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A SYSTEMATIC APPROACH TO RELIABILITY-CENTERED MAINTENANCE

by

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A maintenance philosophy is a strategy of how to best integrate maintenance and repair efforts for a system while ensuring that operational requirements are met. Through the incorporation of reliability-centered maintenance (RCM), it is possible to observe, test, and inspect operating equipment to determine an optimal timeframe for completing this work. This research introduces RCM and develops a five-step methodology, founded in Systems Engineering principles, to capitalize on how to best implement, and continuously improve, a maintenance philosophy. A specific example cited throughout the research is the applicability of this process to the U.S. Coast Guard's newest cutter fleet: the Offshore Patrol Cutter (OPC). Through a decomposition of stakeholder requirements and identification of specific measures of suitability (MOS), operating equipment data is analyzed and a subsequent recommendation for a philosophy is presented. The process, while iterative, is tailorable to any system and is recommended as an initial tool for developing a support strategy with regard to maintenance.

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A SYSTEMATIC APPROACH TO RELIABILITY-CENTERED MAINTENANCE

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ABSTRACT

A maintenance philosophy is a strategy of how to best integrate maintenance and repair efforts for a system while ensuring that operational requirements are met. Through the incorporation of reliability-centered maintenance (RCM), it is possible to observe, test, and inspect operating equipment to determine an optimal timeframe for completing this work. This research introduces RCM and develops a five-step methodology, founded in systems engineering principles, to capitalize on how to best implement, and continuously improve, a maintenance philosophy. A specific example cited throughout the research is the applicability of this process to the U.S. Coast Guard’s newest cutter fleet: the Offshore Patrol Cutter (OPC). Through a decomposition of stakeholder requirements and identification of specific measures of suitability (MOS), operating equipment data is analyzed and a subsequent recommendation for a philosophy is presented. The process, while iterative, is tailorable to any system and is recommended as an initial tool for developing a support strategy with regard to maintenance.

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LIST OF ACRONYMS AND ABBREVIATIONS

AMIO	Alien and Migrant Interdiction Operations
CBM	condition-based maintenance
CBP	cutter-boat pooling
COI	Critical Operational Issue
CONOP	concept of operations
DEI	Diesel Engine Inspection
DoD	Department of Defense
DHS	Department of Homeland Security
EO	Engineer Officer
ICD	Initial Capabilities Document
ILSP	Integrated Logistics Support Plan
LCS	Littoral Combat Ship
MAT	Maintenance Augmentation Team
MBSE	model-based systems engineering
MEC	Medium Endurance Cutter
MEP	Mission Effectiveness Program
MMA	Major Maintenance Availability
MOE	measure of effectiveness
MOP	measure of performance
MOS	measure of suitability
NED	Naval Engineering Department
NOAA	National Oceanographic and Atmospheric Administration
NSC	National Security Cutter
OPC	Offshore Patrol Cutter
ORD	operational requirements document
RADAR	radio detection and ranging
RCM	reliability-centered maintenance
SFLC	Surface Forces Logistics Center
SME	subject matter expert
USCG	United States Coast Guard
USN	United States Navy
TSTA	Tailored Ship’s Training Availability
WCA	Watertight Closure Assessment

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EXECUTIVE SUMMARY

The need to complete maintenance on any system is to ensure correct functionality and performance over the course of its intended life cycle. In an era of ever-emerging technologies, especially those that include various sensor suites to monitor performance and output, there are multiple means for assuring the system is functioning as designed. This continuous monitoring, along with integrated testing and inspection, provide a foundation for using reliability-centered maintenance (RCM). On its own, RCM is a concept that enables the identification of maintenance needs prior to a forecasted milestone such as time or operational hours. It also predicts if, or when, a failure may occur thus enabling the user to take action prior to the casualty.

The purpose of this thesis is to develop a methodology that is used for determining the maintenance philosophy. It is a step-by-step process with a basis in systems engineering. This will allow developers the ability to better understand the need and then apply various stakeholder requirements to illustrate the overall concept of the philosophy. In order to do this, the methodology was presented as a systems engineering "Vee" flowchart and includes multiple opportunities for iteration through verification and validation. Figure ES-1 is the Vee used to present the methodology.

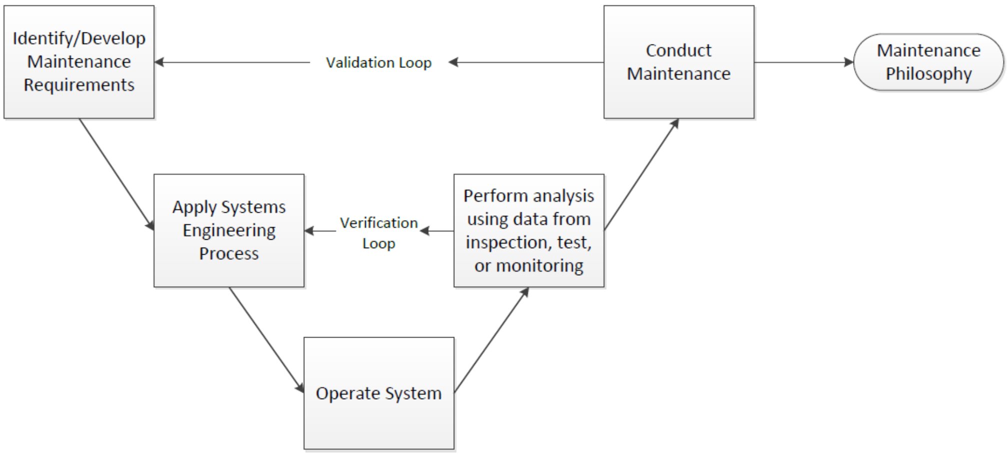

Figure ES-1. Proposed Framework for Developing a Maintenance Philosophy

This thesis presents this process through the decomposition of each step, identifying the inputs, outputs, measures, and controls associated with each. For traceability, it is implied that the outputs from one block correspond to the inputs for the next. An important factor to remember is that this process is iterative; there will not be a one-time solution that will always be true. In addition, this research explores the requirements for the OPC, which serves as case study.

This process is well suited for surface vessels, and this research applies it to the next fleet of U.S. Coast Guard cutters: the Offshore Patrol Cutter (OPC). The OPC is a shipbuilding endeavor to replace an existing fleet that has a mean age of nearly 50 years and suffers from less-reliable systems because of age and use. However, with the advent of this new cutter, a maintenance philosophy should be developed that incorporates RCM and ensures that several requirements from the acquisition Operational Requirement Document (ORD) are met.

The development of this process is the first step in creating a maintenance philosophy. There are other considerations—such as selection of individual components, the resources necessary to place the philosophy into existence, and the current operational requirements—that are driving the performance of the system. The resources include time, funding, personnel, and training, all of which have limitations and require forethought before implementing.

To best use this method, it is essential that regard be given to suitability measures. These include reliability, maintainability, and availability, as well as careful analysis of the raw data that comes from operating the system. Finally, as with many problems, having a clear understanding of stakeholder requirements up front will better enable success throughout the implementation of this process. Future work should include application of this methodology within the acquisition and life cycle sustainment of the OPC including detailed use of mode-based systems engineering (MBSE) to analyze data for further refinement of maintenance practices.

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The accomplishment of this work is by no means an individual effort. First and foremost, I have an incredibly supporting family: my wife, Danielle, and my children, Brooke and Lena. Without your love, devotion, and dedication to enable my long hours of research, study, and copious amounts of typing, this would not be possible. To my parents, I appreciate your guidance, wisdom, and candor over the entirety of my academic journey.

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I. INTRODUCTION

The ability of a navy to accomplish a set of missions is directly related to the size, capability, and operational availability of its fleet of ships. When considering these three aspects, perhaps the one most paramount, and easily impacted, is operational availability. A fundamental consideration for this characteristic is the maintenance, preventive or corrective, of the ship as well as the individual systems comprising it. As there are multiple options for completing the maintenance, determining an optimal approach while considering the costs involved best addresses how to achieve this ability. The idea of developing a maintenance strategy is not a new concept, but one that must be a fundamental design consideration for any ship acquisition or incorporated into a legacy asset's support plan. It is important that it be considered early in the design as well as reviewed at regular intervals.

The U.S. Coast Guard (USCG), known as the fifth member of the United States Armed Services, is primarily charged with operations related to waterborne search and rescue, maritime safety and security, defense readiness, and enforcement of international laws and treaties on the high seas. The existing fleet of vessels, referred to within the USCG as cutters, has a mean age of approximately 50 years, with some dating back to the 1930s. Many of the major cutters, defined as those being 180 feet or greater, have undergone extensive refurbishments and overhauls in an effort to modernize and extend their service life as the timeline for their replacement shifts farther into the future. However, the advent of a fleet-wide modernization program of the late 1990s to present initiated long-needed relief including newer, and more capable, vessels and aircraft. Highlighted programs include the National Security Cutter (NSC), Offshore Patrol Cutter (OPC), and Fast Response Cutter (FRC). While each adds merit to operational capability, the focus of this research is the OPC, primarily due to the current acquisition timeline and availability of supporting documents. A general note is to recognize that many of the principles and recommendations in this analysis are applicable to other navies as well as future and legacy fleets.

A. RESEARCH CONTRIBUTION

The contribution of this thesis is guidance for developing a maintenance philosophy framework, which can be applied to essentially any physical system in existence. Using acquisition and development documents associated with the USCG's OPC, the framework is developed and then exemplified in a case study, thus demonstrating the ability to use this philosophy for a real-world example. This will present a strategy, or methodology, applicable to the USCG, U.S. Navy (USN), National Oceanographic Atmospheric Administration (NOAA), and allied navies worldwide. Not only can this satisfy the maintenance needs for this specific fleet of cutters but also the foundation may be applicable to both future and legacy fleets to support business models and programs for overall betterment and longevity of surface vessels. This study will explore different suitability attributes such as reliability, availability, and maintainability (RAM), and discover their ramifications through trade-off analysis. Finally, with the development of measures of effectiveness (MOE), measures of performance (MOP), and measures of suitability (MOS), a consolidated maintenance philosophy recommendation will be provided.

B. REPORT SUMMARY

This research is a collection of systems engineering concepts stemming from a top-level architecture that serves to develop a maintenance strategy for a surface vessel. The applied context used to analyze this methodology is that of the OPC, the USCG's latest shipbuilding endeavor, which will apply principles of reliability centered maintenance and measures of operational suitability. Specified in the OPC Operational Requirements Document (ORD), a required foundation for maintenance program structure is Reliability-Centered Maintenance (RCM). Blanchard and Fabrycky (2011) define RCM as a "systematic approach to developing a focused, effective, and cost-efficient preventive maintenance program and control plan for a system or product" (439). In essence, RCM is a maintenance practice in which a system's functionality is monitored through the gathering of data or inspections followed by carefully developed, planned, executed, and reviewed maintenance processes.

