanding the history and development of systems thinking tools is the next step. Branching out from there, a broad range of research is available on systems thinking, systems modeling tools, System Dynamic modeling and how the different tools are applied in different areas. The research covers everything from stakeholder engagement to predicting successful interfaces between electric vehicles and the electric grid, and almost everything in between. The goal of this study is to continue expanding this body of research to include using SD modeling to support decision making inside the Coast Guard.

2.1 Coast Guard Policy and Decision Making

In 2015, the Coast Guard codified its decision-making process for determining cutter home ports in Commandant Instruction Manual M3111.1, The Cutter Home Porting Decision Process (CHDP). The goal of this manual was to "update and improve the Cutter Homeport Decision Process and align it with Coast Guard acquisition, budgetary, and planning processes" (Cutter Homeporting Decision Process, 2015, p. 1-1). The Coast Guard worked with contractors, community stakeholders, and a diverse number of offices and directorates within the Coast Guard. To make final home porting decisions, Coast Guard leadership established a process "to achieve these goals through a standardized multidisciplinary approach using quantitative, analytical, and logical decision-making with participation by a broad range of Coast Guard stakeholders. This process must also be flexible to address the unique situation each homeport initiative presents and result in a homeport decision that aligns with the shore facility planning and budgeting process" (Cutter Homeporting Decision Process, 2015, p. 1-1). The process outlined in the CHDP is a codification of systems engineering principles that are designed to engage all pertinent stakeholders and ensure the priorities of the Coast Guard are sufficiently met during this decision process. The Coast Guard defines its priorities as follows:

> a. Enhance overall operational availability and efficiency of the cutter fleet.
>
> b. Align capability with appropriate Operational Commander plans.
>
> c. Limit risks associated with natural disasters or man-made catastrophes.
>
> d. Facilitate access to operating areas and training support assets.
>
> e. Minimize costs when support infrastructure requires extensive recapitalization or repair.
>
> f. Maximize the use of existing infrastructure such as maintenance, training, and support facilities. Also maximize the use of existing organizations and manpower resources in maintenance, training, and support functions by geographical concentration.
>
> g. Provide the greatest possible quality of service and stability for crews and families without compromising the cutter fleet's ability to support operations.
>
> h. Comply with environmental laws and regulations; identify and mitigate potential negative impact on the environment" (Cutter Homeporting Decision Process, 2015, p. 1-1).

This list constitutes the most important components of the Coast Guard's internal planning process, those which are prioritized by the CHDP. Mission performance is at the top of this list of priorities. The list is comprehensive from an internal organizational standpoint; however, it is missing the external component of community economics which is important to stakeholders both in and outside of the Coast Guard.

The CHDP then identifies four phases to the decision process. The phases are the input phase, the identification phase, the evaluation phase and the approval phase. The input phase identifies the inputs needed to make the decision effectively. The identification phase then brings in different home-porting concepts (such as co-locating a cutter with its maintenance hub) and analyzes different specific home ports. The evaluation phase is used for data collection and the approval phase is the final home port decision approved by the Coast Guard Commandant

(Cutter Homeporting Decision Process, 2015). The entire CHDP falls into one of these phases and supports the end goal of that phase and, ultimately, the final decision.

The question posed by this research fits into the input and identification phases as described by the CHDP. During the "Input" phase, both operational needs of the cutter and maintenance needs of the cutter are analyzed. During the "Identification" phase, the option for clustering a cutter in the same home port as other ships and a maintenance team is analyzed against other home port alternatives (alternatives generally do not have a maintenance hub but may have some other Coast Guard support in place). This study takes the Coast Guard's initial codification of the systems engineering process as applied to cutter home port decisions and applies the concept of System Dynamic Modeling to part of the process. This research also tries to extend the systems engineering process to include external stakeholders and to account for the economic benefits that Coast Guard assets bring to small communities.

As with any federal agency, the location of a large asset in a community becomes a political conversation that can affect budgetary decisions. A Coast Guard Cutter can be a huge component of the economy in a small community. Even a small ship (87' patrol boats have crews of about 12 people) introduces a population with steady pay checks, housing allowances and health care. Many crew members have families, bringing spouses who are looking to enter the workforce and children who increase school enrollment. Having these assets spread through rural communities in Alaska is a good thing for small town economies and, by extension, Alaskan politicians. For this reason, these decisions become very high profile very quickly. Even if the Coast Guard can agree on an arrangement for home porting, congressional pressures are real and do influence the final decisions. It is difficult to communicate the real needs of the Coast Guard with these outside stakeholders who care more about the economics of their constituents than the practicality of maintaining and operating ships. The resulting decisions can become a compromise that fail to meet any single stakeholder's needs effectively. SD modeling provides a tool to quantify the priorities of the CHDP and inform Coast Guard decision making. It can also help communicate Coast Guard needs more easily to stakeholders outside the organization.

2.2 Systems Thinking and the Coast Guard

Systems thinking and systems engineering are disciplines that attempt to understand the totality of a problem before trying to solve the problem. Systems thinking provides tools to see how different elements in a system drive one another's behavior. The discipline uses tools to visualize underlying systems structures and so better understand the systems behavior. Systems engineering takes systems thinking concepts and codifies this process into a series of steps that focus on stakeholder engagement, clear communication, and effective project iterations. The systems engineering process is designed to ensure that a project is effectively solving a problem, and that the problem being solved is the CORRECT problem. Systems engineering strives to eliminate assumptions, test theories, and ultimately design projects that meet the true needs of stakeholders. The Coast Guard's CHDP is a system engineering process used to determine the best possible home ports. This is an important step toward ensuring the Coast Guard meets all of its operational goals as effectively as possible. Systems thinking has ebbed and flowed in its popularity and value in the scientific and engineering communities over the years. Currently, many large organizations find that systems engineering is a critical component of successful projects.

Systems thinking emerged organically after the industrial revolution, when the scientific community had shifted deeply into a mechanistic world view that required all things be broken down into their individual parts in order to be better understood. Eventually, the different branches of science started hitting walls in this way of understanding the world. In the early 1900's, scientist's efforts to encapsulate the synergy observed between the parts and the whole led to the birth of systems thinking. It ushered in "a profound revolution in history of Western scientific thought" (Capra, 1996, p. 29), including the realization that "the great school of 20th century science has been that systems cannot be understood by analysis" (Capra, 1996, p. 29). In this context, "Analysis means taking something apart in order to understand it; systems thinking means putting it into the context of a larger whole" (Capra, 1996, p. 30). The key characteristics of systems thinking are:

- Shift from parts to whole
- Ability to shift between system levels
- Acknowledgement that each level has different complexity
- Observation of the contextual environment.
- Explanations of behavior must be grounded in the whole.
- Shift from objects to relationships (Capra, 1996).

The science of cybernetics, an early pre-curser to computer science, contributed greatly to systems thinking. It focused on patters of communication, closed loops and networks. Cybernetics scientists developed ideas of feedback, self-regulation and self-organization.
The goal of the cybernetics community was to "to create an exact science of the mind" (Capra, 1996, p. 56), and they developed the concept of feedback as we currently understand it: "the conveying of information about the results of any process or activity to its source." (Capra, 1996, p. 56) including concepts of self-balancing and self-reinforcing systems. These concepts are core to the discipline of systems thinking as we know it today. Systems thinking was eventually incorporated into business and project management. Throughout the 1950's and 1960's, the world increased dramatically in complexity and interconnection (Capra, 1996).

This growth in understanding of systems as dynamic, changing, evolving and self-sustaining lead to the use of System Dynamic (SD) modeling as a tool across a large range of disciplines. From a qualitative process used to engage stakeholders in conversations of deeper understanding to a highly technical, quantitative modeling programs, SD modeling is a powerful tool that can inform everything from public policy to environmental regulations to project management.

SD modeling was pioneered by J. Forrester in the 1950's. His treatise on using SD modeling to analyze economic systems and industrial organizations, first published in 1956, is still current, providing detailed descriptions of dynamic systems and effective techniques with which to model them (Forrester, 2003). He then used the technique to tackle the wicked problems of his day, famously providing a comprehensive review of U.S urban housing policy and a detailed explanation of why low income housing, designed to help alleviate poverty, instead damages area economics and leaves more people destitute (Forrester, 1971). Shortly before his death in 2016, he wrote about the importance of understanding system dynamics and how this tool should be used in education to better understand problems and examine assumptions. The powerful structure provided by SD modeling, including both the ability to understand behaviors of complex systems and the comprehensive understanding of the assumptions underlying these systems, is why so many organizations rely on systems engineering, systems thinking and SD modeling to produce effective outcomes.

Systems thinking and systems engineering have now become so critical to successful projects that large corporations and government agencies routinely employ Systems Engineers. Systems Engineering has become its own discipline. The Coast Guard's CHDP shows that even large government agencies are actively engaged with the systems engineering process as they strive to make better decisions. System Dynamic modeling is the next step to better understanding systems and making decisions that best support project stakeholders.

2.3 System Dynamic Modeling and its Applications

System Dynamic Modeling uses a tool called a Causal Loop Diagram (CLD). This diagram shows the different elements in a system, which other elements they connect to, and the manner in which the elements cause each other to change. For example:

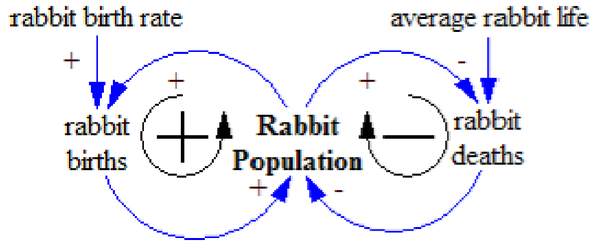

Figure 1: A basic Causal Loop Diagram of population dynamics (Pruyt, 2013, p.36)

In this example, the right-side loop is called a balancing, or negative, loop. This is because the behaviors of its elements balance each other out, pushing one another in opposite directions. If the rabbit population increases, rabbit deaths increase. As rabbit deaths increase, the rabbit population goes down. Balancing loops are commonly found in the natural world. The left side loop is called a re-enforcing, or positive loop. This is because the behavior of each element causes the other element to move in the same direction as the change. As the rabbit populations increases, rabbit births increase. As rabbit births increase, rabbit population increases. Viewed together, it is easy to see that the two loops are connected and each influences the behavior of the other, driving the behavior of the population system. This simple example shows how CLD's are powerful visual tools to show how different elements in a situation interact with one another. A detailed breakdown of CLD's and other SD modeling tools can be found in Sterman (2001).

CLDs are primarily used as qualitative tools and are applied across a wide range of disciplines to engage stakeholders. Visualizing and quantifying a situation may enable those external to a system to intuitively grasp how different components of the system behave in ways that are not always obvious. Examples of the broad range of CLD application include a study by Clapp et al. (2018), which analyzes alcohol and drinking events, one by Pala et al. (2014), which uses CLD's to disrupt corporate decision-making practices that tended to "put good money after bad" because leadership is emotionally invested in a previous decision, and research by Mcglashan et al. (2016), which uses CLD's to create mathematical networks of the factors for childhood obesity that, when mapped as mathematical networks, accurately predict results. Clapp et al. (2018) is a good example of how CLD's and SD modeling can be used to bring together researchers from a wide variety of backgrounds and come up with a better understanding of the situation. In this study, researchers established that there was a huge amount of data on human behavior and alcohol consumption, but a dearth of tools to effectively understand it. This study took a group of engineering and social science doctoral candidates and professors and together used CLD's and SD modeling to analyze human behavior around alcohol consumption. Researchers were able to use data from their respective disciplines, then verbalize and align their assumptions to build an SD model that accurately reflected human behavior. The results gave the researchers a much better understanding of social behavior, group dynamics and alcohol, which would not have been achieved by working within a single discipline (Clapp et al., 2018).

At the other end of the spectrum, Chand et al. (2016) uses CLDs to analyze hospital responses to extreme weather events and how the organizations learned from these disaster responses. The CLDs allowed different stakeholders across the organization to effectively share their experiences of the disaster events and identify short-fallings, areas of improvement and lessons learned. This study did not use quantitative SD modeling, but rather focused on CLD's as tools for understanding the elements of the disaster scenarios and how each element impacted each other. The process focused strongly on stakeholder engagement, understanding the assumptions that different employees brought to the situation, and working through these assumptions in a visual, interconnected way. Ultimately the process shed a lot of light on what took place during a disaster, what lessons learned were retained by the organization, and which stakeholders were under-heard and under-represented in previous debriefs (Chand et al., 2016). In an organization like the Coast Guard which is also expected to respond effectively during emergencies and extreme events, these learnings are very relevant. The study by Chand et al. (2016) provides proof of concept that systems thinking and CLDs help large organizations engage diverse stakeholders and use that information to make good decisions and identify effective paths forward.

In general, this diverse body of research establishes that CLD's are particularly effective as a stakeholder engagement tool, used to get a diverse group of people to a common understanding of a problem. They are very powerful graphical tools used to represent systems thinking concepts and improve understanding.

Stock and Flow diagrams are another systems analysis tool, one that lend themselves to more effective quantitative analysis.