The gathering of data may be in the form of visual observation and documentation of performance or through electronic capabilities that integrate with the equipment. As will be discussed, the latter is a preferred method for continuous real-time data so as to identify potential problematic trends for immediate correction before a significant, or mission degrading, casualty occurs. Inspections are often visual, and performed by a subject matter expert (SME). This study will decompose the essence of these inspections, and specifically discuss who is best suited to perform them, along with exploring training and material needs. To accomplish this, an iterative systems engineering approach, primarily stemming from principles of suitability, is applied.

By delving into the background of RCM, various suitability concepts, and the guiding documents regarding the acquisition and intended operation of the OPC, recommendations for a structured maintenance framework will be presented.

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II. BACKGROUND

The OPC is the latest USCG acquisition to fill a capability gap primarily due to an ever-aging fleet of legacy cutters. Medium Endurance Cutters (MEC), considered the "workhorse of the Coast Guard fleet" were commissioned starting in the 1960s and have undergone numerous extended maintenance availabilities for a myriad of upgrades and repair. Two significant projects were the Major Maintenance Availability (MMA) of the late 1980s through mid-1990s as well as Mission Effectiveness Project (MEP) in the early 2000s. However, with these vessels approaching the half-century mark, their ability to continue serving as reliable assets in a fast-paced and technologically driven world is creating more problems than solutions. Thus, the OPC is a vessel designed to be faster, more agile, a better seakeeping platform, and able to superiorly perform many of the USCG's statutory missions including:

- ports, waterways, and coastal security
- search and rescue
- drug interdiction
- Alien and Migrant Interdiction Operations (AMIO)
- living marine resources
- other law enforcement
- defense readiness

The operational use strategy, a reference to how the USCG will utilize an asset, includes the OPC routinely operating in regions worldwide, with specific emphasis in the Arctic and temperate regions. The target length of patrols is 45–60 days, with a notional requirement of 185 days away from homeport each calendar year. With such a robust generality of operational needs, ensuring that the completion of maintenance is executed on time is a critical consideration. This study will further analyze this consideration, as well as helping to answer the following critical operational issue (COI): "Will the [OPC] be maintainable in its intended operational environment with its intended maintenance construct?" (U.S. Department of Homeland Security 2010, 2–6).

The framework this research provides as a methodology for the maintenance philosophy will be explained in detail in a subsequent section. To illustrate the principles of this research, primarily those that will be discussed within this background chapter, the following illustration is provided for reference and information.

A. USCG AND THE OPC

One initial question that arises is: “How will this vessel operate for such a long service life, an estimated 25 years, and continue to meet operational missions?” There are many factors to consider when answering this. These factors include:

- maintainability measures including planned maintenance, actual maintenance, and performance of maintenance standards
- availability as determined from operational tempo requirements
- supportability measures including availability of spares and replenishment needs

The operational tempo specified in the OPC Operational Requirements Document is 185 days per calendar year. This is consistent with the tempo of existing medium endurance cutters (MEC). The latter two aspects, specifically the performance of maintenance standards, will be analyzed and discussed in this body of work.

B. USCG GENERAL NAVAL ENGINEERING MAINTENANCE PHILOSOPHY

While it is clear that maintenance is a necessity, it is not always clear how and when it is best integrated into the system, most notably when considering impact to the system’s primary mission. This is especially true for a ship as the ability to complete some of the maintenance requirements becomes more complex once the ship puts out to sea for an indefinite period. It should be noted that the term *indefinite period* is provided as a general indicator for vessels in any fleet. The OPC requirements include the aforementioned target of 185 days per year with patrols ranging from 45–60 days. This introduces the question: what is an optimal approach for maintenance of a surface vessel to maximize operational readiness while minimizing costs? In this application, cost is not simply a monetary value, but also a reference to labor hours and operational downtime. Answering this question will aid decision makers in developing specific policy and process guides, within the bounds of operational tempo and available personnel. The consolidated determination for the maintenance practices considers general naval engineering maintenance programs within the USCG, organic support mechanisms, and case study review from other shipbuilding endeavors, specifically the USCG National Security Cutter (NSC) and U.S. Navy's (USN) Littoral Combat Ship (LCS).

The USCG delineates maintenance into two broad categories: organizational and depot. Organizational maintenance is that maintenance intended to be completed by the personnel assigned to the unit with a reasonable expectation of using common tools, consumables, expendables, and components. There are allocations for training to ensure crew members are correctly executing tasks and enable competent quality assurance. Depot maintenance is that maintenance intended to be complete by personnel with advanced training, special tools, and is commonly conducted at a depot facility such as a shipyard (some depot functions such as dockside or emergent casualty response may be completed at a ship's homeport). One theme that this research explores is the consideration of what maintenance is intended to be allocated to the organization and what should be aligned with the depot responsibilities. Elements to support this argument include:

- manpower considerations including the number of individuals and specialties that must be included as part of the cutter's crew
- operational tempo including stakeholder requirements for days away from homeport
- potential training opportunities such as Tailored Ship's Training Availability (TSTA) or recurring crew training
- standard tool sets associated with equipment designed-in as standard configuration

A general notion is to minimize underway maintenance so as to limit crew fatigue and ensure their availability to meet operational requirements.

Before developing a maintenance philosophy, it must first be defined and understood. Tomlinson (2015) suggests that a maintenance strategy, or philosophy, "maintains design intent, achieves availability targets, is affordable, is flexible enough to deal with uncertainty, is sustainable, and is underpinned by sound learning-from-experience and operational assumptions" (1). My interpretation of what a maintenance philosophy is and how it should be applied is the philosophy is an integration of a broad spectrum of programs and processes, carefully orchestrated, so that the operational mission is met as well as completeness of maintenance. Furthermore, completing the maintenance is not enough; completing it *correctly* is paramount. Three elements that must be carefully integrated and planned for include

- the human element including ability, training, and expertise to complete
- available material including expendables, consumables, spares, and miscellaneous resources
- allotted time to correctly complete the maintenance

To further dissect the definition of a maintenance philosophy, the strategies that are best suited to fulfill the need for a philosophy are to develop a regular interval of equipment and material inspections and to incorporate a planned preventive maintenance schedule. Together, these elements provide a basis for reliability-centered maintenance (RCM). As defined by the Department of Defense (DoD), RCM is "a logical, structured process used to determine the optimal failure management strategies for any system, based on system reliability characteristics and the intended operating context" (U.S. Department of Defense 2012, 25). In short, this is a method of observing the performance of equipment and determining what maintenance is *needed* versus what is *wanted*. Prudent engineering, while sound and cemented in experience, may result in an overage of maintenance which can negatively impact system function. With respect to the OPC, the ORD requires that "the [OPC] preventive maintenance requirements and procedures will be founded on RCM principles" (U.S. Department of Homeland Security 2010, 4–4).

The Coast Guard's Mission Support Business Model defines maintenance as a two-tier strategy consisting of organizational maintenance, or unit conducted, and depot maintenance, including that conducted by another organic resource or contractual effort. A determining factor with regards to the demarcation between organizational and depot is with regards to organic Coast Guard resources capable of completing depot maintenance tasks. "Organic" refers to in-service organizations that can provide services without the need for commercial contracting. Ultimately, this research focus is a best effort to maximize organic resources while completing timely maintenance without adverse impact to operations; this is a value-saving consideration as external contracting is not utilized. How can this be accomplished? The use of existing centralized maintenance inspection and repair programs are one solution for further expansion to the OPC fleet. These include watertight closure assessment (WCA), diesel engine inspection (DEI), and cutter boat pooling (CBP). Another solution, as presented by Linton (2011), is to follow suit with the development of programs with a similar goal including equipment vibration monitoring and analysis, motor circuit analysis, laser alignment, boroscopic or internal imaging inspection, and leak detection (28).

C. BRIDGE TO SYSTEMS ENGINEERING

With an understanding of the requirements for the OPC, the USCG maintenance practices including organizational and depot programs, and information related to a maintenance philosophy with RCM principles, the next step is to present systems engineering techniques that aid in developing a sound maintenance strategy. Systems engineering is a technical approach to problem solving that includes refinement of system functions and requirements which enable the development of preliminary and detailed designs. Using this approach, this research will be enhanced with more objective reasoning for implementing an RCM-based maintenance philosophy as well as develop the methodology for doing so.

D. SYSTEMS ENGINEERING AND SUITABILITY METRICS

A complimentary basis for this research is an application of systems engineering. Using this approach, it is possible to expound on the initial requirements and determine suitable approaches to meeting the goal. To support this method, metrics, or measures, of suitability are applied to characterize the system’s performance. In doing so, instantiated solutions begin to present themselves providing decision makers with information and processes for action.

1. Systems Engineering Background and Use

The process for analyzing a capability gap, developing alternatives, and developing recommendations is founded in systems engineering principles. Though there are many definitions for systems engineering, the one preferred by the author is "an interdisciplinary collaborative approach to derive, evolve, and verify a life cycle balanced system solution which satisfies customer expectations and meets public acceptability" (Blanchard and Fabrycky 2011, 18). There are many common elements for systems engineering, and these have application for maintenance programs, including viewing the system as a whole, consider the entirety of the life cycle with the development of the system, knowing and understanding the initial system requirements, and recognizing that system design and development is not done individually, but uses a team approach. Perhaps an additional characteristic, which may have basis as a subset of the system-as-a-whole and knowing system requirements is recognizing the potential impacts associated with the implementation of the system.

There are many models that are useful tools for this process, and one most recognized and commonly referred to is the "Vee" model; a representative image is provided in Figure 1.

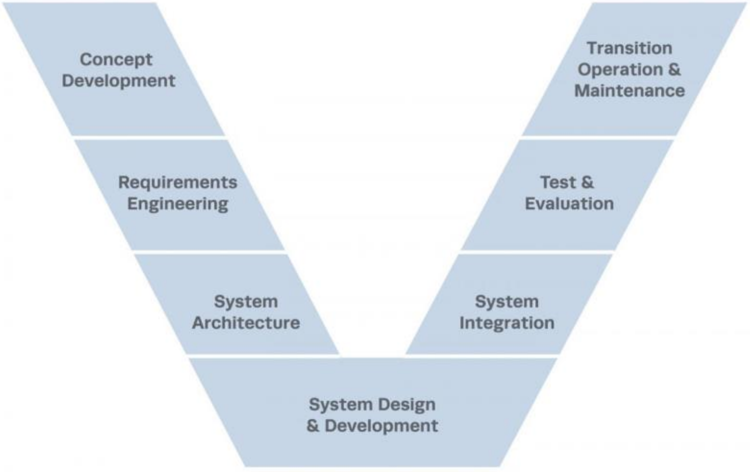

Figure 1. Systems Engineering V-Model. Source: Mitre Corporation (2018).