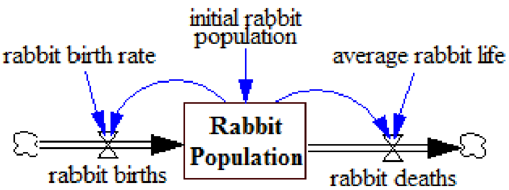

Figure 2: A basic stock-and-flow diagram of population dynamics (Pruyt, 2013, p. 38)

Stock and Flow diagrams are the primary tool for quantitative analysis (Pruyt, 2013). As described by Meadows (2015), a stock is the foundation of any system. Stocks are the elements of the system that you can see, feel, count or measure at any given time" (Meadows, 2015, p.17). Stocks represent parts of the system that can ebb and flow, like the number of parts in inventory or the amount of water in a reservoir. In Figure 2, the stock is represented by the square: rabbit population. In-flows grow the stock at a specific rate, and out-flows deplete the stock, here shown by hour-glass figures coming in and out of the stock. Meadows (2015) describes in-flows and out-flows as faucets that can be turned on and off, changing the stock accordingly over time. The system is also influenced by auxiliary variables, or elements that are neither stocks nor flows (in this case, the initial rabbit population, the birth rate and the average life span). Using stocks and flows, the dynamics of a system can be mapped and quantified. These diagrams and models provide a powerful tool for looking at how a system behaves over time, including the types of feedback delays that come from the slow changing of a stock over time. Stock and flow diagrams are the tool used in this paper to complete a quantitative analysis of cutter home porting decisions for the Coast Guard.

Additional academic research on systems thinking tools such as CLD's and their applications for stakeholder engagement and community learning can be found in Wang et al. (2013), Kopainsky et al. (2016), Kim, S. R. et al. (2018) and Findiastuti et al. (2017). For a comprehensive look at CLD’s applied to organizational thinking, see *The Fifth Discipline: The Art and Practice of the Learning Organization* (Senge, 1994). Additional academic research on quantitative SD modeling as applied to different types of systems and disciplines can be found in works by Abotaleb et al. (2018), Franco et al. (2017), Kim H. S. et al. (2018) , Saryazdi et al. (2018), Sillmann et al. (2018), Tolujevs et al. (2018), and Yaun et al. (2017). For a comprehensive analysis of System Dynamics and their application across organizations and industry, see *Business Dynamics: Systems Thinking and Modeling for a Complex World* (Sterman, 2014).

2.4 Emergence as a Property of Systems

Emergent Properties are defined by C. D. Broad as “those properties that emerge at a certain level of complexity but do not exist at lower levels” (qtd. in Capra, 1996, p. 28). When looking at the elements of a system, defined by Meadows as “elements, interconnection, and a function or purpose” (2015, p.11), emergence is the expression of that function that is not possible by any part alone. A classic example is a bicycle. Individual parts like wheels, chains, gears, a frame and handlebars cannot propel a person down the road. When connected in a certain way, these elements serve a higher purpose and the behavior of a bicycle as a complete system emerges. Emergence can be difficult (some argue impossible) to predict at high levels of system complexity. In simple systems, emergence is the expression of a systems higher purpose, such as the bicycle rolling down the street. In complex, less-understood systems, it is unpredictable and takes many forms. Emergence can be as awe-inspiring as human consciousness and as confounding as backlashes from systems that are designed to do one thing but create the opposite effect. For example, a welfare system designed to alleviate hunger that instead creates dependence, poverty and pain because of the way the different elements in the system interact in unpredictable ways.

Research into emergent behavior abounds, especially as the world grows increasingly interconnected. Scientists, engineers and policy makers strive to understand some of the unintended consequences of decisions before putting those decisions into place. The term “System of Systems” (SOS) captures today’s smart technology and describes how new technologies have to integrate with existing systems in effective ways (Osmundson et al., 2008). New research from the Naval Post-Graduate school uses algorithms that focus on the interfaces between systems to effectively predict emergent behavior in SOS. In this case emergent behavior is specifically defined as negative, ways in which the systems do not work correctly or create new problems for users (Osmundson et al., 2008). Predicting this in advance can have huge implications for creating effective, lucrative and environmentally responsible systems moving forward.

The community of climate researchers looks carefully at emergence. Climate science uses very complex models and also has significant historical data from ice cores with which to validate their models. Climate scientists Anderson et al. (2018) found that complex climate models can predict emergent behavior with respect to temperature and precipitation in the Arctic.

Another definition of emergent behavior, from Moshirpour et al. (2010), defines emergent behavior (not explicitly) as code failures in a computer program due to conflicting or mis-interpreted signals. The research uses an algorithm to detect these conflicts early and prevent them. Fixing these issues after finding them during field trials is very expensive and time-consuming, therefore it is in everyone’s best interest to identify them early and prevent the problems. Their research finds that emergent behavior, using this definition, can be predicted by modeling and can decrease the errors in computer coding (Moshirpour et al., 2010). While this is a narrow definition of emergence, it is an example of applying the concept to a very practical outcome.

Kolen et al. look at emergence through the lens of electrical power distribution and define it as follows: "The specific evolution, which is a result from interactions in the system, and does not coincide with any of the components' behavior, is called emergent behavior" (2018). These researchers found that by programming individual component behaviors and communication capacities, emergent behavior of the system was successfully observed. The observed behavior was not otherwise predicted.

In general, this research is applicable to the Coast Guard and its location choices for cutter home porting because emergence has a tendency to create unpredicted behaviors in the design and decision-making phases of a system. The Coast Guard is intentionally engaging in systems thinking and systems engineering during the CHDP. In this way, the organization strives to make good decisions that support all stakeholders and ensure operational effectiveness. SD modeling and its ability to model real world system behavior is a powerful tool for finding and correcting potential unintended consequences before putting a decision into action. Modeling also allows other learnings to emerge, ones that cannot be predicted by the modelers.

Additional works on emergent behavior include “Causal Analysis of the Emergent Behavior of a Hybrid Dynamic System,” published by Acta Polytechnica Hungarica (2014), Hsu and Butterfield’s work on modeling emergent behavior in System of Systems (2007), and Laurentini et al.’s work on the unintended consequences of environmental improvement policies (2015).

Chapter 3. DESIGN OF THE SYSTEM DYNAMIC MODEL

To design a System Dynamic model of the Coast Guard's home porting process, it is important to employ the systems analysis process in order to properly evaluate the problem. This evaluation ensures that all stakeholders are accounted for, that their concerns are understood, that the problem is understood from many angles and that the design of the final solution meets the needs of the organization and its stakeholders. The end result of the systems analysis process is the outline of a final solution, which in this case is an SD model implemented using modeling software. Through the modeling process, elements are refined and modified in order to work correctly in the software and provide relevant information. Each element in the model is assessed, documenting the assumptions made in order to create the model. The model provides information on critical system components, information that can be used to make more informed decisions and can also provide insights into the emergent behavior of complex dynamic systems. It also provides a new mechanism for engaging stakeholders, surfacing assumptions and working towards a model that most accurately captures the reality of all stakeholders. It should be noted that SD modeling was chosen for this project over other options, such as Discrete Event Simulation, because of the way it uses strong visuals to explain how the system works and the strength of the tool to align stakeholders and refine understanding of assumptions.

3.1 SYSTEMS ANALYSIS METHOD: PHASE ONE, GOAL DEVELOPMENT

The systems analysis method is a structured way of analyzing a problem that ensures the problem is viewed through a systems lens and therefore that the behavior that needs to be corrected is effectively addressed. For example, if a city wants to reduce traffic congestion at an intersection, engineers might decide to add a traffic lane and a stop light. However, without looking at the interconnecting systems of public transportation, parking, housing available near working locations, etc., simply modifying the physical intersection is not likely to fix the traffic problem. The systems analysis process is designed to avoid knee-jerk solutions that do not solve problems.

The systems analysis process starts by generalizing the question and understanding the problem in its current form; then understanding the best-case outcomes of the problem; and finally understanding the stakeholders and their values. Once this legwork is complete, it is important to define the objectives and the performance measures for the solution being designed. Finally, multiple alternate solutions are identified and analyzed in order to find the best solution for the systems problem that is being tackled. The process results in the outline of a final solution that is iterated as new information and refinements become available.

Generalizing the question is an exercise in raising the understanding of the specific question up a level to encompass a broader system perspective. This is a powerful system's thinking tool, one described by Meadows as "aligning the various goals of the subsystems, usually by providing an overarching goal that allows all actors to break out of their bounded rationality" (1996, p.15). This allows stakeholders and problem solvers to work towards a common goal rather than get stuck trying to solve small problems with seemingly contradictory solutions.

The systems analysis process then requires a good understanding of the descriptive and normative scenarios. The descriptive scenario is the situation as it currently stands, including what works well and what areas can be improved. The normative scenario is the situation as it would be in an ideal world. The descriptive scenario is where the system engineer strives to truly understand the current situation, including all of the components that are working well and those that stand to benefit from the project goals. Documenting this scenario helps look at the situation from many angles and identify where the situation needs an intervention. The normative scenario is then an exercise in imagination, envisioning the perfect version of reality and identifying different ways to get there.

Once the scenario is fully understood from both the current and idealized perspective, the next step is to identify stakeholders and their values – stakeholder values, called the axiological component of the analysis – are critical to properly understanding the situation. The broader the stakeholder interviews, the better the understanding of the problem and its potential solutions. Keeping stakeholder engagement too narrow limits a project's ability to create a solution that truly solves a problem holistically.

By this stage in the process, the systems engineer has a great understanding of the problem. This is used to generate an objectives tree for the final engineering solution. The objectives ensure that the final solution meets the goals and needs of the stakeholders. This phase of the process also generates performance indices, metrics by which the systems engineer can evaluate the success of the final solution.

All told, the systems analysis process is a comprehensive method for evaluating a problem, designing a solution that will actually fix the problem, and ensuring metrics are in place to evaluate whether the solution was effective.

3.1.1 *Generalize the Question*

The Systems Engineering process for a SD model to aid the Coast Guard in the Cutter Homeporting Decision Process starts with generalizing the question and identifying the overarching goals of the project. The initial goals of designing an SD model for the CHDP are:

- To empower decisions that make the most operational and economic sense for the Coast Guard
- To provide a quantifiable correlation between maintenance and operations
- To create a tool that helps justify decisions that are good for the Coast Guard to a wider audience of external stakeholders and including external stakeholder voices where appropriate.

The generalized question for the design of the model is "Can dynamic system modeling be used to do a port-to-port comparison and so support the Coast Guard in making rational, quantifiable cutter home porting decisions?" This generalized question provides an umbrella for the systems engineering process and the final system design, ensuring that the process continues to reach back to the project goals.

3.1.2 *Descriptive Scenario*

Internal to the Coast Guard: The Coast Guard CHDP manual is a strong tool for applying the systems engineering process to deciding where to locate new and existing CG assets. It requires input from a wide range of internal stakeholders and uses a repeatable survey process to quantify the importance of different elements such as safety and navigation, logistics, and components important to crew and family success in communities. The survey is then used to quantify how stakeholders feel about the different priorities for locating a cutter. Potential home port options are then analyzed against a series of metrics regarding infrastructure and navigability. These two sets of quantifiable metrics are then used to support the homeporting decision.

This process is a strong start towards applying good systems engineering practices to these important decisions. However, the process still leaves room for more thorough, less qualitative stakeholder engagement. In the current model, stakeholders use personal experience to rate the different decision elements as compared to one another. These ratings are then averaged across the surveyed population and input into the final decision process. This process misses a mechanism for stakeholder engagement that allows decision makers to understand and examine the assumptions of the stakeholders. Instead, it allows stakeholders to quantify their assumptions independently, without further discussion or refinement. These unexamined assumptions are then translated into quantifiable data that is used to support a decision. Additionally, the current process does not account for the dynamic nature of the system, and the way in which trade-offs between different elements impact one another. Ignoring these trade-offs can result in decisions which seem beneficial on paper but are ultimately lacking in ensuring cutters maximize their operational days.

External to the Coast Guard: A Coast Guard asset can be a huge component of the economy in a small community. Even a small ship (for example an 87' patrol boats has crews of about 12 people) introduces a population with steady pay checks, housing allowances and health care. Many Coast Guard members have families, bringing spouses who are looking to enter the workforce and children who increase school enrolment. Having these assets spread through small communities stimulates small town economies. For this reason, these decisions become very high profile very quickly. Even if the Coast Guard can agree on an arrangement for home porting that meets the CG's interests and needs, congressional pressures are real and do influence the final decisions. It is difficult to communicate the real needs of the Coast Guard with stakeholders outside of the organization who care more about the economics of their constituents than the practicality of maintaining and operating ships. The resulting decisions are often a compromise that fail to meet any one stakeholder's needs effectively.

3.1.3 *Normative Scenario*

The current CG CHDP goes a long way towards improving, codifying and standardizing the decision process. In an ideal world, though, stakeholders would have an opportunity to interact and examine their assumptions and priorities with other stakeholders. There would be a mechanism for removing the ambiguity in how different people interpret different elements on the survey. There would be a mechanism for quantifying different elements prioritized by both Coast Guard and external stakeholders and a common language with which to discuss each group's priorities.

In an idealized world, decisions would find a way to harmonize and balance between ship operability, ship maintainability and the economic vibrance of local communities. Ship's crews would be located in places where they are supported as whole people and where their families have access to education and healthcare and meaningful employment. Ship's crews would engage with communities and build trust between the Coast Guard and the fishing and boating communities. Home porting decisions would be made such that all of these elements were discussed, balanced, and accurately prioritized.

Many of these elements are outside the scope of this study, which strives to apply SD modeling to the CG CHDP. However, it is important to capture the totality of the normative scenario such that future work and other people tackling related problems can benefit from the systems engineering understanding of the final goal.

3.1.4 *Stakeholder Engagement and Axiological Component*

In order to determine a comprehensive list of stakeholders, it is important to talk to as many people involved in all levels of the decision process and those who are most impacted by the decision. This list was compiled after interviewing people involved in the CHDP in the

Coast Guard, as well as operators and engineers who have recently been involved with both new home port decisions in action and decisions for cutter home porting in the very near future. Stakeholders in the Coast Guard CHDP include:

- CG Headquarters and high-level decision makers
- Politicians
- Rural community residents
- Rural community businesses
- Area mariners, fishers and boaters
- CG Ship operators
- CG Ship maintainers
- Public
- Ship repair contractors

While there is always room to find more stakeholders, this list captures the primary people involved and impacted by the decision of where to locate a Coast Guard Cutter.

Axiological components, or values, derived from the stakeholders are important because what a person or a group values most can very much influence the solution that stakeholder is looking for. For example, adding an extra lane of traffic to decrease congestion in a neighborhood that prioritizes quiet and walkability would not be in line with the values of those stakeholders and therefore would not be a good solution. The axiological component, or values, derived from the respective stakeholders in the CHDP are:

- Operators prioritize transit time/distance to operational areas, crew endurance metrics, operational effectiveness.
- Operators assigned to ships prioritize easy access to support and maintenance facilities.
- Operators and engineers have a cutter "Days Away from Home Port" (DAFHP) requirement that both operations and maintenance must fit into.
- Engineers prioritize efficient repair and maintenance abilities (so as to maintain operational effectiveness) and believe well designed maintenance capabilities are more important to executing the mission than location relative to the operational area.
- Political values and priorities are a moving target, are rarely aligned with individual federal agencies, and are almost impossible to quantify.
- The CG as an organization prioritizes operational effectiveness and cutter operational days.

- The public values the presence of the CG and its ability to effectively execute rescue missions and keep people safe on the water. The CG provides an important service that is valued by the public.

These stakeholder values and priorities inform the systems engineering process and are an important component to ensuring that the final engineering solution is reached.

3.1.5 *Objectives Tree and Performance Indices*

An objectives tree is a way to break down the systems engineering process into more tangible goals at a high level, then work down in granularity towards more specific goals. The objectives tree for this problem starts with the generalized question in statement form: To empower the Coast Guard to make quantifiable, informed cutter home porting decisions. The tree then works down to very specific goals, such as quantifying cutter maintenance time and cutter response time to an operational area.

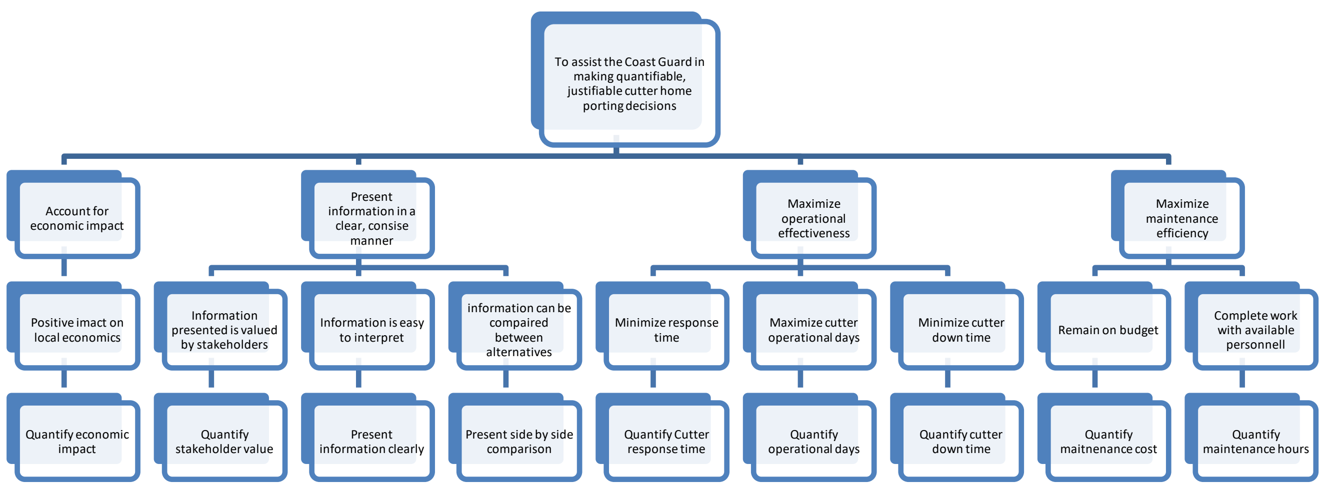

Figure 3: Objectives Tree for Improving the CHDP

The objectives tree is an important starting place for identifying performance indices, or quantifiable metrics against which the final solution can be compared. In general, the bottom level of the objectives tree should provide the metrics for the final system design. In this case, specific metrics for the SD modeling include:

- Does the model quantify cutter response time?
- Does the model quantify cutter underway time?
- Does the model quantify planned and unplanned ship down time?
- Does the model quantify cost of maintenance?
- Does the model quantify man hours required for maintenance?
- Does the model quantify local economic impacts?
- Is the information presented valued by stakeholders?
- Is the information presented easy to interpret and understand?
- Is the information presented such that it can easily be compared between scenarios?

It is also important to identify performance indices that ensure the final system solution is on track with the big picture goals of the stakeholders. In this case, the high-level performance indices are used to identify and evaluate the final model elements and ensure that these elements capture the Coast Guard's goals and priorities effectively and accurately. For this model, the high-level performance indices are:

- Is this element a priority for the stakeholder(s)?
- Is this element supported by data?
- Is this element relevant and appropriate to the system goals and system boundaries?

These questions are used to jump into the first design phase in the systems engineering process, in which different alternatives are identified and evaluated. These indices are used to evaluate the different potential system solutions and ensure that the final solution is in line with the systems analysis and stakeholder priorities. In the "Analysis of Alternatives" section, these indices are translated into numerical scores for each potential model element, scores which are used for final model element selection. For the purposes of this study, the three groups of stakeholders considered are Coast Guard leadership, Coast Guard members conducting operations, and community members interested in the economic benefits of Coast Guard assets.

3.1.6 *Analysis of Alternatives*

This study starts with the premise that SD modeling will be used as a tool to assist and augment the CHDP. In order to design a model that effectively captures stakeholder priorities, it is important to cast a wide net around many elements of the system, then use a comprehensive evaluation to determine the most critical elements and the ones that fall inside the system boundary. As in the case of all interconnected systems, it is important to draw boundaries so that models do not get too large and too cumbersome to be helpful. In this study, a list of important elements was gathered from stakeholder interviews and from the current CHDP.

The alternatives analysis looks at the broad range of elements that can be included in the model. It separates the model into four broad categories: Operation Elements, Engineering Elements, Economic Elements and Other CG Elements. In each category is a series of elements drawn from a combination of current CG homeporting analysis, interviews with CG officials who specialize in ship maintenance, and interviews with ship operators at the shipboard level and the area operational level. These elements formed the basis of the model and were prioritized using an evaluation process.

To ensure a comprehensive review of all the elements from a variety of perspectives, the elements were evaluated from the perspective of three different stakeholders: CG personnel at the operational level, CG leadership at the Headquarters level, and stakeholders interested in local economics. Each element was rated three times, each time from the perspective of one group of stakeholders, including numeric scores based on each of the performance indices.

Elements that were rated high by two out of three stakeholders were retained as final model elements. Elements that were not were set aside.

It should be noted that systems engineering is a highly iterative process, and that some elements needed to be broken down into more refined elements for modeling purposes, and some elements were kept outside the SD model for additional analysis by other means prior to the final decision. Specifics of the element analysis are provided in Appendix A.

The systems analysis process is an important component of ensuring a thorough systems understanding and designing a model that is accurate, useful and worthwhile. This process is the foundation for designing an SD model of Coast Guard Cutter home porting. It is also highly iterative and can be revisited throughout the course of the project as new information becomes available.

3.2 FINAL MODEL DESCRIPTION

The final working SD model for analyzing potential Coast Guard cutter home ports is the result of a thorough systems analysis, a clear understanding of the project goals, and interview with myriad stakeholders involved in cutter operations, ship repair and organizational strategic planning. The modeling environment is in a program called Vensim, using the VenSimple version available for academic research. This software can be purchased are compatible with Coast Guard computer systems. Vensim uses a broad range of equations and iterations of the systems over time to simulate behavior over time of each model element. The model takes the form of a stock and flow diagram, which is the most effective way to complete quantitative modeling in Vensim.

3.2.1 *Model Overview*

The model elements center around three interrelated systems: Planned Cutter Maintenance, Unplanned Cutter Maintenance, and Cutter Operations. Deferred maintenance is also a critical element of the system, as it captures the difference between the planned maintenance a cutter needs and the planned maintenance it receives. After a time-delay, these deferred maintenance days normally become casualties, and need to be dealt with by taking unplanned maintenance days.

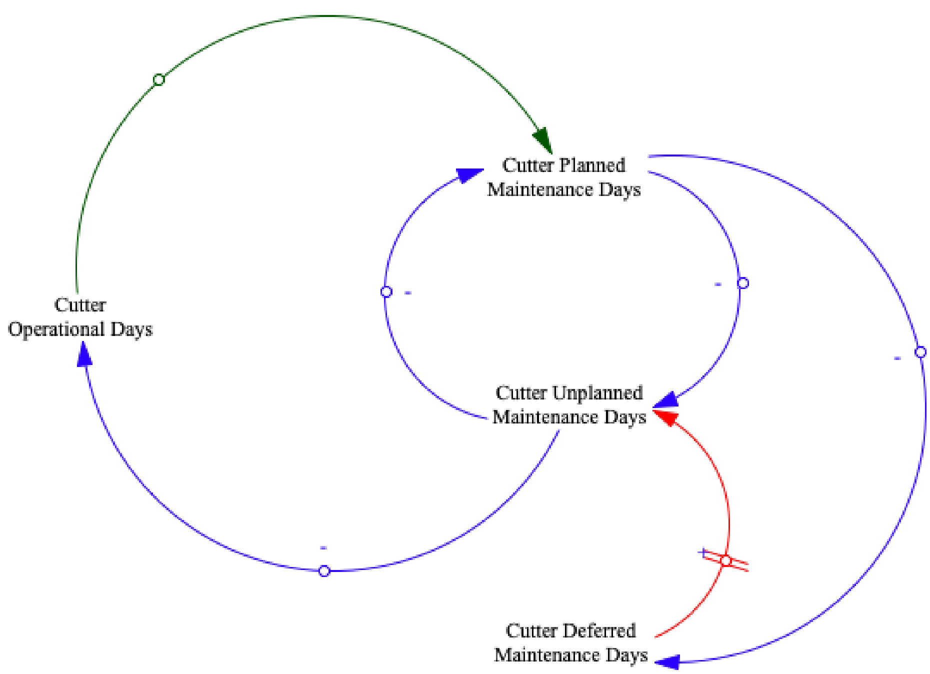

Figure 4: A high-level Causal Loop Diagram of the ship maintenance system. Blue arrows indicate a negative relationship between the elements, so an increase in one element results in a decrease to the other. Red arrows indicate positive relationships, where an increase to one element results in an increase to the other. The double hash marks between Deferred Maintenance and Unplanned Maintenance indicate a time delay. The green arrow between Operational Days and Planned Maintenance is sometimes positive and sometimes negative, depending on several factors. These complexities can be captured in the coding of an SD model.

The model runs over a two-year period using one-month time steps. The integration interval is 0.125 (months) and the model uses the Euler integration method. The Vensim Modeling Guide describes Euler integration as the simplest integration form, suitable for social models and businesses, in which the program assumes that a rate calculated at the beginning of a time step remain constant through that time step (Vensim Modeling Guide, Integration). Since the actual equations in this model are fairly basic and the time step small, this integration type was selected. The sub-systems show in Figure 4, Operational Days, Planned Maintenance Days, Unplanned Maintenance Days and Differed Maintenance Days are represented in the model using stocks. The stocks capture actual days used of each type, and act as counters. For example, if you take three vacation days, the stock would increase to three. When you take two more vacation days, the stock would increase to five. In this way, the stock captures actual days used (rather than a bank of days, in which days are earned and used). These stocks can then be evaluated at the end of the two-year model cycle to see if the total number of operational, maintenance and differed days are on track with organizational goals.

Each stock is fed by rates, in this case rates of days per month that increase each stock. The sum of the rates into each stock is integrated over time to achieve the stock values. The rates are influenced by auxiliary variables. These auxiliary variables are coded to capture the behavior of the real-life variables using data or approximations. The coding of these variables, and the elements that influence each stock, are the core of the model and are each specifically captured in Appendix B. They are also powerful tools for engaging stakeholders involved in the CHDP. Gathering many stakeholders in one place and reviewing the model is integral to the process, including the assumptions that go into the equations driving each element. This provides a mechanism for surfacing assumptions about what is important, how variables affect each component of the system, and coming to an agreement about the inputs to the model. While this requires a more hands-on approach than the current survey method, it has potential to gather much more accurate feedback and leverage that feedback into a single, quantifiable result which also accounts for dynamic system behavior.

3.2.2 *Model Elements and Coding*

The stocks used in the model are Operational Days, Maintenance Days and Deferred Maintenance Days. Each stock is an integral over time of the rates entering the stock. Because these stocks are counting actual days used of each type (rather than providing a bank from which days are added and withdrawn) the model uses rates going into the stocks only. There are no rates exiting the stocks. The integration method used is Euler, with an integration timestep of 0.125 months. An example of the equation for a stock is shown here, for the stock that captures Maintenance Days:

$$CMD(t) = \int_0^{24} (M)dt$$

Where:

CMD = Cutter Maintenance Days (Days)
M = Maintenance Days (Days/Month)

Operational Days and Deferred Maintenance Days are similarly captured, with exact equations found in Appendix B. The stock-and-flow diagram for Maintenance Days is shown in Figure 5.