When applied to the development of a system, this begins with understanding the capability gap through development of a problem statement from a stakeholder analysis. The process flow is to decompose the problem through the development of system requirements, allocate functions to subsystems, create a detail design of components, conduct verification at different levels starting with components so as to end with the full system, and deliver the system as operationally ready. For this thesis, the system is the maintenance philosophy. An innovative characteristic of any systems process is iteration; successful programs are regularly reviewed and updated to suit any updates or changes to the system development strategy. In general, this document will focus on the elements up to, and inclusive of, the design of components into a singular system, with recommendations for future work for system verification and validation.

An additional manner of developing a system, primarily from its functions is through the use of Integrated Definition for Function modeling, or IDEF. IDEF is a "standard for process definition" and was developed in the 1960s by the U.S. DoD (Straker 2018). In essence, this utilizes multiple levels of visual aids, called ICOM charts, to decompose a system's functions. Within this research, levels of IDEF are not presented, but the visual aid of ICOM is. ICOM is an acronym derived from the four pillars that are associated with a "blackbox" system: input, output, control, and mechanism. According to Dennis Buede in *The Engineering Design of Systems* (2011), the idea is to convert inputs into outputs using guidance from controls, or constraints, and that the conversion will be performed by mechanisms, or physical items conducting the work (87). A control may be a specification, physical boundary, or environmental limitation; a mechanism may be a person, computer, tool, or other device.

While there are no limits for the number of each attribute, it is recommended to limit to no more than four so as not to cluster the chart and make it unreadable. Additionally, the presence of more items indicates that more refinement is needed, and so additional levels of IDEF may be necessary. Figure 2 is an example of an ICOM; this will be used throughout the Maintenance Philosophy Methodology section as a visual aid for working through the development flowchart.

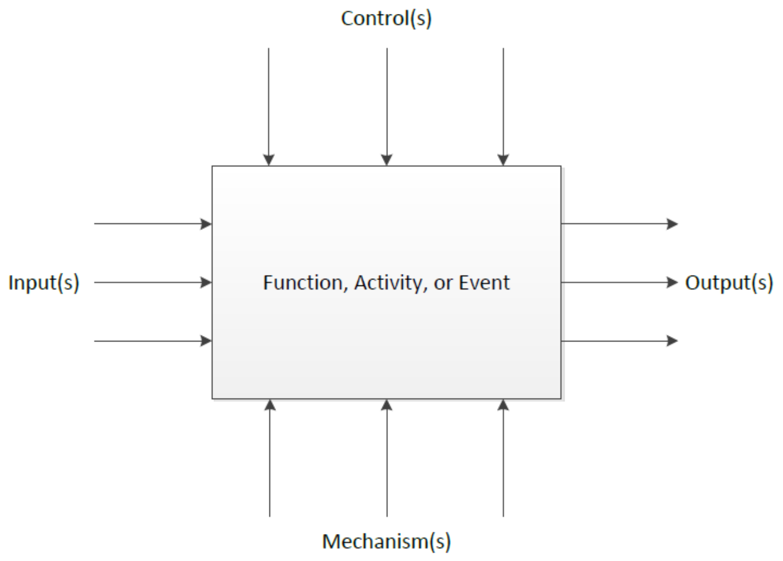

Figure 2. Sample ICOM Chart. Adapted from Parnell and Driscoll (2008).

A subset of systems engineering, steeped in metrics and observable performance parameters, is suitability. System suitability considers how the system will perform in an effective and efficient manner over the course of its life cycle. There are innumerable "ilities" that are associated with suitability, essentially any performance criteria that is tested and compared to a given or desired value. For this thesis, the following elements will have emphasis: reliability, maintainability, availability, supportability, and human systems integration. Together, they form a nucleus of a sound systems engineering approach which, when properly leveraged, allows for capitalizing on an RCM methodology maximizing effectiveness.

2. Maintenance Considerations and RCM Integration

Often, maintainers perform superfluous tasks on a too-frequent basis; this is typically due to following a maintenance practice from when the system was first introduced and without any subsequent review or update. Over time, process changes occurred that, in general, were a positive trend in improved system reliability without the need for as much hands-on effort. The advent of effective manufacturing efforts along with standardized quality assurance oversight led to an overall better end product. Characteristic of this effort was that the follow-on support was tailored from antiquated means with the integration of modernized processes, tools, or equipment; thus, a decreased amount of maintenance. However, a problem occurs when systems, originally designed with the intent of using outdated maintenance processes, are still in active operation and use. The crux of the problem results from a decrease in system reliability with age and the maintenance response is one that no longer has the capability of responding to the system or operator's need.

When the MECs were first commissioned in the 1960s, the analysis at the time is archaic in comparison to today's manufacturing standards, new invention, and science and discovery. A specific example is when watchstanders are required to conduct hourly rounds and document a number of operating parameters on equipment throughout the ship. For much of the equipment, a parameter recorded is the system's temperature. While temperature of the equipment is important to observe, and can be indicative of potential failure, hourly data points are inadequate for having real-time knowledge of the system's performance. In addition, could the time served doing this hourly round be better utilized elsewhere? Could some sort of monitoring device be integrated that can send real-time data to a central hub for regular monitoring? The answer to both questions is yes.

When developing a maintenance program with RCM as a focal point, there are several questions to consider:

- What is RCM and why use it?
- What are the manning requirements for these cutters?
- What standard training will be provided to the crew on a pre-deployment basis and/or annually?
- What organic resources exist for assisting the crew with completing maintenance?
- What standard maintenance practices should be considered and implemented for consistency across the fleet?

To aid in answering these questions and to provide one perspective, a review of the OPC Integrated Logistics Support Plan (ILSP) was conducted. Subsequent chapters will provide extensive detail of the information in this document, but a few items to specifically consider include "minimally manned crew for operations" and language stating that standard training programs will be created for use across the fleet (U.S. Department of Homeland Security 2014, 61). As well, the ORD provides the following requirement with regards to supporting maintenance personnel: “maintenance personnel shall be provided the necessary diagnostics data and information, tools and test equipment/sets, technical documentation, material, and skills to perform maintenance” (U.S. Department of Homeland Security 2010, 4–4). In essence, technicians should expect to be set-up for success and receive the logistics support tools and material necessary.

E. RELATED STUDIES

The development of a maintenance philosophy or planning for different maintenance events has been addressed in research before. One may argue that the need for a maintenance program for a system has been in existence as long as the system itself. However, the approach to developing the philosophy includes a broad conglomeration of different strategies and practices, many based on experience and knowledge of other programs.

One approach, presented by Khan and Haddara (2003), focused on elements of maintenance planning and inspection using risk based assessments. This uses an application of risk, based on system operation and performance, to target best opportunities for conducting maintenance as well as considering the risk associated with the maintenance. When considering strictly reliability measures, Weinstein and Chung (1999), Lapa, Pereira, and Barros (2006), and Soares, Garbatov, and Teixeira (2010) each present means for developing systems with reliability in mind that includes component selection and hierarchy for how components interact. Specific to the latter were references to reliability application for ship hull and floating platform maintenance programs. Additional studies researched the integration of planning and scheduling for individual systems such as a single machine as was characterized by Cassady and Kutanoglu (2005).

While the essence of these different topics is applicable in the general development of a philosophy, and the findings are plausible, the uniqueness of delving into extensive systems engineering, and more specific system suitability, presents a more-informed architecture for generating and iterating a philosophy.

F. RCM AS A MAINTENANCE STRATEGY

1. Integration as an Approach to Maintenance

Reliability-centered maintenance is a method that maximizes the operational capability of a piece of equipment, considers potential failure conditions of this equipment in a stand-alone setting, and further analyzes the impacts to the system as a whole should the equipment fail. With a typical integrated engineering plant consisting of a multitude of auxiliary, propulsion, and electronics systems, there is a significant probability that something will fail. The questions to consider are:

- What could fail?
- How often failure may occur?
- When it fails, will it cause significant operational degradation to the cutter?

The challenge is to not perform excessive work, or as is commonly termed in a colloquial sense: "if it ain't broke, don't fix it." In essence, RCM is the overarching program for analysis, but there are more elements to consider.

A product of RCM is the analysis and extraction of data from the equipment or machinery. In essence, this is a combination of tests, inspections, and monitoring devices to evaluate the functionality of a piece of equipment so that trend data is extracted and recommendations for specific maintenance, whether preventive or corrective, can be developed and analyzed. The tests and inspections are often performed by the crew as an organizational maintenance requirement. These may be a visual inspection for any signs of failure such as chaffing of cable insulation or corrosion on a pipe due to a leak. The test may also be a determination of flow rate through a pipe to ensure that there is not internal blockage or mineral deposit that is creating a restriction. The monitoring may be a self-diagnosing feature that includes a built-in system from the manufacturer or could be an after-market addition that is programed specific to the user's needs. An example would be the use of pyrometers for an engine to determine pressure and temperature at various locations. The results of tests, inspections, and monitoring are inputs that aid in the determination of what maintenance is necessary. Figure 3 provides a visual depiction of how these concepts integrate for a common theme.

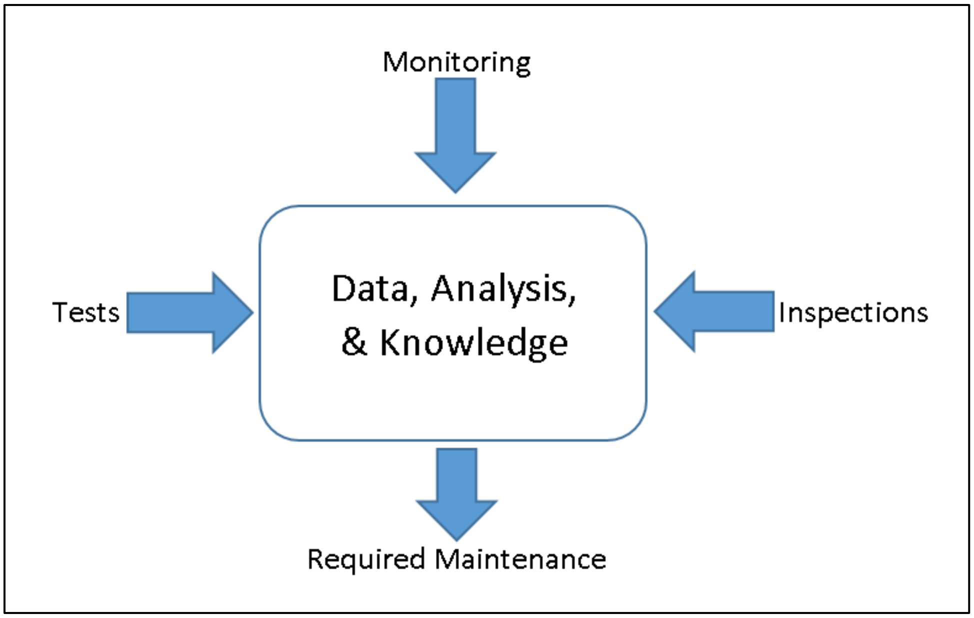

Figure 3. Integrating Aspects of RCM

A subset of RCM is condition-based maintenance, or CBM. It is a program that is common across industry, and is also a maintenance platform already in use by the Coast Guard and the U.S. Navy. This is an important step in the use of RCM as it dictates the schedule and periodicity of performing the maintenance. It is also important to understand that the maintenance schedule may, and most likely will, change over time as the machinery operates longer and closer towards the end of its life cycle. Figure 4 is an example of a reliability bathtub curve. In essence, this curve is a general representation of how a system will evolve over time with a substantial amount of mid-life in a plateaued or constant rate of failure.

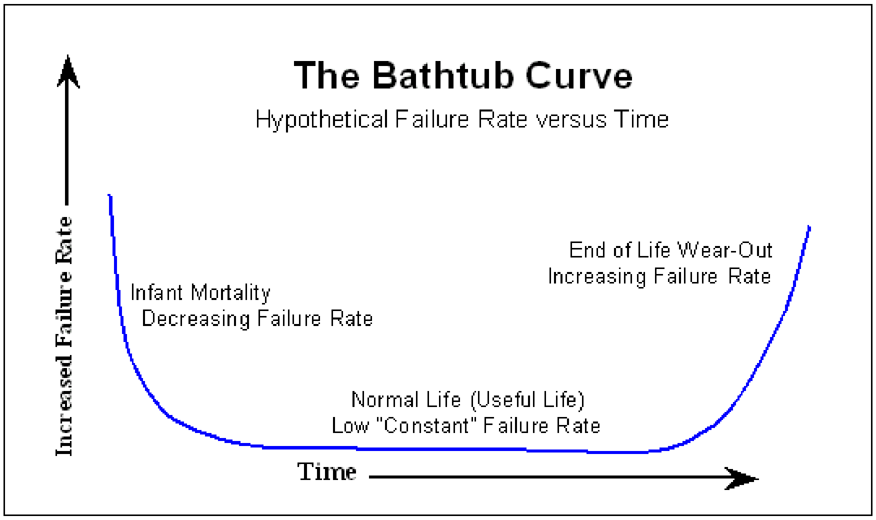

Figure 4. Reliability Bathtub Curve for Expected Failure Rate over Time. Source: Weibull (2013).

For most systems, the curve is not this clear-cut and stable as different events in the life of the system may alter it. For example, when considering the intended 25-year life cycle of the OPC, it is expected that there will be, at a minimum, six dry dock availabilities. This is determined using the USCG standard of docking a cutter every four years. With each availability of this magnitude, a significant amount of repair, and potentially upgrades, are conducted which will decrease the upward trending failure rate due to use. Following each availability, there will be a gradual increase of failures until the next availability. A goal of RCM with CBM is to identify these trends early and to take action to return the system to the desired low constant failure rate.

A challenge with CBM is the determination of what maintenance is actually necessary and what is recommended. Different perspectives and backgrounds will determine what may, or may not, be necessary at different intervals, so it is important that the technical authority responsible have final determination; in the case of the Coast Guard, this is the cognizant Product Line Manager. The next section provides information related to specific programs, processes, and practices for implementation of RCM.

The inspection element is an important aspect of RCM. This is an activity that may be performed through direct human interface, but could also be the result of some type of sensor suite that continuously monitors the operation of machinery and equipment. The results of the inspection provide the user, who may be the operator or maintainer, with invaluable information regarding how well the equipment is working, trend analysis based on use and/or age, and recommended actions to ensure the equipment meets acceptable availability standards. Furthermore, this information, if inserted into an RCM database, aids decision makers with determining the periodicity for preventive maintenance, essential to the schedulers with developing both a distributed maritime force-laydown of operations as well as maintenance cycles. For the latter, this includes regular maintenance on installed equipment, such as an oil change on an engine, but also supports when to perform a major maintenance availability such as a dockside or dry dock.

Test is another element of RCM. When considering test in this perspective, this is not a reference to the acquisition definition that includes Development or Operational Test and Evaluation (DT&E and OT&E, respectively). In this context, test is simply conduction of an experiment or some type of interaction to gather data for analysis and gaining knowledge. A test feature may be incorporated into a component, such as a GFI electrical outlet having a test button to determine if the circuit is grounded or safe to use. A test may be a maintenance procedure itself such as using falling-ball measurement to determine the viscous properties of engine oil. In fact, as the latter test provides one indication of how an engine is performing, using RCM may also dictate the periodicity at which the falling-ball test must be conducted. When placed into an RCM database, the results of the test, including raw data and analysis, further aid in plotting trends and forecasting the effective functionality of a piece of equipment.

The final element to consider is monitoring. There are instances where the best method for determining how a system is functioning is simply by monitoring its behavior. This could be a visual observation, a series of inspections or tests, or through aural detection of a problem. An example would be attempting to identify the source of ship propeller cavitation which is defined as the formation of vapor bubbles leading to surface erosion and vibration. Underwater propulsion gear is difficult to inspect and diagnose without removing the vessel from the water, and so using inherent sense may be the best tool. Through monitoring, it would be possible to determine if the cavitation is occurring at random periods with various machinery in operation, changing with different ship speeds, or if it is getting worse over time, which would be determined from feeling increased vibration or noise.

Ultimately, integrating these three elements, and most importantly, gaining data for analyzing and learning of the system’s performance is the crux for RCM. As stated in their individual descriptions, many cross-overs exist, which is beneficial in having a checks-and-balance system for gaining a better understanding of the system’s operation including any potential failure symptoms that may be developing, which could result in some degree of casualty.

Having provided information regarding systems engineering processes, the OPC, and RCM, the next step is to present a detailed step-by-step methodology for developing the maintenance philosophy. This methodology will follow the systems “Vee” model approach and include specific input and output data and criteria for each step. Further, the method will assimilate suitability metrics including reliability, availability, and maintainability which are measures for determining how well the system is performing while at the same time useful as feedback to stakeholders regarding how well their requirements are met. The intended outcome of the methodology is a maintenance philosophy; the reader is cautioned, and will be again, that application of the systems engineering process implies iteration so there will not be a singular solution.

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III. RESEARCH METHODOLOGY

Having a sound understanding by delving into the background and fundamentals of any problem greatly improves the ability to not only derive a solution, but to also ensure that the solution satisfies the need and meets the expectations of the stakeholders. As the OPC progresses as an acquisition program, there are innumerable decisions that are necessary, many of which will influence future ones. One decision, the focus of this thesis, is the maintenance philosophy. In general, the maintenance philosophy provides guidance for answering the following questions:

- How do we maintain the cutter?
- What expectations do we have with regards to maintenance completion?
- What are the potential operational impacts, both positive and negative, regarding completion of maintenance?
- Who will complete the maintenance?
- What tools, training, and other resources are needed to complete the maintenance?
- When will maintenance be completed?

As an example, there are requirements outlined in both the Operational Requirements Document (ORD) and Integrated Logistics Support Plan (ILSP); these requirements are provided in Table 1.

Table 1. OPC Top-Level Maintenance Requirements. Source: U.S. Department of Homeland Security (2010).

Requirement 1	The essence of maintenance performed aboard the OPC shall be based on RCM fundamentals
Requirement 2	The maintenance necessary for safe and correct operation of the cutter shall be conducted by the crew
Requirement 3	The crew will be provided with all tools, training, and material so as to complete maintenance
Requirement 4	Shoreside support shall be available to augment the crew’s completion of depot and organizational maintenance

These requirements provide the systems engineer, or problem solver, with information related to what the stakeholders desire.

Figure 5 was developed as an aid in the development of the methodology, and to provide the reader with a top-level view of the proposed framework. This figure is intended to provide a multi-step "roadmap" to aid in determining different process input and outputs as well as controls and measures. Notice that this figure is represented in the way of the systems engineering "Vee." This is intentional to utilize a well-established decomposition method that incorporates iterative loops for verifying that the system is correct and validating that the right system was created. This decomposition and iteration aids in developing the philosophy, which may change over time based on the methodology flow. The subsequent sections will present each step and discuss various elements related to this step.

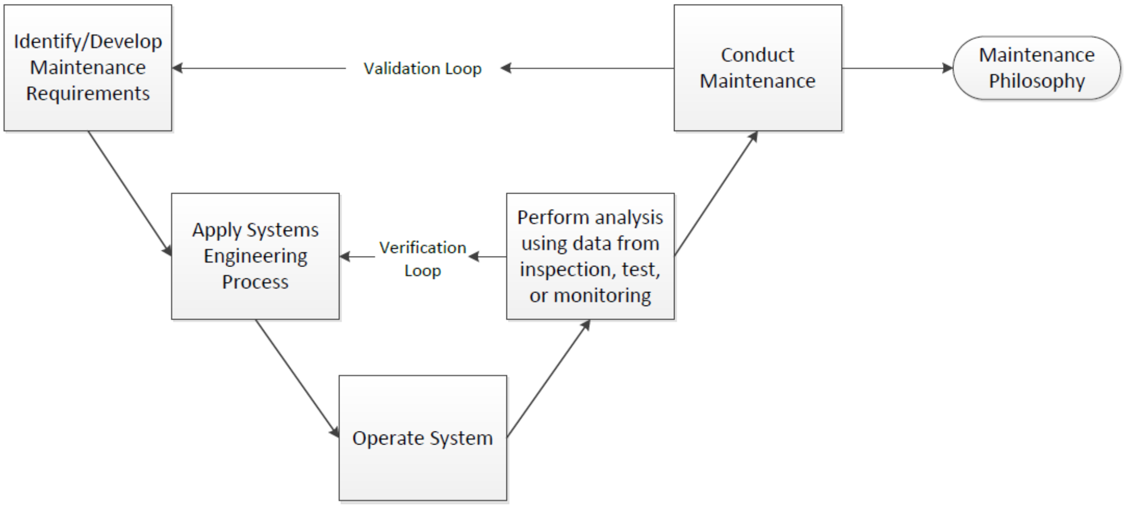

Figure 5. Proposed Framework for Developing Maintenance Philosophy

A final note of clarification is to inform the reader that the methodology is presented as a discrete, step-by-step process, with specific inputs and outputs. The framework for this process, which is explained in detail in the following section, is modelled after a method development concept utilized by O'Halloran et al. (2014).

A. STEP 1: IDENTIFY AND DEVELOP MAINTENANCE REQUIREMENTS

The first step is to identify and develop maintenance requirements. This will primarily begin with stakeholder analysis and determine their primary desires with regards to the system. It is important to filter out the "wants" from the "needs" so that the problem statement develop correctly addresses the capability gap. From the maintenance philosophy roadmap, Figure 6 is derived, along with associated inputs, outputs, controls, and mechanisms.