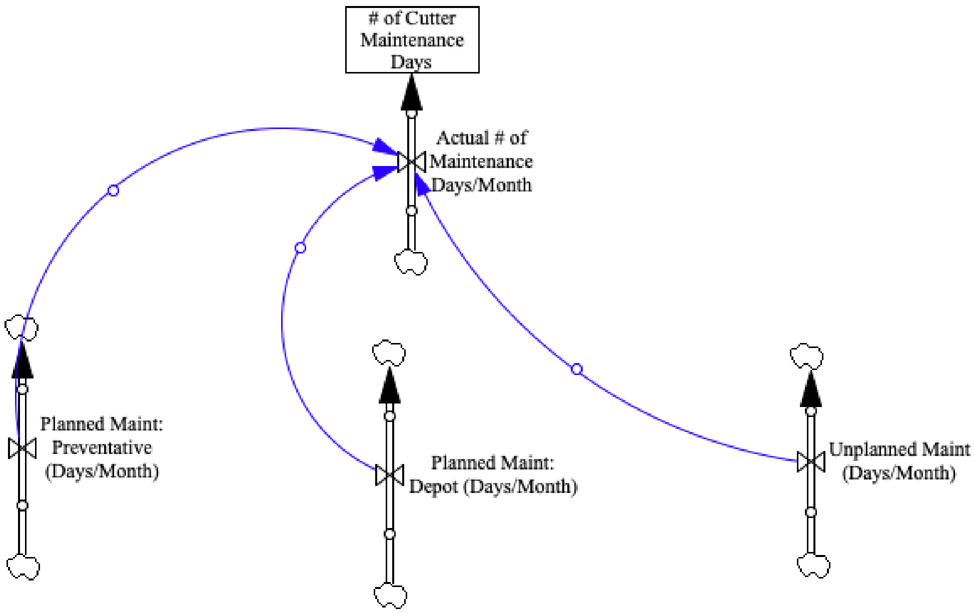

Figure 5: Rates impacting the stock of actual maintenance days for a cutter over a two-year period.

The rates entering the three main model stocks are all in units of days per month (Days/Month). These rates provide the meat of the SD model and can take the form of step functions, if-then-else functions, and others as appropriate to best approximate the real-world behavior of the rate. Error and uncertainty are also important to include in these functions. In this model, error is captured through a normal distribution added to elements where it is appropriate. The parameters of this normal distribution can be manipulated based on stakeholder input and assumptions as they are refined. It can also be varied during sensitivity analysis to determine how much of an impact the error in a specific element has on the model outputs. An example of an if-then-else function that also includes error in the rate for Unplanned Maintenance (Days/Month):

$$UM = \begin{cases} 5 + TD + CD + \varepsilon & if\ DM \geq 30 \\ 0 + \varepsilon & if\ DM < 30 \end{cases}$$
$$\varepsilon \sim (N|3.5,3.5)$$

Where:
UM = Unplanned Maintenance (Days/Month)
TD = Travel Delays (Days/Month)
CD = Contractor Delays (Days/Month)
DM = Deferred Maintenance (Days/Month)

Rates enter the three stock variables. The five rates captured by the model are Deferred Maintenance (Days/Month), Unplanned Maintenance (Days/Month), Preventative Maintenance (Days/Month), Program Depot Maintenance (Days/Month) and Operational Days (Days/Month). These rates work off a series of auxiliary variables, each other, and the stocks. The stocks act as time delays, an important component of modeling real-world dynamic systems. For example, differing maintenance does not result in a casualty until enough maintenance has been deferred to cause equipment to fail. There is a time delay in the feedback between skipping a maintenance task and that piece of equipment breaking. This is captured in the model by linking the deferred maintenance stock to the unplanned maintenance rate. The rate does not start reflecting the deferred maintenance until that stock reaches a certain level, providing a time delay. Figure 6 shows the model for the rate of Unplanned Maintenance, including the auxiliary variables that feed it:

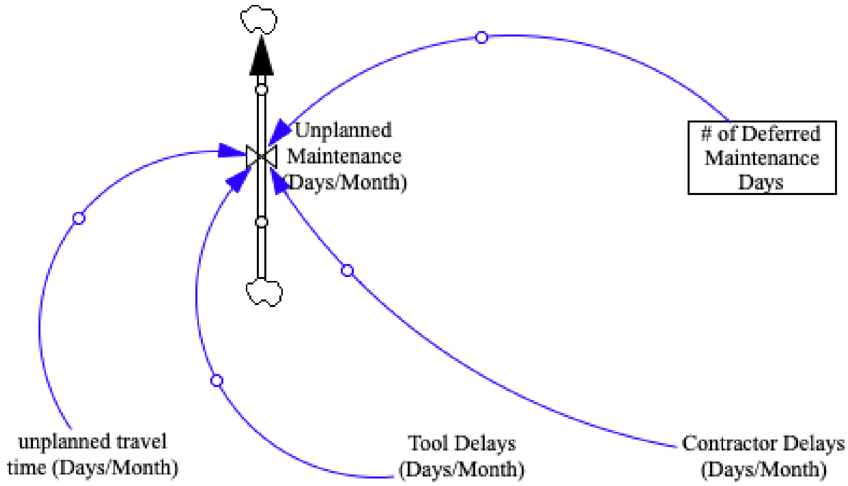

Figure 6: The auxiliary variables that feed the rate of unplanned maintenance days per month are unplanned travel time, tool delays and contractor delays. The stock of deferred maintenance days also feeds this rate, and acts as a time delay between maintenance that is not completed, and systems failures that result from skipped maintenance.

The auxiliary variables capture the additional elements needed as inputs to the main stocks and rates of the model. They are based on real world experience, stakeholder interviews, data, and vetting by subject matter experts. Each is coded appropriately to best capture real work behavior of that element. Some auxiliary variables, such as travel delays between a maintenance hub and a cutter home port, are based on real world data. Flight times, flight delays and flight cancelation rates are available for most airports and can be translated into auxiliary variables.

An example of this is the auxiliary variable Travel Delays (Days/Trip), which is coded as follows:

$$TD = \begin{cases} 1 + \varepsilon & in\ January\ and\ November \\ 0.5 + \varepsilon & in\ all\ other\ months \end{cases}$$
$$\varepsilon \sim (N|1.25,1)$$

Where:
TD = Travel Delays (Days/Trip)

Figure 7 is an expanded view of Figure 6, showing how the auxiliary variable “unplanned travel time” is calculated from additional variables and the stock of deferred maintenance days:

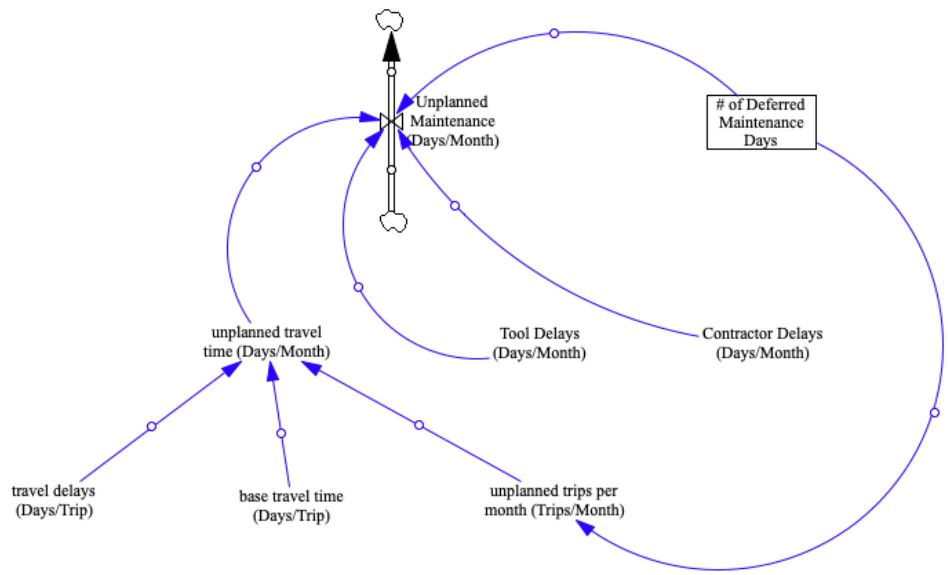

Figure 7: An expanded view of Figure 6, including the auxiliary variables that feed “unplanned travel time”. Note that the stock of deferred maintenance days again acts as a time delay, eventually increasing the number of unplanned maintenance trips needed every month.

Some auxiliary variables are hard-coded based on Coast Guard policy and procedures, such as Preventative Maintenance Trips per Month. This is currently set by the Coast Guard at 10 trips per year, so the variable can be set at 10/12. Other auxiliary variables, such as cutter transit speed, are coded based on the speed profile of the cutter and can be changed to capture different operational missions, weather conditions, etc. Finally, this model uses a unique auxiliary variable called “Distance to Maintenance Hub Multiplier.” This variable provides a way to capture additional delays created by having a cutter located away from the people who maintain it, such as delays in getting special tools to the cutter’s location and delays in getting contractors on site. As with the rate variables, the equations driving each auxiliary variable can be discussed with stakeholders and modified to capture assumptions that everyone agrees upon.

The primary output of the SD model is the number of operational days accumulated over a two-year period, given all the other factors that compete for a cutter's time. This value can then be compared to the goal of 185 operational days per year (180 maintenance days per year). This is the generic Coast Guard split between planned operational days and planned maintenance days. The equations driving the model through stocks, rates and auxiliary variables can be modified to compare specific home ports, modified to look at different operational profiles, and modified to more accurately reflect stakeholder feedback. Ultimately the model will be used to complete a side by side comparison between two home ports, including a detailed sensitivity analysis of different components that can be changed and the impact of those components on the final number of operational days. This is evaluated in Chapter 4 of this study.

The SD model of the CHDP focuses on the Coast Guard's most important metric – how many days a cutter is operating. When operational, Coast Guard Cutters execute critical missions such as fisheries law enforcement, search and rescue, marine inspections and interdiction of illicit traffic. Whenever a cutter is in a maintenance period longer than planned, whenever casualties keep a cutter tied up, critical mission days are lost. It is essential that cutters be homeported in places that maximize their access to operational areas while also ensuring a robust maintenance program to prevent unplanned casualties and extended maintenance periods. This model is designed to simulate the system dynamics at play between operations, maintenance and location. It provides opportunities for stakeholder engagement, surfacing of assumptions, and working towards quantifying elements that best capture the reality of the situation. Using this model, a new layer of understanding can be achieved before making final cutter home porting decisions.

Chapter 4: A Comparison Between Two Home Ports

The final SD model to assist the Coast Guard in making quantifiable decisions about cutter home porting is designed to simulate a side-by-side comparison of two potential home ports. One of the largest internal decision factors for the organization is whether ships should be home-ported in clusters, meaning several of the same type of ship on the same home port. When this occurs, the home port is generally outfitted with a Coast Guard maintenance facility, so that preventative maintenance can take place without maintenance teams needing to travel. These hub locations also tend to be larger cities, where access to tools, contractors, materials and parts is easier than in remote locations. The trade-off is that cutters then have to transit farther to some critical operational areas. When ships transit longer distances at higher speeds, they require more maintenance. For example, many preventative maintenance tasks are based on the hours that equipment runs. If a ship has to transit an extra 12 hours to reach its destination, the maintenance on its engine will be required 12 hours sooner than the ship that is co-located with its operational area. The model allows users to alter inputs and complete a side by side comparison of two home port options, then compare cutter operational days between the two home ports.

For the purposes of this section, Homeport A is the home port co-located with the maintenance hub. Homeport B is the remote home port, approximately 150 miles north of the maintenance hub. For geographic-specific model inputs, Ketchikan, AK is used as Port A and Sitka, AK is used as Port B. This model is set up for Coast Guard Fast Response Cutters (FRC), the Coast Guard's newest patrol boat acquisition. Once the comparison between home ports is developed, the model is verified and validated through a combination of subject matter experts and comparison to early data regarding this new class of ship.

As with all models, this model makes many assumptions. The sensitivity analysis addresses which of these assumptions have a statistically significant impact on the model outputs. This information is most valuable with respect to stakeholder engagement. The model elements and assumptions with statistically relevant impact on the model outcomes are the starting point for stakeholder engagement and assumption validation. When diverse stakeholders can agree on the assumptions (and therefore coding) underlying these elements, the model will have the most relevant outputs to the decision. In this way, the model becomes a tool for both quantitative decisions making and effective stakeholder engagement.

Local economic impact is an important component of the final home porting decision. Because a full SD model looking at the dynamics and intricacies of local economics was outside the practical scope of this study, the topic is addressed in the port to port comparison, looking at economic indicators for each community and the impact CG personnel could have in that area.

Finally, emergent behavior as an observable outcome of SD modeling is discussed. Emergent behavior is behavior exhibited by a combination of components, which is not able to be predicted by a simple sum of parts. SD modeling can sometimes predict emergent behavior.

4.1 Comparison of Cutter Operational Days

According to the Coast Guard CHDP, the first priority is to "enhance overall operational availability and efficiency of the cutter fleet" (Cutter Homeporting Decision Process, 2015, 1-1). This requires planning, maintenance, training, funding, and myriad other inputs. Most simply, though, it means having operational cutters ready to complete the mission. In order to boil down the goals of the CHDP into something that can be effectively modeled, this priority is captured with the factor "Total Operational Days". This is the key output metric of the model, and the one that is compared between two home ports. The home port that results in the most operational cutter days is the home port most likely to meet the Coast Guard's objectives.