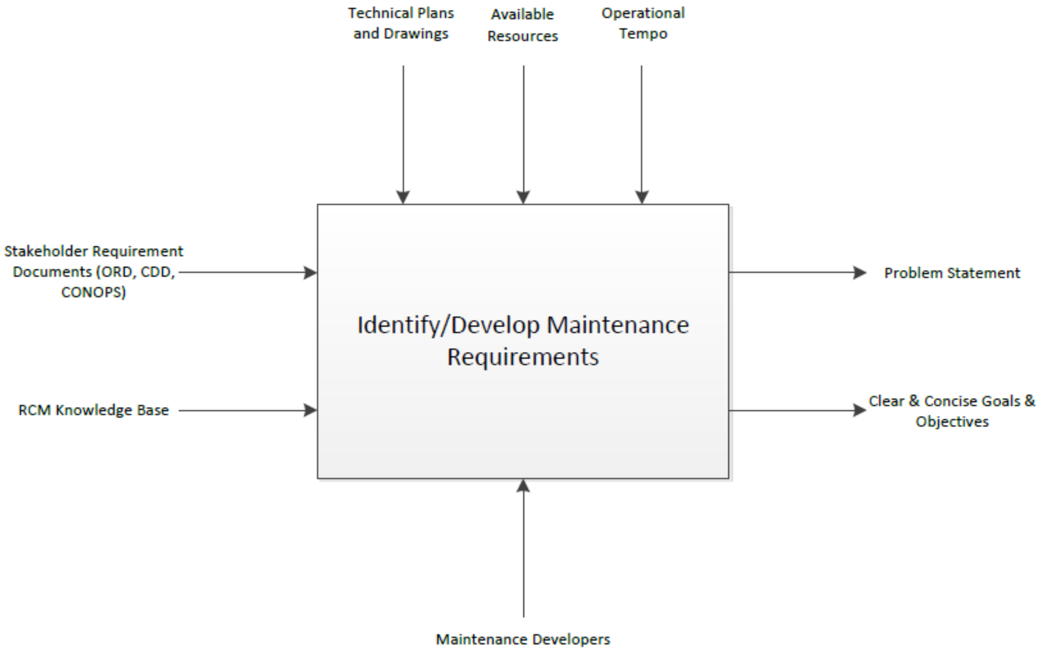

Figure 6. Step 1 for Developing a Maintenance Philosophy

From Figure 6, it is evident that the primary inputs include the stakeholder requirements, which are often provided as capability documents or concepts of operation, and a knowledge base for applying RCM as a maintenance strategy. There are three primary controls to consider:

(1) technical plans and drawings

(2) available resources

(3) operational tempo

The first two are included as constraints to the system development based on the logistical support available. The third stems from the stakeholder requirements, but is provided as a control in this case as the expectation is the operational mission will have priority over maintenance completion. The mechanisms for developing the requirements are, for simplicity, referred to as maintenance developers though this will most likely be a multiple-organization effort to ensure all stakeholders are included. Finally, the primary outputs are the problem statement along with clear and concise objectives with regards to the development of the maintenance system. It is imperative that these outputs be as objective and concrete as possible to ensure understanding and adherence across the spectrum of applications.

The problem need statement is an objective statement that highlights what the problem is without providing a probable, or desired, solution. For this research, the elements include developing a maintenance strategy, incorporate RCM, reduce the maintenance burden to the permanent crew, and ensure all resources are available. Continuing with the example of the OPC, a problem need statement for the OPC with regard to maintenance would be "Develop an overarching maintenance philosophy that, in general, identifies means of completing all maintenance associated with ensuring the cutter can meet an operational tempo of 185 days away from homeport, minimize overall crew maintenance requirements through the incorporation of reliability centered maintenance, and identify and provide all resources necessary to meet this strategy."

B. STEP 2: APPLY SYSTEMS ENGINEERING PROCESSES

The second step is to apply systems engineering processes. While this could be construed as a very broad consideration, the concept is to determine system functions, requirements, and thoroughly decompose through analysis to develop the breadth of the system. Figure 7 is an enhanced image of step two, with the corresponding ICOM information.

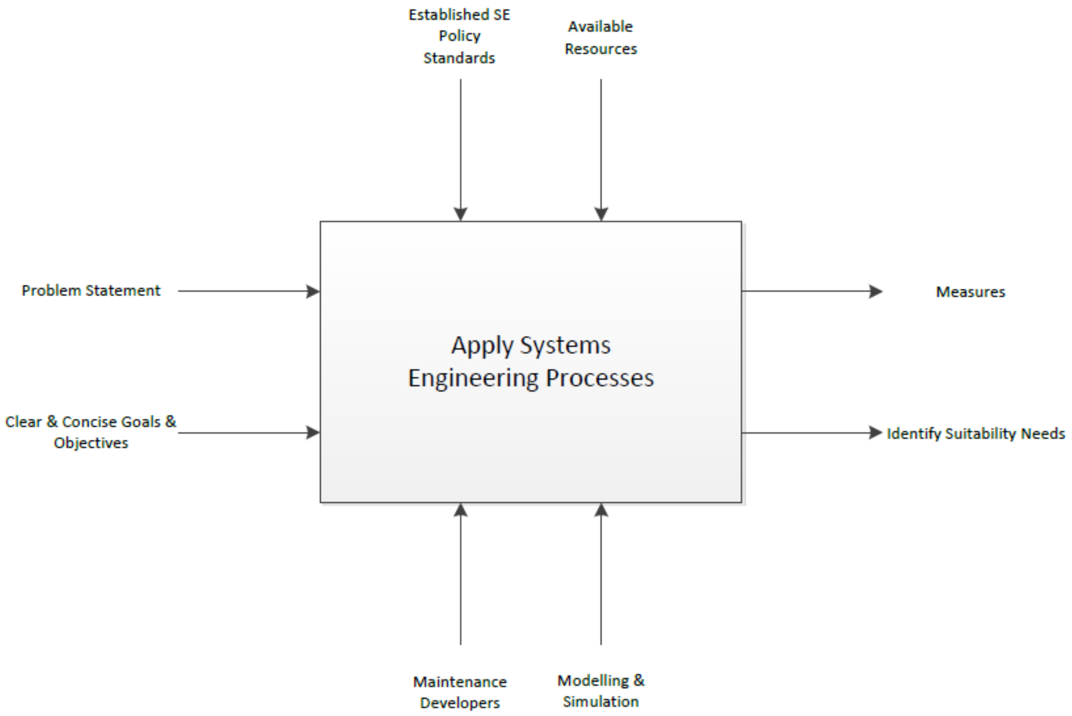

Figure 7. Step 2 for Developing a Maintenance Philosophy

This is perhaps the most important step with regard to developing the philosophy. This is when the designer begins to clearly identify and articulate how the system should function. From the derived problem statement, it is possible to develop system functions and requirements, which are an essential aspect of the architecture, especially with how it will interface with the physical components requiring maintenance. To aid in this development is a key facet of systems engineering: modeling and simulation. There are any number of means for accomplishing this, including discrete values iterated multiple times, stochastic means in a similar multi-run fashion, and even some degree of prototyping or demonstration of a maintenance method to ensure it is meeting requirements. This latter also describes the verification loop, which is introduced at this level. From step four, which will be discussed in a subsequent section, there is a designed-in mechanism to return to this process to ensure that the results of the analysis are what is desired. If the analysis appears incorrect or faults are identified, it is necessary to re-apply systems engineering.

The outputs for this step are measures and suitability needs. Measures refer to measures of effectiveness, performance, or suitability. In essence, this is a reflection for how well the system is functioning as a result of completed maintenance. For instance, a measure of performance, with regard to an engine, may state: ability to meet full power requirements for a duration of at least 10 hours. Similarly, a measure of suitability, for the same engine, may state: ability to operate without failure for 3000 hours between oil changes.

Before proceeding into the application of systems engineering, there is a baseline of maintenance tasks to consider. This baseline is typically derived from practices and actions on similar platforms, or even with similar ship-types. For instance, the OPC will be propulsed by two diesel engines with shafted controllable pitch propellers. A starting point would be to develop maintenance tasks that are used for the MEC cutter fleet. This may not be the best alternative moving forward, but it provides the designer with some context and point for initiation. Through the iteration of the SE process, additional solutions may present themselves for comparison, or may supersede, this baseline.

The four requirements provided in Table 1 are the fundamental knowledge for understanding how maintenance is to be conducted for the OPC. They not only provide stakeholder expectations, but also the basis for the overarching framework of RCM. Figure 8 provides further visual understanding of their interaction and use.

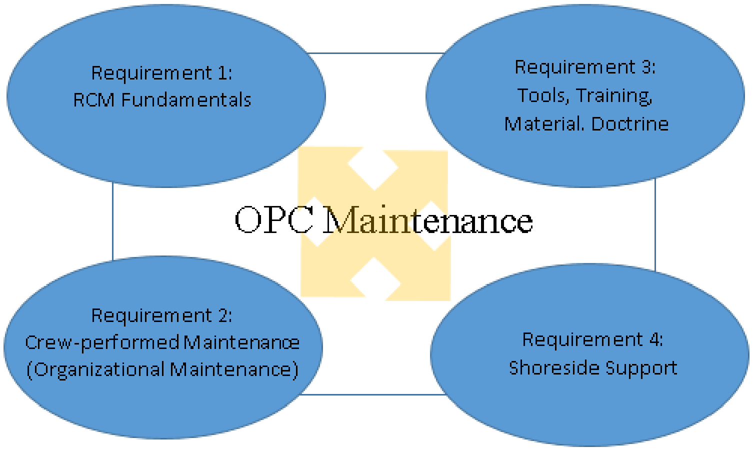

Figure 8. Concept of OPC Maintenance with Interconnectivity of Maintenance Requirements

1. Mandatory Use of RCM

This section discusses the first requirement: The essence of maintenance performed aboard the OPC shall be based on RCM fundamentals. As there are many different approaches to completing maintenance, there are also many different perspectives on what is right and what is wrong. In the essence of RCM, there is not a clear distinction of what is right; however, this uses actual data to determine optimized methods for completing maintenance with an inherent step to update as the system operates. Thus, the subjective desire to do this or do that is removed as quantitative measures are the focus of decision making.

2. Maintenance Completed by Crew

This section discusses the second requirement: the maintenance necessary for safe and correct operation of the cutter shall be conducted by the crew. It is considered common knowledge that when a ship is at sea, it must be self-sustainable until it enters a port or some sort of assistance arrives to offer support. For a Coast Guard cutter, this is a requirement for shipboard maintenance program. The crew is comprised of a number of specialty rates employed, each has some responsibility for maintenance. A "specialty rate" is a term common to the USCG and USN referring to specialty occupation designations for enlisted personnel. It may be a boatswain's mate (BM) completing hull preservation, a machinery technician conducting an oil change on an engine, an electronics technician (ET) repairing a radio, or a damage controlman (DC) cleaning and maintaining a fire plug. This would not include extensive repairs performed at discrete periods by an SME such as the overhaul of a generator's prime mover, those of an unforeseen or unplanned casualty such as the renewal of multiple length of a critical piping system that ruptured, or a fleet-wide engineering change such as the replacements of a classified communications system. The latter is a "gray area" that is not easily discernible as there are multiple influences, such as the mission's operational requirement, the overall importance of the system, the ease at which the casualty is corrected, and the potential impacts if the system were operated in an unsafe or incorrect manner. A careful balance and mixture of these different specialties is important for ensuring the effective, and efficient, completion of maintenance to meet operational requirements.