To compare Port A – a port co-located with a maintenance hub – and Port B – a remote home port, the model uses several key auxiliary variables. The first is the "Distance to Hub Multiplier". This variable is modeled as normal distribution with a range of zero to five days, and it captures delays in getting tools and contractors to a remote location. This variable primarily affects unplanned maintenance days. This multiplier is set to zero when cutters are co-located with their maintenance hubs. The second key set of elements is travel time and travel delays. Travel delays between Ketchikan, AK and Sitka, AK are both real and well documented. For the purposes of this comparison, the actual travel time of 0.5 days between the cities is used. The actual flight delay and cancelation data is then used to capture further delays (variable by season) that can be expected between the two locations. The specific class of ship for this analysis is the Fast Response Cutter (FRC), the Coast Guard's newest Patrol Boat.

Finally, cutter transit from home port to operational area is factored into the model. The cutter in Port A has a longer transit to key operational areas than the cutter in Port B. Again, for this comparison, the geographic data compares the transit distance a Ketchikan cutter travels to the Fairweather Fishing Grounds of Sitka, AK, compared to the transit distance for a cutter based in Sitka. It should be noted that the Coast Guard currently classifies all underway days as operational. This model deviates from that classification by considering days spent specifically transiting from home port to operational as non-operational days as an improvement in modeling accuracy comparted to current organizational metrics. Similarly, days transiting to a planned Dry Dock availability are counted as part of that Dry Dock availability for the purposes of this study. They are not operational days, since a cutter would not deviate from a transit to a planned availability unless an extreme Search and Rescue event took place. This study sees this deviation as an improvement in accuracy from the current way of classifying underway time. However, this assumption could be updated depending on the priorities of other model users, and additional feedback collected in the stakeholder engagement process.

The SD simulation model was run 12 times per home port scenario, using 12 different stream ID's to generate different random seeds for the model elements that include stochasticity. The two data sets for the stock of Cutter Operational Days (calculated over a two-year period) were then compared. The comparison was completed using a two-tailed t-distribution for data sets with unknown or unequal variance with an α = 0.05, or a 95% confidence interval, and an n = 12. This test determines the statistical likelihood of the two data sets coming from a distribution with the same mean, given the mean and degrees of freedom of each data set. The test looks like this:

$$H_o:\ \mu_{Homeport\ A\ Cutter\ Operational\ Days} = \mu_{Homeport\ B\ Cutter\ Operational\ Days}$$

$$H_A:\ \mu_{Homeport\ A\ Cutter\ Operational\ Days} \neq \mu_{Homeport\ B\ Cutter\ Operational\ Days}$$

If the P-value generated from the T-test is smaller than α = 0.05, then it can be stated with 95% confidence that the data sets did not come from the same statistical distribution. In this case the Null Hypothesis, H_o, is rejected and the Alternate Hypothesis, H_A, is accepted. The two samples are considered different in a statistically significant way. If the P-value is larger than α = 0.05, then the two data sets are not significantly different, and the Null Hypothesis is accepted (T Test in Excel: Easy Steps with Video). The analysis between Homeport A and Homeport B is as follows:

Table 1: Statistical analysis of the number of operational days between two different home ports as show by the SD model.

	Port A	*Port B*
Mean	248.37	241.518
Variance	2.038	1.97
Standard Deviation	1.43	1.40
Observations	12	12
Hypothesized Mean Difference	0	
Df	22	
t Stat	-11.87	
P(T<=t) two-tail	4.92E-11	
t Critical two-tail	2.07	

Based on this analysis, there is a statistically significant difference between the Operational Days when a cutter is in Port A, or co-located with its maintenance hub, vs Port B, remotely located from its maintenance hub. The base model shows seven additional operational days over the two-year simulation run by removing delays associated with planned and casualty maintenance.

Viewed another way, 95% of a normally distributed data set is within two standard deviations above and below the mean. Even if the average number of days different between the two home ports was only 5.7 days, the difference would be statistically significant. Seven days of operations makes a big difference. Take it from the perspective if what the Coast Guard accomplishes every day. Every day, the U.S Coast Guard:

- conducts 45 search and rescue cases
- saves 10 lives
- saves over $1.2M in property
- seizes 874 pounds of cocaine and 214 pounds of marijuana
- conducts 57 waterborne patrols of critical maritime infrastructure
- interdicts 17 illegal migrants; escorts 5 high-capacity passenger vessels
- conducts 24 security boardings in and around U.S. ports
- screens 360 merchant vessels for potential security threats prior to arrival in U.S. ports
- conducts 14 fisheries conservation boardings
- services 82 buoys and fixed aids to navigation
- investigates 35 pollution incidents

- completes 26 safety examinations on foreign vessels
- conducts 105 marine inspections
- investigates 14 marine casualties involving commercial vessels
- facilitates movement of $8.7 billion worth of goods and commodities through the nation's maritime transportation system (A Day in the Life of the Coast Guard: Monday)

Viewed from an organizational perspective, seven days matter. Sevan days matters when compounded across every home porting decision, every ship, and every community. Seven days is statistically significant, even if it seems like a small number, it is organizationally significant too. Models are helpful tools for making decisions, but do not make decisions in place of humans. This information, along with additional information in the sensitivity analysis section and the local economics section, is important to take into account when making the final decision.

4.2 Model Validation and Verification

George Box, a British mathematician, famously stated that "all models are wrong; some models are useful" (wikiquote.org). Model validation and verification are important components of simulation modeling. Verification is defined as ensuring that assumptions are well-vetted and accurately translated into the model structure (coding, etc) (Law, 2015). Model validation is "the process of determining whether a simulation model is an accurate representation of the system for the particular objectives of the study" (Law, 2015, p.247). The initial result of the model, presented in Section 4.1, allows for final discussion of model validation. Model verification has been an iterative process throughout the study.

For this study, model verification was conducted using subject matter experts (SME) from the Coast Guard and from academia. Many Coast Guard stakeholders were interviewed, and these interviews were used to generate baseline assumptions and entering arguments. These assumptions, and the model coding used to capture them, were presented to two Coast Guard

SME's with backgrounds in deck-plate Naval Engineering, including service as Engineer Officers on Coast Guard Cutters, experience in Coast Guard engineering policy, and academic backgrounds in Electrical Engineering and Systems Engineering at the Masters level. The coding was also vetted from a modeling, coding and logic perspective. The SME's reviewed the model logic, coding, and translation of assumptions into modeling. Their feedback was integrated through several model iterations. The final model is verified from the perspective of the three SMEs. It accurately captures real-world trade-offs, such as cutter planned maintenance days diminishing when too much unplanned maintenance prevents the ship from meeting operational goals; such as deferred maintenance eventually translating into casualties and unplanned maintenance; such as time of year and weather conditions impacting the speed at which a cutter can transit to an operational area. For example, a cutter transiting at average speeds of 20kts will lose two days of transit time over two years compared to a cutter transiting at 24kts. A cutter experiencing an average delay in receiving tools and contracting support of 1.5 days will have 14 more operational days over a two-year period than a cutter experiencing an average support delay of 5 days. These trade-offs, demonstrated by the model, are validated by Coast Guard SMEs.

For model validation, it is necessary to have historical data with which to compare model results and ensure the model is accurately capturing past scenarios. This is a good indicator of the model's ability to predict future outcomes with a useful level of accuracy. In this situation, the Coast Guard Fast Response Cutter is a relatively new platform. Limited historical data is available. This model is based on a generic Coast Guard goal of an approximate 50/50 split between maintenance days and operational days per cutter per year. In an ideal world, cutters would experience 182.5 days of each per year, or 365 total operational days in a two-year period. The numbers returned by this model are significantly lower than this ideal.

The highest number of operational days output by the base model over a two-year period is 248 days, or 124 operational days per year. Data for the FRC class spans from August of 2017 to January of 2019. In this time, 32 hulls were surveyed. The fleet averaged 181.2 days per year of operational days. This is a significant difference between the days predicted by the model and the days averaged by the fleet in real time over the 18 months during which data has been collected. There are two primary reasons for the difference between the model and the fleet-wide data.

First, the model makes a few assumptions that are slightly different from current Coast Guard metrics. These differences are the assumption that days transiting to an operational area do not count as operational days (because a cutter would not be tasked with an operational mission during this transit). Cutters transit days to a planned depot maintenance availability (a dry dock or major dockside) are also not counted towards operational days. While the cutter is capable of operating during these times, operations are not the cutter's primary task. In this way, the model strives to represent actual on-scene operational days between the cutter's two potential home ports. Removing these two assumptions from the model, and running the simulation based on current Coast Guard metrics, results in a model high of 140 operational days per year. This is still 20% lower than shown by the actual data. It is reasonable to conclude that the model is more conservative in its operational day metrics than the data the Coast Guard currently maintains.

The second major difference is that the fleet wide data only captures when the cutters are fully mission capable, or AVAILABLE for operations. The model tallies actual operational days based on days taken for maintenance, both planned and unplanned. It is possible that a cutter is fully mission capable but is tied to the pier for planned maintenance. For example, completing oil and filter changes on main engines. This would not be reflected in the fleet wide data. It is reasonable to assume that this difference in tracking results in close to the 20% difference between the model predicted operational days and the operational days reflected in data.

Finally, it is reasonable that the model is not a perfect predictor of operational days. Model assumptions need to be worked into equations, and so will always lack the granularity of real-world data. The model predicts a 2.7% difference in operational days between a cutter co-located with its maintenance hub and a cutter located remotely. This is 9.8 days per year if applied to a 365-day calendar. While the model may not predict exact numbers with perfect accuracy, it predicts trends that are important to consider when making a home parting decision. These trends are confirmed by SMEs who validated the model's ability to accurately capture behavior. There is room to continue refining equations and assumptions to better predict real world numbers.

An additional important component of model validation and verification is to continually return to the goals and analysis set out in the Goal Development phase of the Systems Analysis process. Since systems engineering is iterative, revisiting this discussion is imperative to creating a valid, verified model.

The Systems Analysis process and the goal development phase of this study resulted in a general question for the project, several model element performance indices, and a list of detailed performance indices for the final model. All need to be reviewed now that the first iteration of the project and the SD model are completed.

The general question posed is: Can dynamic system modeling be used to do a port-to-port comparison and so support the Coast Guard in making rational, quantifiable cutter home porting decisions? The answer is yes. SD modeling can be used to complete a port-to-port comparison, including different simulation runs with stochasticity and a statistical analysis to determine if the results for the different home ports show a significant difference. This can support the Coast Guard in making rational and quantifiable home porting decisions both with the model results and with the stakeholder engagement and assumption vetting process that goes into making a useful SD model.

The three PIs for model elements are:

- Is this element a priority for the stakeholder(s)?
- Is this element supported by data?
- Is this element relevant and appropriate to the system goals and system boundaries?

Of the elements selected for the final SD model, all were either a priority for the primary stakeholder or necessary to effectively calculate elements that were a priority for the Coast Guard. All were supported by actual data or assumed relationships. Some of the assumed relationships have potential to be supported by actual data in the future. All of the elements were relevant and appropriate to the system goals and boundaries.

A series of detailed PIs were identified during the System Analysis phase of the project. In order to keep the SD model simple enough to be useful, several of these detailed PIs were dropped as inappropriate to the final model. Of the remaining, applicable PIs, all were effectively satisfied:

- Does the model quantify cutter response time? Yes, transit speed and distance.
- Does the model quantify cutter underway time? Yes, operational days.
- Does the model quantify planned and unplanned ship down time? Yes, planned and unplanned maintenance.

- Does the model quantify man hours required for maintenance? Model quantified maintenance in days.
- Is the information presented valued by stakeholders? Yes, focuses on total operational days.
- Is the information presented easy to interpret and understand? Yes, through documentation of model assumptions, coding and equations.
- Is the information presented such that it can easily be compared between scenarios? The information can be presented clearly between scenarios. Running multiple scenarios is time intensive because of the software used for the simulation.

Through the system analysis process and the iterations of developing the SD model, limitations relevant to two of the original PIs were determined:

- Does the model quantify cost of maintenance? No, removed to keep model simple. The Coast Guard keeps comprehensive coast records that can be applied to operational days, maintenance days and deferred maintenance day projections from the model.
- Does the model quantify local economic impacts? No, removed to keep model simple and analyzes separately. While local economic impacts are an important component of the final homeport decision, inclusion in the actual SD model overcomplicated the model to the point of making it less useful and accurate.

One of the major pitfalls in SD modeling is making models so complex with boundaries so expansive that they do not effectively capture the behavior of the system. These two factors were removed from the SD model to keep the model simple and effective and were instead set aside for separate discussion. Overall the system analysis process was effective in identifying goals and P's to support those goals. The project effectively worked towards the big picture goal while meeting relevant PI's and intentionally removing PI's as they became irrelevant.

4.3 Sensitivity Analysis: An Opportunity for Stakeholder Engagement

Sensitivity analysis is the practice of holding all components of a model equal except for one, varying that one element, and seeing if it has an impact on the outcome of the model. In this model, all assumptions were assessed using a sensitivity analysis except elements based on actual data. The elements assessed via sensitivity analysis were: number of months spent in Dry Dock availability, range of random unplanned maintenance days, the number of unplanned maintenance days added by accumulated deferred maintenance , the mean distance-to-hub multiplier distribution, cut-off days when deferred maintenance becomes unplanned maintenance, the distance to the operational area, the cutter transit speed, and the minimum number of maintenance days needed per month when a cutter is operating minimally (for example, if a cutter is tied to the pier, it still needs five maintenance days that month. If it operates for five days, it needs five maintenance days that month. Once it operates for ten days, it requires seven maintenance days, with increasing maintenance needs as operational hours increase. This variable is the base number of maintenance days needed regardless of operational hours). Of these elements, several showed no difference in operational days per month. Of the ones that showed a difference in maintenance days when varied over a range of values, a paired t-test was conducted to determine if the effect on the final operational days was statistically significant.

The paired t-test was conducted on the simulation for Port B only, since the model has more variable elements when the cutter is located remotely from its maintenance hub. The test was conducted with 12 simulation runs using different Stream ID's to introduce stochasticity to the elements of the model that include error. The following elements are statistically significant to the outcome of the model when varied over a series of reasonable values: number of months in Dry Dock availability, range of random unplanned maintenance days, mean distance-to-hub multiplier distribution, distance to the operational area, cutter transit speed, and minimum number of maintenance days needed per month when a cutter is operating minimally. Of these elements, the range of random unplanned maintenance days and the distance to the operational area had the most significance. The transit speed had the least significance. Detailed statistical calculations can be found in Appendix C.

Table 2: Summary of model elements and their statistical significance.

Element	Range	Statistical Significance (Y/N)
Length of Planned Dry Dock	1 month to 4 months	Y
Max of error applied to Casualty Maintenance Days/month	3 days to 15 days	Y
# of casualty days added when deferred maintenance reaches a critical threshold	5 days to 15 days	N
Mean of the tool and contractor delay caused by a ship being remote from its maintenance hub	1.5 days to 5 days	Y
Critical value of deferred maintenance, when it translated to unplanned maintenance	30 days to 120 days	N
Distance to operational area	200nm to 500nm	Y
Transit speed	18kts to 28kts	Y
Minimum maintenance needed during minimal operation time	3 days to 8 days	Y

The most important component of this sensitivity analysis is the opportunity for stakeholder engagement and assumption validation. The elements listed above have a significant impact on the model outcome, and therefore are the best place to start with respect to having conversations with stakeholders about their experiences, assumptions and understandings of these elements. Having a list of significant elements, their ranges, and the manner in which they are implemented is a very detailed and thorough way to start a conversation that ultimately gets a diverse room full of stakeholders aligned in how a system works. In simulation modeling, this is called keeping a written assumptions document and conducting a structured walk through. Both of these tools are critical to ensuring accurate, useful simulations. The structured walk through has everyone with an interest in a working model in the same room and walks through the process of validating and assessing each assumption in the model. In this way, a group of stakeholders and SMEs apply their collective knowledge to the model to make it as accurate as possible (Law, 2015). At the same time, it provides an opportunity for surfacing the assumptions and priorities of stakeholders and working through those assumptions until all parties have a mutual understanding of the situation and the priorities. This process is as beneficial as the model itself.

4.4 Local Economic Impact

Local economic impact is assessed by comparing the financial benefit of a Coast Guard crew in a community to the overall economics of that community. Because of the complexities of modeling economies, this question was not included in the SD model. Economic impact is an independent consideration, and one generally prioritized by stakeholders outside the Coast Guard. For these reasons, it was not necessary or helpful to include it in the SD model. It is, however, an important comparison topic that warrants discussion. In this port-to-port comparison, Port A uses the economics of Ketchikan, AK and Port B uses the economics of Sitka, AK. An FRC crew consists of 24 personnel ranging in rank from E-2 to 0-4. Each crew member comes with a steady pay check and a housing allowance (calculated at two different rates, with and without dependents). For this analysis, it was assumed that 1/3 of the crew had dependents (spouses and/or children) and received housing allowance for the community calculated with dependents.

Coast Guard members are valuable assets for communities. In additional to bringing high paying jobs to small communities, Coast Guard spouses are often looking for work and contribute to the local economies. Coast Guard families bring children to sometimes underenrolled school systems, helping bolster small community schools. Housing allowances increase demand for buying and renting homes. All of these factors contribute to the stability of small economies. That being said, 24 jobs are a small number of jobs, even for small communities. Below is a comparison of the relative contribution of an FRC crew, 24 people, in Ketchikan, AK and Sitka, AK.

Table 3: Comparison of the Coast Guard's economic impact in Ketchikan, a home port where a cutter is co-located with its maintenance hub, vs. Sitka, where the cutter is remotely located from its maintenance hub (U.S Census Bureau, 2017) (Fried, 2019).

Element	**Port A – Ketchikan**	**Port B – Sitka**
Annual economic contribution	$1,411,488	$1,479,540
$/Coast Guard member	$61,369	$64,327
Income Per Capita (2017)	$65,034	$65,745
Total Revenue in Community (2017)	$901,111,104	$571,258,305
% Community Revenue contributed by CG members	0.15%.	0.25%.
Average annual income (2017)	$45,828	$43,488
CG member pay as percentage of average annual income	134%	$148%
Population (2017)	13,856	8,689
% of population contributed by 24-person crew	0.17%	0.28%

Given this analysis, stationing an FRC in Sitka has a greater economic impact for the local community than stationing an FRC in Ketchikan. The Sitka crew contributes 0.28% of the local economy, compared to a 0.17% contribution to the Ketchikan economy. This must be weighed against the model output of 7 additional operational days per year gained from stationing the ship in Ketchikan, co-located with the maintenance hub. As discussed in section 4.3, this value can be refined by increasing stakeholder engagement and model validation, then continuing to evaluate the need for more operational days against the Coast Guard's contribution to local economies.

4.5 EMERGENT BEHAVIOR

Emergence is the idea that systems exhibit behavior that cannot be predicted by analyzing the system components alone. SD modeling has some capacity to predict emergence, including showing the behavior over time of different system elements. Mapping this behavior can often provide insights into the behavior of the system that would otherwise be invisible. In this study, the behavior over time of several variables is noteworthy and offers insights into how system dynamics play into cutter operation time and cutter maintenance time. This behavior is not obvious and the potential of predicting it is a distinct benefit of SD modeling.

The final SD model for completing a port to port comparison to aid the CG CHDP does not express any surprising emergent behavior. It does capture behavior over time of key rates such as operational days per month, maintenance days per month and deferred maintenance days per month. It captures important relationships such as the need for increasing maintenance based on increasing cutter operations, and also the ability of the Coast Guard to cancel planned maintenance days in favor of operational days if operational days get too low. Some of the most telling outcomes of the model are the elements that are and are not significant to increasing operational days. This gives decision makers a place to focus and strive to reduce the delays that take away from operational days while putting less time towards those elements that have minimal impact. These behaviors are interesting and dynamic, and shed light on the way the system operates.

Using an SD model for side by side comparison between two potential Coast Guard cutter home ports provides interesting insights, new opportunities for stakeholder engagement, and quantitative inputs to compare how the decision impacts local economics. The model designed and executed in this study does show a statistically significant difference between a cutter's total operational days when home-ported at its maintenance facility vs when it is home ported remotely. This is based on data and assumptions for the type of ship, the locations of the home ports relative to the operational areas, and other delay factors for both maintenance and operations.

One of the key take-aways from the model and the modeling process is the opportunity to engage with stakeholders and SMEs in a model-vetting process that surfaces everyone's assumptions and priorities and works towards aligning them. This results in both a better, more useful model and also facilitates a conversation that helps Coast Guard leadership better understand the needs of the diverse group of stakeholders impacted by the decision. Going through this process then also provides relevant, quantitative information to support a home porting decision in the best interest of the Coast Guard.

Chapter 5: Results, Conclusions and Additional Research

This study is essentially the first iteration of an SD model to support the Coast Guard CHDP. This study used several sets of stakeholder interviews, data from two potential home port options, SME verification, and a series of assumptions used to capture the interplay of model elements as effectively as possible. The study generated compelling results and conclusions as well as a wide range of opportunities for future work and refinement.

5.1 Results

The results of this study show that an SD model comparing two potential Coast Guard cutter home porting options, one co-located with a maintenance hub and one remote from the maintenance hub, do project statistically significant differences in total operational days. The cutter home ported with the maintenance hub has more operational days per year than the cutter that is remote from the maintenance hub. This is important because the Coast Guard values operational days during which assets are executing the mission. Any delays or detractions from operational days takes away from mission execution.

The goal of using an SD model was to quantify information to improve stakeholder engagement and validate assumptions. The SD process, when applied effectively, provides a powerful tool for stakeholder engagement. The base model has several elements that are statistically significant to the model outcome, and therefore are the perfect starting point to work on stakeholder validation and agreement of parameters and modeling methods. This process allows stakeholders to voice assumptions and then work through those assumptions such that the model represents a reality that all stakeholders agree upon. This process provides the dual benefit of stakeholder alignment and more accurate, useful modeling.

Local economic impact is an important component of deciding where a cutter gets homeported. Using basic economic metrics and comparing the income brought to a community by a Coast Guard crew is a good starting point for quantifying economic impact. This, when combined with quantifiable data coming out of an SD model, provide metrics which can be compared and balanced when making the final home porting decision.

Based on the SD model, this study recommends co-location of the cutter with its maintenance hub. This is represented by Port A in the model. Colocation of the cutter with its maintenance hub eliminates the elements that have the largest negative impact on operational days. Colocation with the maintenance hub prioritizes cutter maintenance so that cutters are operational for more days of any given year. In this port-to-port comparison, locating the cutter remotely has a larger impact on that local economy. However, both communities are small towns that benefit from an influx of jobs that pay better than average. The impact to the total local economy only changes by 0.11% between the two home port options. Given the importance of operational days to effectively completing the Coast Guard mission, maximizing operational days is the priority. Maximum operational days are achieved by co-locating a cutter with its maintenance hub.

The Systems Analysis process carried out using SD modeling is a dynamic and iterative process. While this study had strong verification throughout the process, the model validation against historic data was not strong. This shows room both for more accurate data gathering moving forward, and the opportunity to refine the model assumptions to align more closely with historical data. These potential iterations and improvements are discussed further in section 5.3, additional research opportunities.

5.2 ADDITIONAL RESEARCH OPPORTUNITIES

As a start to the SD modeling process for the CG CHDP, this study leaves myriad opportunities for additional research and ways to improve and expand the model. First, the CG CHDP lays out a series of priorities in addition to the operation and maintenance of cutters. This includes resilience in the event of an earthquake, tsunami or other major natural disaster. Adding resilience planning and natural disaster recovery into an SD model (most likely a stand-alone model from the one presented in this study) would be an interesting and valuable interdisciplinary project that would shed light on areas of risk associated with home porting decisions.

Another opportunity for interdisciplinary SD modeling work is to include local economics and the Coast Guard's impact on them. The current study did not have the expertise to effectively and accurately incorporate complex economics into the SD model. However, many modelers and academics work in this arena and stand to add great benefit to this study. Similarly, an interdisciplinary team focused on including costs of maintenance and operations in the SD model would provide valuable insight for future decision making.

This study also proposes an intense stakeholder engagement process for future Coast Guard SD modeling work. Another iteration of this SD model, using the process of maintaining an assumptions document and conducting structured walk-throughs with high level stakeholders, would be an interesting follow up. This process would definitely result in updated assumptions that would change how this model is coded and how it behaves. This level of refinement would create a model with high level stakeholder buy-in and allow the model to have even greater usefulness and impact on Coast Guard decision making. Along similar lines, working more closely with both operational and engineering community stakeholders to refine the parts of the model using real data (such as distance to operational areas, effective operational speeds, and at what point deferred maintenance starts becoming unplanned maintenance) would lend an additional level of accuracy to the current model.

5.3 Conclusion

The system analysis process applied to an SD model to analyze two homeport options for Coast Guard Fast Response Cutters proved effective. The model was designed through an iterative process that involved generalizing the question, stakeholder engagement, understanding the current homeport decision process, understanding improvements that would benefit the process, analyzing alternatives and designing the model. Through this process, the model scope narrowed to ensure an effective, relevant model. The primary output of the model is the number of actual cutter operational days over a two-year period. This metric is the critical factor needed for the Coast Guard to execute the mission. The study determined that there is a statistically significant difference between the number of operational days executed by a cutter that is co-located with its maintenance hub compared to one that is located remotely. The cutter co-located with its maintenance hub has more operational days per year. The model was verified and validated by SMEs and preliminary Coast Guard data. The model could be more accurate with more involved stakeholder engagement and vetting of assumptions. This stakeholder engagement process is an additional benefit of the systems analysis process and an area where creating and vetting an SD model stands to dramatically improve the information flowing through the Coast Guard Homeporting Decision Process.

The final SD model provides interesting insights for a port to port comparison for locating a new Coast Guard FRC. The current model uses data and assumptions verified by a small group of SMEs. The current model meets the goals and PIs established by the initial systems analysis process. The model focuses on the top two priorities of the CG CHDP without diving into other priorities called out in the process. The model could improve accuracy by working with better real-world data, engaging with a wider range of high-level stakeholders, and expanding to work with interdisciplinary teams to better capture impact on economics.

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APPENDIX A: MODEL ELEMENT ANALYSIS

The Model Element Analysis is a component of the Systems Analysis process. Model elements were generated from interviews with stakeholders and review of the Coast Guard's current home porting decision process. The different elements were then reviewed from the perspective of three key stakeholders and rated against the indices of performance (IP) for the system. Elements that rated high for each stakeholder group were retained for the final model. The IP's for this analysis are:

IP A: Is this an element a priority for the stakeholder(s)? Primary stakeholders are (1) Coast Guard leadership (2) Coast Guard members at the operational level (3) Community members and community political leadership.

IP B: Is the element supported by data?

IP C: Is the element relevant and appropriate to the system goals and system boundaries?