Operational requirements refer to performing the mission set for which the cutter is deployed. There may be many missions included in a singular concept of operations (CONOP) ranging from Alien and Migrant Interdiction Operations (AMIO) to counter-narcotics, but in general the ship is at sea, navigating and steaming under its own power. As this is the case, there are a few assumptions with regard to what systems must be included, and functioning, for the ship to operate including the example components listed in Table 2.

Table 2. Common Shipboard Systems

System	**Example Components**
Propulsion	main machinery, shafts, propulsor
Steering	rudders, hydraulics, rams
Navigation	helm, throttle control, ship's whistle
Electrical	generator, switchboards, motors
Auxiliaries	water, sewage, refrigeration, ventilation
Habitability/Subsistence	galley, furnishings, outfit

While not a primary focus of this research, being knowledgeable of shipboard systems and recognizing their contribution to the mission success is vital for having a vested interest in maintenance planning and completion.

In addition, a military vessel will also employ combat and weapons systems including radio detection and ranging (RADAR), multiple frequency communications systems, electronically controlled and fire-capable deck guns, and crew served weapons. Finally, there is a consideration of non-primary work activities including standing watch and conducting law enforcement. This further illustrates the broad spectrum of specialties needed for the OPC. This summary of personnel and their specialties will aid in the development of what maintenance is practical to complete based on a standard expectation for maintenance commensurate with daily operations.

3. Crew Provided with Tools, Training, and Materials

This section discusses the third maintenance requirement: the crew will be provided with all tools, training, and material so as to complete maintenance. Having the personnel to complete maintenance is a portion of the effort; a substantial intrinsic portion is having the correct tools, material, and training. The tools may be considered standard hand tools such as drivers, wrenches, hammers, and the like, though there will most likely be specialty tools. For example, these types of tools include specific instruments for inspecting and tuning the installed diesel engine, diagnostic devices for testing electrical equipment for grounds or faults, or measurement sensors for the thickness of metal plate. Ensuring that these tools are available, correctly functioning, calibrated (as needed), and easily replaceable in the event of failure is paramount for the correct application of maintenance. As the adage goes: use the right tool for the job.

Training is a reference to an abridged learning environment with hands-on application for knowledge building. It may occur in a classroom, shop, or at the “deck plate” level with supervisory oversight. It would be an unreasonable expectation for a member to be assigned to a unit with the understanding they are capable of performing tasks without any training or experience. As well, it would be unfair to expect that the training a member received in the past, perhaps 10 years or greater, remains the correct knowledge for updated practices. Recall there are two basic precepts with completing maintenance for operational use: on time and correct. Going through the motions for maintenance simply “checks the block” without ensuring it is correct, and as a result further casualties may occur which affect critical operational abilities.

The Coast Guard provides a number of training opportunities, carefully orchestrated through two training centers as well as various partners-in-industry settings. A baseline training regimen should be established for each member of the crew, which includes basic shipboard fundamentals such as damage control, and expand to the curricula associated with their position description. In theory, completing this training prior to arriving at the cutter would be ideal, and if not able, then immediate training prior to performing the maintenance.

Material is a broad term used to refer to consumables, expendables, and replacement parts. These items all play a role in the completion of maintenance, and must be readily available for the maintainer to complete the task to not negatively impact operations. Consumables are defined as supplies that are intended to be used and discarded. This includes oils, greases, and solvents that are a necessity for various maintenance tasks such as an oil change on an engine or the application of a coating system when conducting preservation. Expendables are defined as supplies that may be sacrificed in order to complete an objective. The responsible party for purchasing, storing, and using consumables and expendables should be delineated and enforced. One concept is the “Push-Parts” program utilized by the Coast Guard’s Surface Forces Logistics Center (SFLC). This is a program that aides in the control of maintenance tasks by issuing a set number of material for the completion of some period of maintenance tasks and automatically replenishing the supply as the period nears the end. The benefits are inventory and replacement costs are controlled and storage space aboard the vessel is less cluttered.

Replacement parts are those that are necessary for specific corrective actions such as the rebuild of a piece of auxiliary machinery or a primary component for a system; an example of the latter would be a display monitor for a radar system. Numerous studies are available, across the military and industry, regarding the available spares necessary for assurance of some desired operational availability. With regard to cutter maintenance, this may include parts that are kept aboard for immediate access or may be located in a centralized inventory. Existing maintenance processes in the Coast Guard preclude the retention of repair parts other than those that are easily shelved or stowed. In fact, annual inventories require the designation of what parts are allowable at each unit, along with identifying information, so that quick access for other units is possible in the event they suffer a casualty or a failure. The allowance and availability of consumables, expendables, and replacement parts is a significant prerequisite for the completion of maintenance. Proper planning by the maintainer and technical authority will assure that tasks may be completed on time, and correctly.

In summary, the guidelines presented with respect to tools, training, and materials seem to be common sense, but must be more than words on paper. Programs must be established that impart these ideas with adequate oversight to ensure adherence. As well, checks and balances must exist between these three concepts to maximize the notional benefit of completing maintenance correct the first time, in the allotted time, with the correct tools, and readily available parts and material.

4. Availability and Use of Shore-side Support

This section discusses the fourth, and last requirement: shore-side support shall be available to augment the crew's completion of depot and organizational maintenance. Shore-side support: a broad and taxing challenge to define, let alone execute. Within the Coast Guard's mission support structure, shore-side support is a general conglomeration of technical experts and professionals who may be called upon for a litany of tasks from parts management to multilevel applications of work with respect to Coast Guard property or assets. To allow the reader to remain attentive to the idea of maintenance, specifically with regard to cutters, this discussion of shore-side support will focus specifically on naval engineering. The primary naval engineering support network within the Coast Guard is the Surface Forces Logistics Center (SFLC).

This organization is comprised of multiple fleet-centric product lines who provide tiered support for general support for an asset and engineering management, programmed depot maintenance oversight and execution, and technical expertise related to various disciplines in engineering (for example naval architecture, mechanical engineering, or electrical engineering). It includes multiple hubs of expertise, geographically distributed across the United States. While these hubs provide the first level of response with regard to technical support and logistics, there are additional subunits available for local response. These subunits are the premise with regard to the shore-side support that must be available for supporting the cutters.

The subunits are established through multiple means. They may be available as a direct naval engineering, or industrial activity, such as a Maintenance Augmentation Team (MAT) or they may be a subordinate department under the administrative control of a Coast Guard Base, such as a Naval Engineering Department (NED). Bases are established as a primary logistical support command, and dispersed in broad geographic fashion to support the needs of the operational commander, usually at the District level. There are several departments associated with a Base, but the two that are most often called upon for cutter support are NEDs and Electronics Departments (ED). This is where actionable tasks for the cutters, from a shore-side support unit, initiates. An expectation with regard to OPCs is they will be co-located with these support elements so that when the cutter is in port, additional resources are immediately available for support.

The first question that arises is if these shore-side elements are available, and the expectation is they will be performing maintenance, then who is the cognizant authority for ensuring the maintenance is completed on-time and correctly? At all times, the responsibility for ensuring the OPC is ready-for-operations (RFO) rests with the cutter's commanding officer, but there is certainly shared ownership with the technical authority. It must be clear where any lines of demarcation exist between what the cutter crew is always/responsible for and what the shore-side unit is always responsible for. Traditionally, this demarcation line is the separation between organizational and depot level maintenance, but more and more an impetus is on minimizing the impact to the crew to ensure operations are paramount and the cutter functions with only what is necessary.

An example would be the ability of a cutter's crew to disassemble and clean in place a fuel oil purifier (FOP). The FOP, usually a centrifugal filtering system, is used to clean bunker fuel before transfer to ready-service tanks. Over time, the FOP becomes fouled with carbon, dirt, and other debris and requires cleaning. While the cutter crew is able to disassemble and wipe-clean all surfaces, there are advanced tools, training, and knowledge that allow for in-depth cleaning. The determination for the level of cleaning may be based on industrial standards, in this case correlating to the amount of fouling that exists.

As the resources needed for the machinery and certification are high in value, there are a limited number of available units. This is where the demarcation line exists between organization and depot level maintenance. The crew activity may occur multiple times before requiring depot support. Once this line is crossed, a clear understanding of technical authority and maintenance ownership must be understood; ultimately, the cutter crew will continue to have a vested interest as operators and general maintainers. Figure 9 is provided as a general process to follow when considering whether maintenance should be organizational or depot.

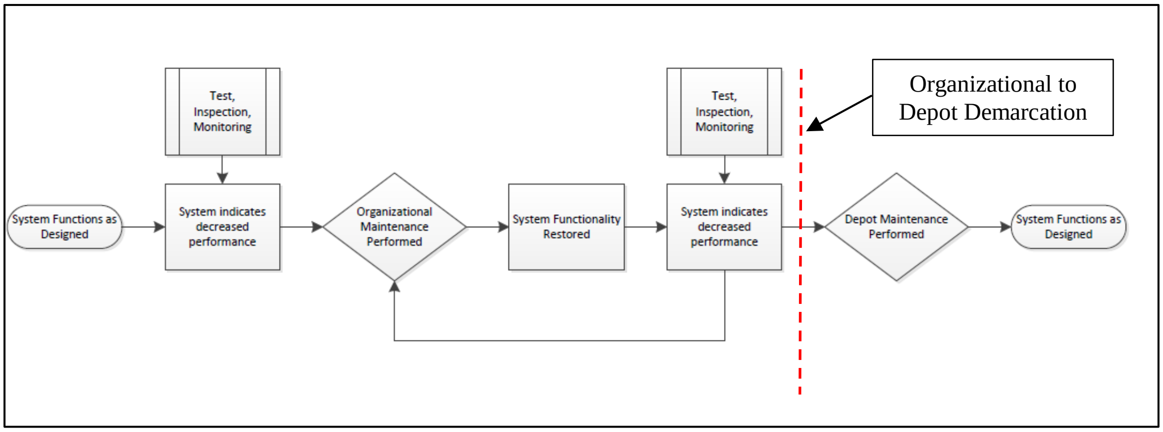

Figure 9. Separation between Organizational and Depot Maintenance Activities

An essential skill that is a necessity for success any endeavor is communication. There must be regular communication between the cutter leadership and the shore-side support element without barriers of ownership. Often there are tasks cast aside or priorities re-routed based on differences of opinions or directing an agenda not consistent with published standards. This problem is easily overcome through early identification of what is needed, verifying the need, and then working together to capably satisfy the need. For instance, the shore-side support provided to a Coast Guard cutter from a MAT is an example. MATs are subunits of NEDs, and are commonly naval engineering-centric, though there be a weapons support activity attached. Their primary purpose is to complete scheduled depot-level maintenance tasks, usually on a quarterly cycle to align with the cutter's deployment schedule. A successful maintenance period is indicative of a cutter with an engineering department that is very proactive in completing as much maintenance as possible, while remaining fully transparent on what had to be deferred. In preparation for the quarterly MAT visits, these maintenance items were discussed early as potential follow-on work AFTER the depot efforts were completed. To ensure success, the engineering department's sole focus was to work alongside the MAT so that all requirements were satisfied. The end result was maintenance completed correctly, timely, and learning occurred from both groups.