Model elements reviewed from the perspective of Coast Guard Headquarters

Element Rating Scale		
IP A	**IP B**	**IP C**
0 = not a priority		
1 = valuable	1 = no	1= no
2 = top priority	2 = yes	2 = yes

	A	B	C	Total Score (high score = most important)			
Operations Elements							
Distance to regular patrol areas	1	2	2	5			Score of 4-6
Distance to high SAR areas	1	2	2	5			Score of 2-3
# of Operational Cutters	2	2	2	6			
Transit time to regular patrol areas	2	2	2	6			

Transit time to regular SAR areas	2	2	2	6			
Cost of transit at speed	1	2	2	5			
# of rescues	2	2	2	6			
# of boardings	2	2	2	6			
# of DAFHP	2	2	2	6			
Engineering Elements							
# of Operational Cutters	2	2	2	6			
Casualty response time	2	2	2	6			
Casualty repair time	2	2	2	6			
Routine Maintenance travel time	1	2	2	5			
Routine maintenance execution time	2	2	2	6			
Geographic distance between cutter and maintenance hub	1	2	2	5			
Availability of tools	1	2	2	5			
Availability of contractors	1	1	2	4			
cost of contractors	1	1	2	4			
cost of maintenance travel	1	2	2	5			
cost of maintenance	2	2	2	6			
Economic Elements							
# of CG members stationed in a community	0	2	2	4			
housing required for CG members	1	2	2	5			
cost of rent	1	2	1	4			
cost of homes	1	2	1	4			
unemployment	0	2	1	3			
strength of the economy	0	1	1	2			
school enrollment	0	2	1	3			
Other CG Elements							
Cost of infrastructure improvements	2	2	2	6			

Number of additional maintenance billets needed	2	2	2	6			
CG to Community relationship	1	1	1	3			
CG command climate	1	1	1	3			
CG access to prof dev and mentorship	1	1	1	3			
Law Enforcement relationship with community	0	1	1	2			

Model elements reviewed from the perspective of Coast Guard members at the operational level

IP A: Is this an element a priority for the stakeholder(s)? Primary stakeholders are (1) Coast Guard leadership (2) Coast Guard members at the operational level (3) Community members and community political leadership.

IP B: Is the element supported by data?

IP C: Is the element relevant and appropriate to the system goals and system boundaries?

Element Rating Scale		
IP A	**IP B**	**IP C**
0 = not a priority		
1 = valuable	1 = no	1= no
2 = top priority	2 = yes	2 = yes

	A	B	C	Total Score (high score = more important)			
Operations Elements							
Distance to regular patrol areas	2	2	2	6			Score of 4-6
Distance to high SAR areas	2	2	2	6			Score of 2-3
# of Operational Cutters	2	2	2	6			
Transit time to regular patrol areas	1	2	2	5			
Transit time to regular SAR areas	1	2	2	5			
Cost of transit at speed	1	2	2	5			
# of rescues	2	2	2	6			

# of boardings	2	2	2	6			
# of DAFHP	2	2	2	6			
Engineering Elements							
# of Operational Cutters	2	2	2	6			
Casualty response time	2	2	2	6			
Casualty repair time	2	2	2	6			
Routine Maintenance travel time	2	2	2	6			
Routine maintenance execution time	2	2	2	6			
Geographic distance between cutter and maintenance hub	2	2	2	6			
Availability of tools	2	2	2	6			
Availability of contractors	2	1	1	4			
cost of contractors	1	1	1	3			
cost of maintenance travel	1	2	2	5			
cost of maintenance	1	2	2	5			
Economic Elements							
# of CG members stationed in a community	2	2	2	6			
housing required for CG members	2	2	2	6			
cost of rent	2	2	1	5			
cost of homes	2	2	1	5			
unemployment	1	2	1	4			
strength of the economy	1	1	1	3			
school enrollment	1	2	1	4			
Other CG Elements							
Cost of infrastructure improvements	0	2	2	4			
Number of additional maintenance billets needed	2	2	2	6			

CG to Community relationship	2	1	1	4			
CG command climate	2	1	1	4			
CG access to prof dev and mentorship	2	1	1	4			
Law Enforcement relationship with community	2	1	1	4			

Model Element Analysis from the perspective of community members and community political entities.

IP A: Is this an element a priority for the stakeholder(s)? Primary stakeholders are (1) Coast Guard leadership (2) Coast Guard members at the operational level (3) Community members and community political leadership.

IP B: Is the element supported by data?

IP C: Is the element relevant and appropriate to the system goals and system boundaries?

Element Rating Scale		
IP A	**IP B**	**IP C**
0 = not a priority		
1 = valuable	1 = no	1= no
2 = top priority	2 = yes	2 = yes

	A	B	C	Total Score (high score = more important)			
Operations Elements							
Distance to regular patrol areas	1	2	2	5			Score of 4-6
Distance to high SAR areas	1	2	2	5			Score of 2-3
# of Operational Cutters	2	2	2	6			
Transit time to regular patrol areas	1	2	2	5			
Transit time to regular SAR areas	1	2	2	5			
Cost of transit at speed	0	2	2	4			
# of rescues	2	2	2	6			
# of boardings	2	2	2	6			
# of DAFHP	1	2	2	5			

Engineering Elements							
# of Operational Cutters	2	2	2	6			
Casualty response time	1	2	2	5			
Casualty repair time	1	2	2	5			
Routine Maintenance travel time	0	2	2	4			
Routine maintenance execution time	0	2	2	4			
Geographic distance between cutter and maintenance hub	0	2	2	4			
Availability of tools	0	2	2	4			
Availability of contractors	2	1	1	4			
cost of contractors	2	1	1	4			
cost of maintenance travel	1	2	2	5			
cost of maintenance	0	2	2	4			
Economic Elements							
# of CG members stationed in a community	2	2	2	6			
housing required for CG members	2	2	2	6			
cost of rent	2	2	1	5			
cost of homes	2	2	1	5			
unemployment	2	2	1	5			
strength of the economy	2	1	1	4			
school enrollment	2	2	1	5			
Other CG Elements							
Cost of infrastructure improvements	2	2	2	6			
Number of additional maintenance billets needed	1	2	2	5			
CG to Community relationship	2	1	1	4			
CG command climate	0	1	1	2			
CG access to prof dev and mentorship	0	1	1	2			

Law Enforcement relationship with community	2	1	1	4			

The final model element analysis is a combination of all the elements that rated four or higher by at least two out of three stakeholder groups. The final SD model uses these elements, either specifically or generically, to model system behavior. Elements that could not fit into the SD model exactly are included in the study as additional discussion points.

Final Model Elements

(red)	2 out of 3 stakeholders rate 2 or 3		
(green)	2 out of 3 stakeholders rate 4-6		
Operations Elements			
Distance to regular patrol areas			
Distance to high SAR areas			
# of Operational Cutters			
Transit time to regular patrol areas			
Transit time to regular SAR areas			
Cost of transit at speed			
# of rescues			
# of boardings			
# of DAFHP			
Engineering Elements			
# of Operational Cutters			
Casualty response time			
Casualty repair time			
Routine Maint travel time			
Routine maint execution time			
Geographic distance btwn cutter and maint hub			
Availability of tools			
Availability of contractors			

cost of contractors			
cost of maint travel			
cost of maintenance			
Economic Elements			
# of CG members stationed in a community			
housing required for CG members			
cost of rent			
cost of homes			
unemployment			
strenght of the economy			
school enrollment			
Other CG Elements			
Cost of infrastructure improvements			
Number of additional maint billets needed			
CG to Community relationship			
CG command climate			
CG access to prof dev and mentorshio			
Law Enforcement relationship with community			

APPENDIX B: FINAL MODEL AND MODEL CODE

The final model is created in VensimPLE, a version of Vensim modeling software that is free for academic use. The model is a stock and flow diagram designed to output total actual Operational days, Maintenance Days and Deferred Maintenance Days over a two-year period. The elements, equations and actual code for each are shown in the table below. A visual of the final stock-and-flow diagram is at the end of this appendix.

<table>
<tr><th>Element name, type and designator</th><th>Element equation</th><th>Code in Vensim</th></tr>
<tr><td>Distance to operational area, auxiliary variable, DOA

Units = Nautical Miles
t = months</td><td>$$= \begin{cases} 300 + \varepsilon, & 0 \le t < 4 \\ 100 + \epsilon, & 4 \le t < 8 \\ 300 + \varepsilon, & 8 \le t < 12 \\ 100 + \varepsilon, & 12 \le t < 16 \\ 300 + \varepsilon, & 16 \le t < 20 \\ 100 + \varepsilon, & 20 \le t < 24 \end{cases}$$
$\varepsilon \sim (N|25,25)$</td><td>RANDOM NORMAL(0 , 50 , 25 , 25 , 0)+STEP(300,0)-STEP(200,4)+STEP(200,8)-STEP(200,12)+STEP(200,16)-STEP(200,20)+STEP(200,24)</td></tr>
<tr><td colspan="3">DOA assumptions: This variable can be modified to accurately reflect a ship's operational area and transit distances. The current coding captures seasonality and variable area assignments.</td></tr>
<tr><td>Transit speed, auxiliary variable, TS

Units = speed in knots
t = months</td><td>$$= \begin{cases} 20 & 0 \le t < 4 \\ 25 & 4 \le t < 10 \\ 20 & 10 \le t < 1 \\ 25 & 16 \le t < 22 \\ 20 & 22 \le t < 24 \end{cases}$$</td><td>STEP(20 , 0)+STEP(5,4)-STEP(5,10)+STEP(5,16)-STEP(5,22)</td></tr>
<tr><td colspan="3">TS assumptions: This variable can be modified to accurately reflect the ship's operational speeds. The current coding captures seasonality of weather conditions that can affect speed.</td></tr>
<tr><td>Transit time, auxiliary variable, TT

Units = Days/Trip</td><td>$$= \frac{DOA \times TS}{24}$$</td><td>(distance to op area/transit speed)/24</td></tr>
<tr><td>Trips per Month,</td><td>= Constant</td><td>2</td></tr>
</table>

<table>
<tr><td>auxiliary variable, TPM

Units = Trips/Month</td><td></td><td></td></tr>
<tr><td colspan="3">TPM assumptions: This variable can be changed to reflect different operational profiles and schedules</td></tr>
<tr><td># of transit days per month, auxiliary variable, TDM

Units = Days/Month</td><td>$= TPM \times TT$</td><td>transit time to op area*"trips/mo"</td></tr>
<tr><td># of Operational Days per Month, rate, ODM

Units = Days/Month</td><td>$= \begin{cases} 0 & MD \geq 30 \\ 31 - TDM - MD & MD < 30 \end{cases}$</td><td>IF THEN ELSE("actual # of maintenance days/mo">=30 , 0 , (31-"# of transit days/mo"-"actual # of maintenance days/mo"))</td></tr>
<tr><td colspan="3">ODM Assumptions: When a cutter is in a depot maintenance period (planned dry dock) there are no operational days that month. When a cutter is operating, operational days are total days per month minus days used for maintenance and days transiting to the operational area.</td></tr>
<tr><td>Operational days, stock, OD

Units = Days</td><td>$OD(t) = \int_0^{24} (ODM) dt$</td><td>INTEG("# of operational days/mo")</td></tr>
<tr><td>Planned Maintenance Trips per Month, auxiliary variable, PMTM

Units = Trips/Month</td><td>$= \begin{cases} 0.5 & \frac{OD}{1+t} \leq 10 \\ 0.83 & \frac{OD}{1+t} > 10 \end{cases}$</td><td>IF THEN ELSE(("# of operational days"/(1+Time))<=10, 0.5, 10/12)</td></tr>
<tr><td colspan="3">PMTM Assumptions: If operational days start dropping below an average of 10 days per month, planned maintenance trips are cut down to once every two months. As long as</td></tr>
</table>

<table>
<tr><td colspan="3">operational days remain above 10 per month on average, the intended schedule of 10 trips per year, or 10/12 = 0.83, is maintained. The 1+t in the denominator is to prevent a “divided by zero” error in the model.</td></tr>
<tr><td>Travel Delays, auxiliary variable, TD

Units = Days/Trip</td><td>$= \begin{cases} 1+\varepsilon & \mathit{in\ January\ and\ November} \\ 0.5+\varepsilon & \mathit{in\ all\ other\ months} \end{cases}$
$\varepsilon \sim (N|1.25,1)$</td><td>RANDOM NORMAL(0.75, 1.25 , 1 , 1 , 0)-STEP(0.5, 2)+STEP(0.5,11)-STEP(0.5,12)+STEP(0.5,13)-STEP(0.5,14)+STEP(0.5,23)-STEP(0.5,24)</td></tr>
<tr><td colspan="3">TD assumptions: This delay information is based on actual travel delays calculated between Ketchikan, AK (maintenance hub) and Sitka, AK (remote port) airports. This section needs to be modified to specifically reflect travel delay numbers between two ports being comparted.</td></tr>
<tr><td>Base travel time, auxiliary variable, BTT

Units = Days/Trip</td><td>= Constant</td><td>0.5</td></tr>
<tr><td colspan="3">BTT assumptions: The base travel time between Ketchikan, AK (maintenance hub) and Sitka, AK (remote port) is half a day. This section needs to be modified to specifically reflect travel delay numbers between two ports being comparted.</td></tr>
<tr><td>Unplanned Trips per Month, auxiliary variable, UTM

Units = Trips/Month</td><td>$= \begin{cases} 2 & DM > 30 \\ 0 & DM \leq 30 \end{cases}$</td><td>IF THEN ELSE("# of differed maintenance days">30, 2, 0)</td></tr>
<tr><td colspan="3">UTM assumptions: When deferred maintenance (DM) reaches a certain level, in this case set to an accumulated stock of 30 days, it translated into unplanned maintenance. This model is set to add two unplanned maintenance days per month once a stock of 30 deferred maintenance days is reached. This assumption is a good place to work towards stakeholder engagement and alignment.</td></tr>
<tr><td>Distance to maintenance hub multiplier, auxiliary variable, DMHM</td><td>$\varepsilon \sim (N|2.5,2.5)$</td><td>RANDOM NORMAL(0, 5 , 2.5 , 2.5 , 0)</td></tr>
</table>