Another aspect of shore-side support is contractual. Contractual labor is often a slippery slope, with different elements from mission support focusing on the level of effort a dollar may buy versus the overall education and experience gained from hands-on endeavors. As well, there are some tasks that are best suited for a singular level of expertise that may not often be found within the Coast Guard. This may apply to equipment inspections as well as level of effort. A beneficial aspect for RCM is by developing some recurrence of depot-level tasks that use an individual, or very small pool, of contractors to complete will allow for further analysis of trending as the same individuals are inspecting and observing the fleet as a whole.

A final thought with regard to shore-side support is not unlike that previously stated with regard to resources. Just as the cutter crew requires specific tools, training, and abilities, the shore-side support unit requires the same, if not more. These units may be considered SMEs to an extent, and so their presence is not simply for completing any work, but also to train and educate others for future benefit. Having the correct tool and repair parts ensure the maintenance is completed as designed and decreases the probability of failure due to incorrect processes. Figure 10 is a general synopsis of maintenance determining factors and subsequent decisions.

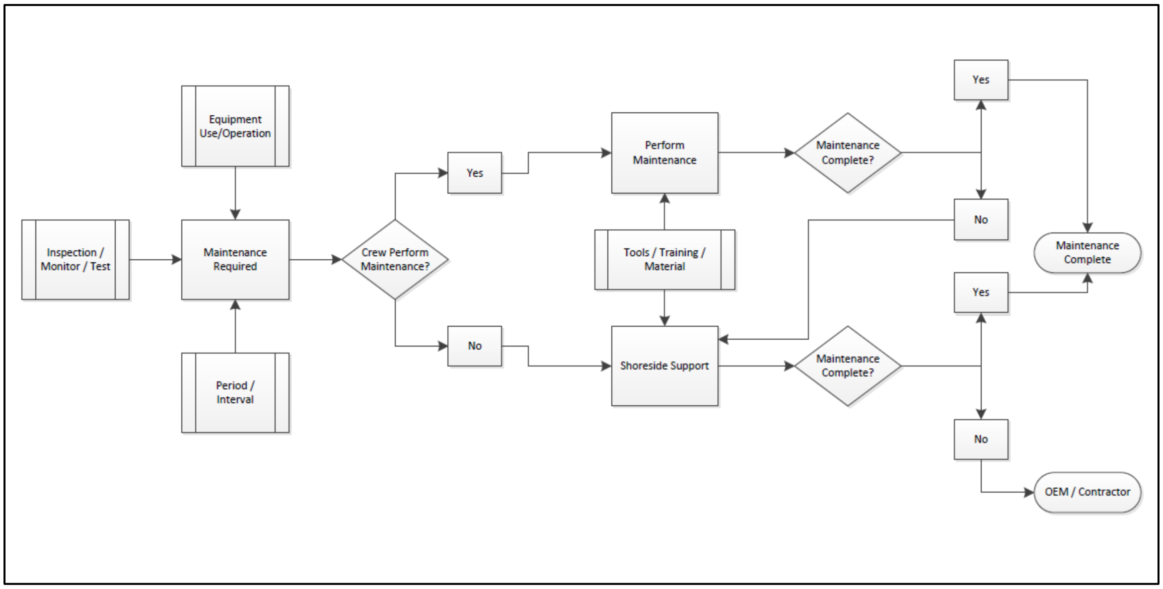

Figure 10. General Maintenance Flow and Completion Decisions

C. STEP 3: OPERATE SYSTEM

Step three is highlighted by a transition from paper to product. At this point, having determined the crux of the problem and decomposing the requirements to determine how the system should be operated, it is now time to operate the system. Figure 11 is provided as the enhanced view of step three.

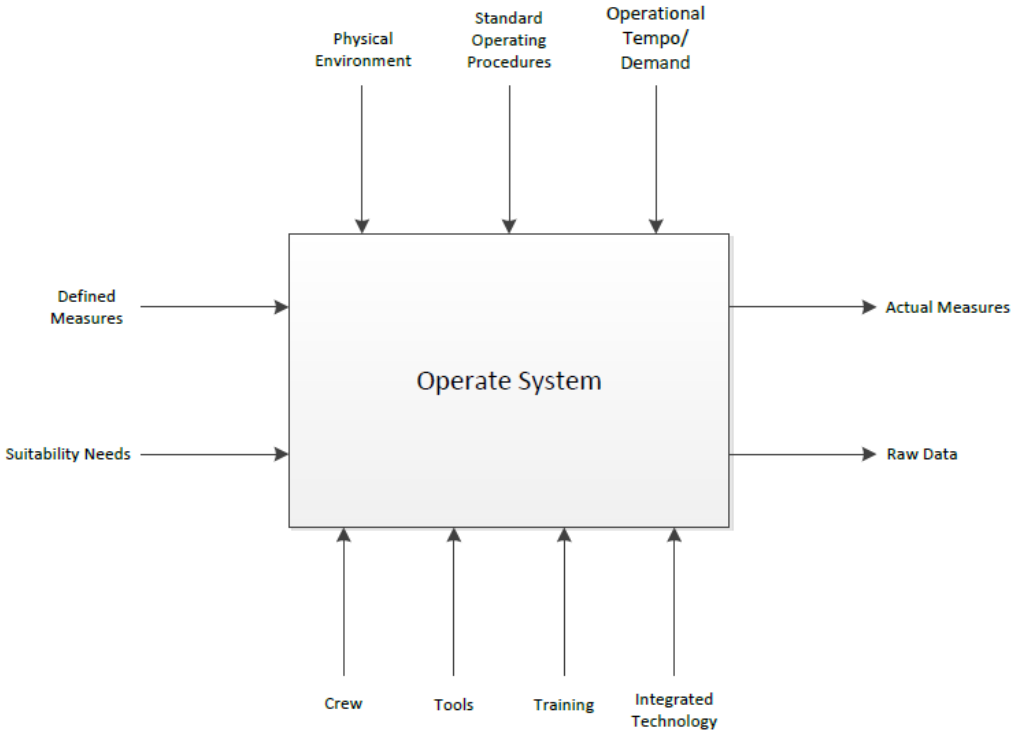

Figure 11. Step 3 for Developing a Maintenance Philosophy

Operating the system is a vital aspect for achieving functionality. When it comes to equipment or machinery for achieving any need, there are physical limitations and correct operating sequences associated with its use. As well, there are expected performance capabilities, which is what *defined measures* refers to. As well, the suitability needs refer to those items such as reliability and maintainability, which must be defined into it. There are several controls for this step, which all relate to how the system is intended to be used. When considering the OPC as a system on its own, there are standard operating procedures for starting or energizing any piece of machinery as well as navigation standards for the safe operation and transit of the cutter. The physical environment is a reference to the weather and sea conditions, which there will always exist conditions that limit the ability of a ship to perform as designed.

The mechanisms for this step are broad, and it is here where we begin to introduce more of the human element and the potential for error. To prepare, and potentially correct, for the latter, the correct tools, training, and material must be utilized to ensure misuse or incorrect practices are not adopted. Furthermore, as technology continues to progress, the use of integration capabilities, such as a programmable logic controller, may also be utilized for automatic start and stop, if equipped. What is truly of interest for this step are the outputs: raw data and actual measures. The raw data is simply how the system is operating. When considering a reverse osmosis desalination plant, this may be a specified number of gallons of water per hour. This same value may be compared to the defined measure, which is how *actual measure* is defined. Having this information is invaluable in allowing the operator and maintainer to better understand how their system is operating and prepare to move to the next step.

Through operation, a goal is to identify how well the system is performing based on measures of suitability (MOS) and effectiveness (MOE). These measures will aid in the evaluation of alternative architectures that, collectively, will be used to develop the overall maintenance strategy. This will most likely not be a one-time occurrence and will require multiple iterations; this is where the verification loop is introduced so as to compare actual results against theoretical measures.

A measure of effectiveness (MOE) is a measure used to correspond to accomplishment of mission objectives and achievement of desired results. In essence, it is an indicator of how well a mission requirement is being met. These are typically quantified and the desire is to be representative of a system's ability within its operating environment. To further support MOEs, measures of performance (MOP) are also established which relate to the achievement of a particular MOE. By developing these measures, it is possible for those involved in the development and execution of a system to recognize, identify, and understand the system's performance. With respect to a cutter, there are a great many MOEs that could be discussed.

It is important to identify and develop these measures early in the process, perhaps as early as the development of the ICD, as they can assist with the architecture and framework of the design so that stakeholder needs are met. During their development, it is also prudent to determine an objective or threshold value for assurance that a system requirement is met. An objective value is a desired value and threshold is a required value. There may be a difference between the two; for example, a performance requirement for a ship includes an objective speed of 24 knots and a threshold speed of 22 knots. This difference is valuable information as this is trade space. Trade space is a tool that aids in a "give and take" to create improvement or increase performance. However, it usually comes at a cost. Referring back to the example of ship speed, to increase the speed from 22 to 24 knots, it may require larger engines, hull redesign, or larger propellers. In turn, this will add weight, most likely require more people, and may include additional components that must be inspected and maintained.

Many of the MOEs associated with a ship are common performance criteria. For instance, one may be interested in the vessel's top speed, transit speed, sea keeping ability, efficiency with regard to fuel consumption, delivered horsepower, or physical dimensions. But how do these relate to maintenance? What facets of a maintenance program must be considered to satisfy an operational need? Simply put, if maintenance is performed correctly, and on time, then the operational requirements are met with the ship completing its mission. But to what degree of effectiveness? To best answer these questions, a concept referred to as *design for suitability* is considered.

A measure of suitability (MOS), as defined in the Defense Acquisition Glossary, is "a measure of an item's ability to be supported in its intended operational environment" (Hagan 2015, B-163). Suitability is a generic term that incorporates an ever-increasing list of characteristics that commonly, but not always, end in "ility." The list includes concepts such as reliability, availability, transportability, supportability, killability, and so on. For the purposes of this analysis, the primary descriptors considered will be reliability, availability, maintainability, supportability, and usability, which is also referred to as human systems integration. Each will be expounded upon in detail, including specific traits to consider when evaluating system performance as well as inputs for modeling.