<table>
<tr><td>Units =
Days/month</td><td></td><td></td></tr>
<tr><td colspan="3">DMHM assumptions: This error term captures delays caused by the distance between a cutter and its maintenance hub. It is specifically applied to delays in getting tools and contractors on site for unplanned maintenance. It is set around a standard work week, with a minimum delay of zero days and a maximum delay of five days on a normal distribution.</td></tr>
<tr><td>Contractor delays, auxiliary variable, CD

Units =
Days/Month</td><td>$= 1 \times DMHM$</td><td>1*distance to maint hub multiplier</td></tr>
<tr><td colspan="3">CD assumptions: when a ship is located remotely, there will be delays in getting contractor assistance to work on unplanned repairs.</td></tr>
<tr><td>Tool delays, auxiliary variable, TLD

Units =
Days/Month</td><td>$= \frac{DMHM}{2}$</td><td>distance to maint hub multiplier/2</td></tr>
<tr><td colspan="3">TLD assumptions: Special tools will have to be shipped from a maintenance hub to a remote location. This will incur delays, though shipping logistics are strong in most locations, making this variable set to half the DMHM delay length.</td></tr>
<tr><td>Unplanned travel time, auxiliary variable, UPTT

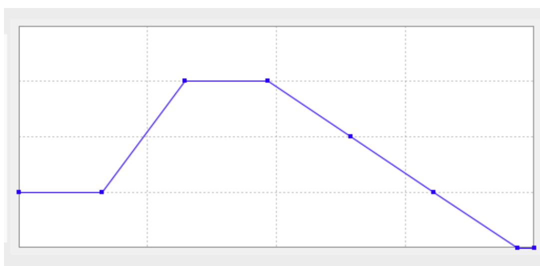
Units =
Days/Month</td><td>$= (BTT + TD) \times UTM$</td><td>("base travel time days/trip"+"travel delays days/trip")*unplanned trips per month</td></tr>
<tr><td>Unplanned Maintenance Days per Month, rate, UM

Units =
Days/Month</td><td>$= \begin{cases} 5 + UPTT + TLD + CD + \epsilon & DM > 30 \\ 0 + \varepsilon & DM \leq 30 \end{cases}$
$\varepsilon \sim (N|3.5,3,5)$</td><td>RANDOM NORMAL(1, 7 , 3.5 , 3.5 , 0)+(IF THEN ELSE("# of differed maintenance days">30, 5+"unplanned travel time days/mo"+"contractor delays days/mo"+"tool delays days/mo" , 0))</td></tr>
<tr><td colspan="3">UM assumptions: The rate of unplanned maintenance has a base level captured by ε, which is a normal distribution centered on a seven-day week. When the total stock of deferred maintenance goes over 30 days, an additional five days of unplanned maintenance is added per month. This is a good assumption to vet during the stakeholder engagement process.</td></tr>
</table>

<table>
<tr><td>Planned travel delays, auxiliary variable, PTD

Units = Days/Month</td><td>$= PMTM \times TD$</td><td>"Planned Maint Trips/mo"*"travel delays days/trip"</td></tr>
<tr><td>Average operational days, auxiliary variable, AOD

Units = Days/month</td><td>$= \frac{OD}{1 + t}$</td><td>"# of operational days"/(1+Time)</td></tr>
<tr><td colspan="3">AOD assumptions: This variable is needed to use a Lookup function to capture the relationship between needed maintenance days and cutter operational days.</td></tr>
<tr><td>Average operational days to maintenance conversion, auxiliary variable, AODMC

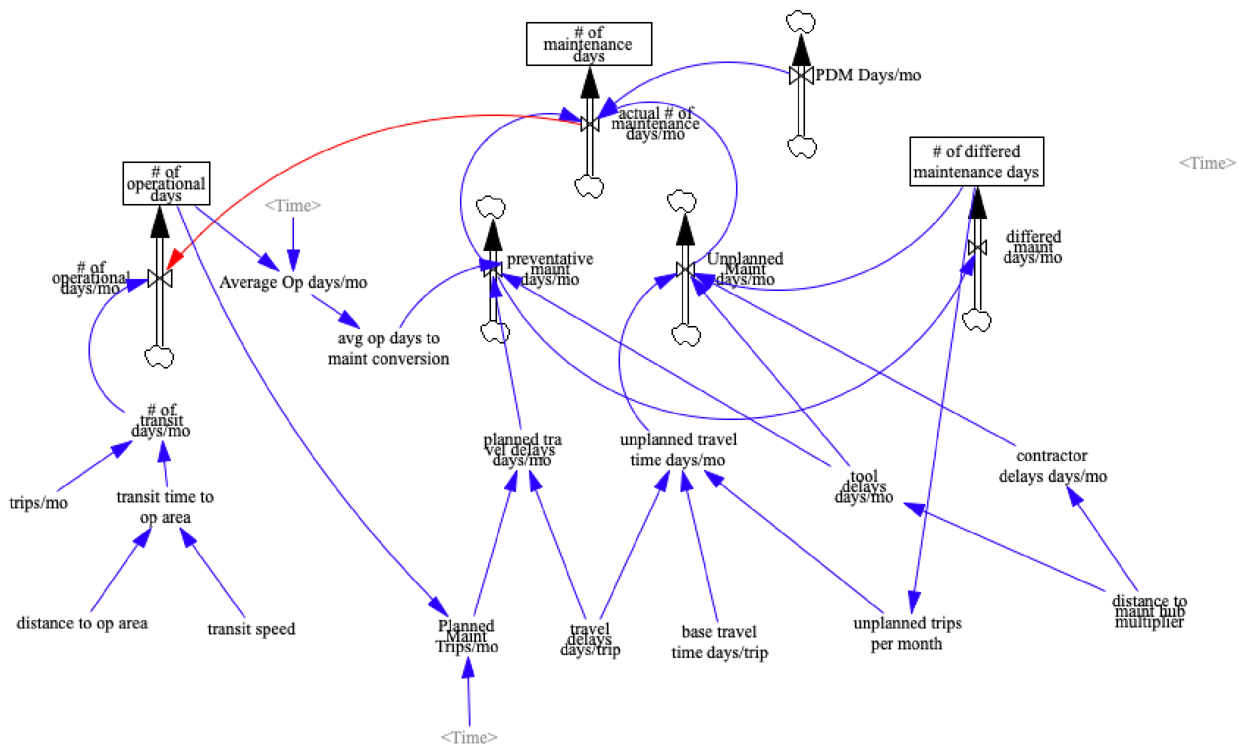
Units = dimensionless</td><td></td><td>WITHLOOKUP ("Average Op days/mo")

Look up(([(0,0)-(31,20)],(0,5),(5,5),(10,15),(15,15),(20,10),(25,5),(30,0),(31,0)))</td></tr>
<tr><td colspan="3">AODMC assumptions: This lookup function is used to capture the non-linear relationship between operational days and needed maintenance days per month. If a cutter is not operational or minimally operational, a base of five maintenance days is still needed. As a cutter operates more, between 10 and 15 days per month, 15 maintenance days are needed. As operational pace increases above 20 days per month, maintenance days are eroded and drop to nothing, even though the maintenance is still needed. This assumption is a good point to work through during the stakeholder engagement process.</td></tr>
<tr><td>Preventative maintenance days per month, rate, MD

Units = Days/Month</td><td>$= AODMC + PTD + TLD$</td><td>avg op days to maint conversion+"planned travel delays days/mo"+"tool delays days/mo"</td></tr>
<tr><td colspan="3">MD assumptions: the actual planned, preventative maintenance days per month are a combination of the days granted to the ship for maintenance (captured by the non-linear</td></tr>
</table>

relationship between operational days and maintenance days in the AODMC variable) and additional delays experienced by both the maintenance team traveling to the cutter and tools being shipped to the cutter.		
Program depot maintenance days per month, rate, PDM Units = Days/Month	$= \begin{cases} 30 & \mathit{Months}\ 13\ \mathit{and}\ 14 \\ 0 & \mathit{All\ other\ months} \end{cases}$	STEP(30 , 12)-STEP(30,14)
PDM assumptions: A cutter has one scheduled two-month dry dock during the two year simulation time. No operations are conducted during this time. This time includes transit to/from the dry dock facility and can be modified accordingly.		
Actual maintenance days per month, rate, M Units = days/month	$= PDM + MD + UM$	"Unplanned Maint days/mo"+"preventative maint days/mo"+"PDM Days/mo"
Maintenance Days, stock, AMD Units = Days	$AMD(t) = \int_0^{24} (M)dt$	INTEG("actual # of maintenance days/mo")
Deferred maintenance days per month, rate, DMM Units = Days/Month	$= \begin{cases} 15 - MD & MD < 15 \\ 0 & MD \geq 15 \end{cases}$	IF THEN ELSE("preventative maint days/mo">=15, 0 , 15-"preventative maint days/mo")
DMM assumptions: The normal number of scheduled maintenance days is 15 days per month. When the rate of actual maintenance days per month drops below this, the difference is captured by the stock of deferred maintenance days.		
Deferred maintenance days, stock, DM Units = Days	$DM(t) = \int_0^{24} (DMM)dt$	INTEG("differed maint days/mo")

All of these elements come together in a master stock and flow diagram that can be manipulated based on stakeholder assumptions, Coast Guard policy, AOR's and home port selections. The final model looks like this when input into the Vensim program:



APPENDIX C: ELEMENT SENSITIVITY ANALYSIS

The elements that were modified and resulted in different model outputs for the total number of operational days were analyzed using a paired t-test to determine statistical significance. The elements and their statistical analysis are shown below. For all elements, n=12 and $\alpha = 0.05$.

Paired two sample t-test for Dry Dock Length - 1mo vs. 4mo
t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	245.6159167	229.952333
Variance	1.714220083	1.85151624
Observations	12	12
Pearson Correlation	0.941102014	
Hypothesized Mean Difference	0	
df	11	
t Stat	117.7061173	
P(T<=t) one-tail	1.04106E-18	
t Critical one-tail	1.795884819	
P(T<=t) two-tail	2.08213E-18	
t Critical two-tail	2.20098516	

p<<0.05 therefore reject Null and accept alternate, there is a significant difference between operational days based on length of DD period

Pared two-sample t-test for the distance maintenance multiplier (delay associated with tools, contractors, etc) from a mean of 1.5 to a mean of 5
t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	245.4949167	232.135833
Variance	1.903757356	9.72862652
Observations	12	12
Pearson Correlation	0.542536179	
Hypothesized Mean Difference	0	
df	11	
t Stat	17.53797204	

P(T<=t) two-tail	2.17663E-09
t Critical two-tail	2.20098516

p<<0.05 therefore reject Null and accept alternate, there is a significant difference between operational days based on the range of the distance to hub multiplier

Paired two sample t-test for a random casualty maintenance day range 1-3 days vs. 1-15 days

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	261.1584167	145.29125
Variance	1.572035538	13.0276369
Observations	12	12
Pearson Correlation	0.142846913	
Hypothesized Mean Difference	0	
df	11	
t Stat	110.0308938	
P(T<=t) two-tail	4.36901E-18	
t Critical two-tail	2.20098516	

p<<0.05 therefore reject Null and accept alternate, there is a significant difference between operational days based on the range of casualty maintenance days

Paired two-sample t-test for varying distance to operational area

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	238.59	243.095917
Variance	11.67643636	11.7733092
Observations	12	12
Pearson Correlation	0.999099964	
Hypothesized Mean Difference	0	
df	11	
t Stat	-106.9368845	
P(T<=t) two-tail	5.97756E-18	
t Critical two-tail	2.20098516	

p<<0.05 therefore reject Null and accept alternate, there is a significant difference between operational days based on the variation of the distance to operational area

Paired two-sample t-test for varying transit speed
t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	241.1609167	242.199583
Variance	4.045502811	4.29385663
Observations	12	12
Pearson Correlation	0.916020109	
Hypothesized Mean Difference	0	
df	11	
t Stat	-4.289086212	
P(T<=t) two-tail	0.001279109	
t Critical two-tail	2.20098516	

p<<0.05 therefore reject Null and accept alternate, there is a significant difference between operational days based on the variation of the cutter transit speed

Paired two-sample t-test for the minimum number of maintenance days for a low-hours cutter
t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	243.3943333	238.693583
Variance	3.365294424	5.89284681
Observations	12	12
Pearson Correlation	0.996719318	
Hypothesized Mean Difference	0	
df	11	
t Stat	26.38397042	
P(T<=t) two-tail	2.68988E-11	
t Critical two-tail	2.20098516	

p<<0.05 therefore reject Null and accept alternate, there is a significant difference between operational days based on the variation of the base number of maintenance days

VITA

Dianna Garfield is an entrepreneur, a Coast Guard engineer, a wife and mother, and an outdoor enthusiast. She started Seabright Seafood, a small-scale fishing company specializing in traceable wild Alaskan salmon, with her husband Brent in 2011. In the Coast Guard, she spends time as a Chief Engineer on ships and a project manager for major ship repair contracts. She received her MBA in Sustainable Systems from Pinchot University in 2016 and leveraged her love of systems thinking into the University of Washington Industrial and Systems Engineering program. When not working or engaged in academic programs, she enjoys fishing, hunting, hiking and cooking-all with her husband, son and dog.