Designing for suitability is not always an easy task. In fact, this is a concept that quickly escalates based on the numerous trade-offs with more and more "ilities" included. A trade-off is a compromise between at least two parties to balance between at least two desirable, but incompatible features. This is where an understanding of the "ilities" being considered is important, including how they relate to each other. In fact, as will be discussed, the results of one study, such as reliability, may impact maintainability, which may in turn impact availability. Designing for suitability is an important concept to quantitatively provide decision makers with a realistic expectation of what the performance level should be and to deter from an archaic approach of "[I] want a specific reliability percentage, so make it happen."

D. STEP 4: PERFORM ANALYSIS USING DATA FROM INSPECTION, TEST, OR MONITORING

With the system operating, and raw data collected in the form of an MOE or MOS, the next step is to analyze this data. The analysis should not be from one source, but an integrated product that relies on the three different pillars of RCM, as presented in Figure 12. This is where verification begins, and the results may have significant impact on modifications to the system based on how it is operating. The following figure is an enhanced view of step four of the maintenance philosophy framework.

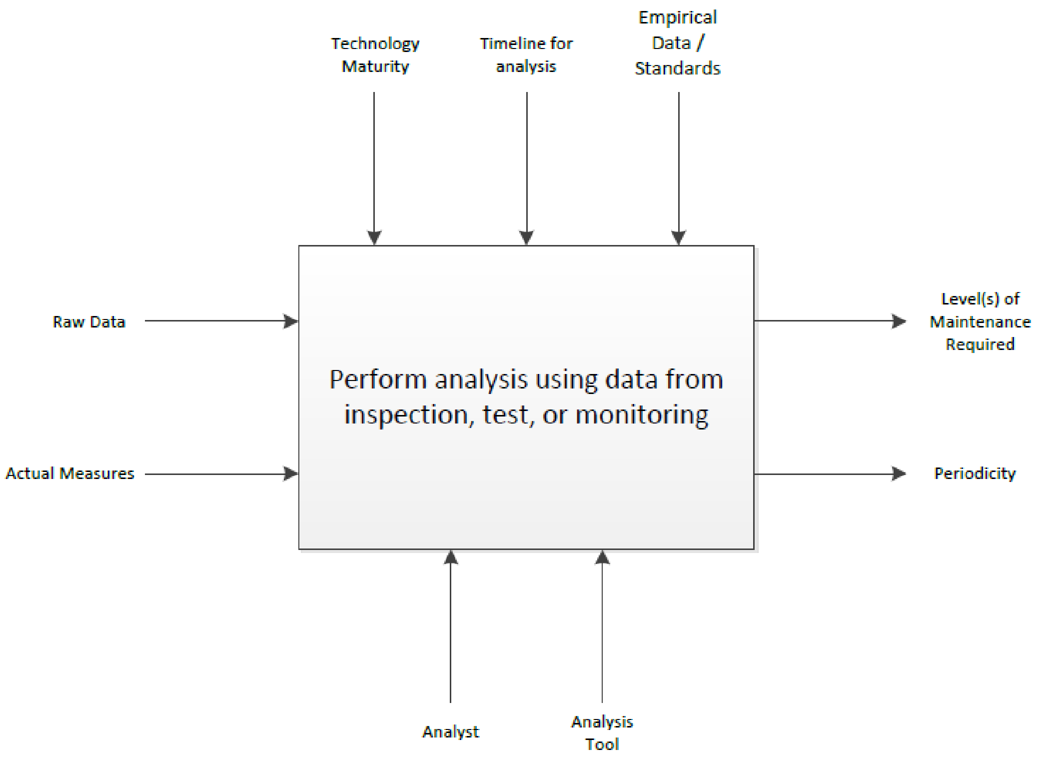

Figure 12. Step 4 for Developing a Maintenance Philosophy

With raw data and measured values collected, it is now possible to conduct analysis which serves two purposes: how well the system is performing and what maintenance is needed. Further, this aids in determining the level of maintenance require if it is needed. The level is a consideration of organizational versus depot. The controls associated with this step include the maturity of the technology, timeline for analysis, and empirical data or standards associated with the performance. As technology is a broad term that can be affixed to essentially any piece of equipment, it must be scoped for the purposes of this development process. Technology, in this instance, is a reference to how mature, or established the piece of equipment is that is being analyzed. This is not a concern of performance as much as it is a reference to the ease at which maintenance is applied. That attribute is shared with the empirical data and standards as this information will be factored in as comparative analytics with the raw data as well as any measures calculated from the raw data. With respect to the timeline, it is important that any analysis be completed and briefed in a timely manner. This timeline will vary from program to program, but the general idea is that the longer it takes, the less valuable the analysis is as more recent data is now available.

Performing the analysis involves using skilled individuals, ideally with a background associated with the parameters analyzed. In essence, a pool of SMEs that are not simply number crunchers and can provide some validation of the analysis. Additionally, established analytical tools are necessary to enable the manipulation of the data and develop credible and presentable information for decision makers. Whichever tool is selected, it is important that it be able to provide useable information that can be tailored to the system being analyzed.

The outputs for this step are a determination of the levels of maintenance and periodicity. Use analytics to supplement the use of RCM methods of monitoring, testing, and inspection, all involved will have a better understanding of how well the system is performing and if any early telltale indications are present that could signify pending losses in function or failure. This is used for determining what the period for maintenance should be; the period refers to how often such as daily, weekly, or quarterly. In addition, depending on how the system is operating, and any variation from how it should be performing, may indicate if the cutter crew is capable of completing the maintenance or if a higher-level technician, either organic USCG or contractor, is necessary. For both factors, it is important to remember that this will most likely change from time to time. It is hypothesized that as the system ages closer to its expected life cycle, a shorter period and more depot maintenance will most likely be required.

With respect to analyzing suitability, there are several formal measures that are applicable. These measures are typical factors associated with most every system, and can provide a quick snapshot of how the system is function as a whole. The measures of suitability that will be discussed include reliability, maintainability, and availability. Two additional measures that would not have immediate feedback as they are more abstract that quantitative are supportability and usability.

1. Reliability

Reliability is an ability of a system, or component, to function under stated conditions for a specified period of time. A simple analogy is with regard to a basic internal combustion engine. When running, an operator expects, and assumes, that the engine will run for an indefinite period as long as the requisite inputs such as fuel, air, etc., are available. If, after so many thousands of hours the engine fails, it is possible to quantitatively determine the engine's degree of reliability. This is perhaps the most important concept for this study; reliability centered maintenance is focused around the ability to allow machinery to operate, in a normal environment under normal load conditions, until some sort of failure occurs or an integrated sensing system determines that some sort of maintenance is necessary. When this occurs, the time frame that is associated with it is referred to as the mean time between failure (MTBF). This value is used for various calculations, some of which are presented for the reader's ability to model system performance. Another characteristic determined from this information is the failure rate (λ), which is simply the inverse of the MTBF, as illustrated in the following equation.

$$\lambda = \frac{1}{MTBF} \qquad (1.1)$$

Reliability aboard a ship is a very complex, and lengthy, calculation to complete. The reason being is to determine an exact value, one would need to know the reliability metrics associated with every component of every system onboard. Thus, for ease of calculation, and to provide a simple “back of the envelope” calculation, the author’s recommendation is to identify those systems that have the potential of creating the most impact through their use, then determine the reliability associated with their functionality. However, a caution is that if the entirety of the system is considered wholly, there is the potential that an overlooked component may impact the system negatively. Deciding what components to include is a topic for discussion and individual experiences may provide a significant role in their selection. In addition, using this information and determining a desired confidence level based on sample statistical data will allow decision makers to better grasp the variance in what a reasonable reliability measure is as well as identify if any trends, negative or positive, are occurring.

Reliability is calculated primarily from the failure rate and time, but can be modelled using many different distribution functions. These typically include the exponential, normal, Poisson, or Weibull. One must have a sound understanding of how the system is performing, especially its failure behavior, to select the best model. Typically, the exponential is used as this considers failure to occur randomly, but that is not always the case. To calculate reliability using the exponential distribution, the following equation is applied:

$$R(t) = e^{-\lambda t} \tag{1.2}$$

For a majority of the time, reliability of a system can be described in terms of being in parallel or in series. If in series, one would simply multiply the reliabilities of the individual components to determine system reliability. If in parallel, one would need to multiply the complements of the component reliability and then subtract that from unity. The following two equations provide these relationships:

$$Series: \prod_{i=1}^{n} R_i \tag{1.3}$$

$$Parallel: 1-\left(\prod_{i=1}^{n}\left(1-R_i\right)\right) \tag{1.4}$$

An important distinction is that parallel reliability is a product of redundancy, and is always better than series. The tradeoffs for improving reliability normally include added cost, more machinery, less space, more system complexity, or more personnel.

2. Maintainability

A second consideration with respect to system suitability, and a primary focus of this thesis, is that of maintainability. Maintainability, as defined by Blanchard and Fabrycky (2011), is "the ability of a system to be maintained and/or repaired (in the event of failure) and returned to service rapidly and efficiently" (410). This element is considered an enabler of improved system reliability, and focuses on how well, how often, and to what degree maintenance should be performed. To maximize its features, the earlier maintainability is introduced and incorporated into a system, the better; it must be built-into the system architecture and design. General descriptors evident of designed-for maintainability include separations between equipment for ease of access, minimizing different components for ease of maintenance, common spare parts, and having an optimized maintenance schedule.

There are several metrics related to maintainability. With regard to system design and function, these metrics relate to the frequency of conducting maintenance, the factors that affect that frequency, the time it takes to actually complete the maintenance task, and the cost. An important concept is that requirements associated with maintainability do not only relate directly to the system itself, and its ability to be maintained, but also logistic and support infrastructure that enables this. It is paramount that the stakeholders establish some expectation regarding system readiness, or availability which will be discussed later, so that the factors affecting frequency are designed to meet their desire.

In general, there are two broad categories of maintenance: corrective and preventive. Corrective is a response to some unscheduled failure event that requires restoring a system or product to a specified level of performance. Having a response plan, including training and sound engineering acumen is often one's best method of preparation for completing corrective maintenance, though a reasonable answer, based on the conditions, may be to do nothing until there are additional resources at hand. The time it takes to complete a corrective or restorative action is determined and represented as the mean corrective time ($\overline{M}ct$) or mean time to repair (MTTR). This is an important metric that factors into the overall down-time of a system as a result of maintenance. As a primary purpose of this analysis is to provide guidance and direction related to day-to-day activities involving maintenance, corrective maintenance will not be further discussed in detail. Preventive maintenance, in contrast, is.

Preventive maintenance is maintenance performed at a regularly scheduled frequency to retain a system at a specified level of performance. It includes tasks associated with general upkeep of a system and may also include diagnostic measures such as an inspection or test. This category is an architectural driver for answering the following maintenance philosophy questions:

- What components should be included in a system and to what degree of technical difficulty are they?
- What resources are needed for meeting system readiness? Resources include people, tools, consumables, expendables, spare parts, and training.
- How often should a system undergo preventive maintenance versus how often must a system undergo preventive maintenance. Furthermore, can maintenance be deferred and, if so, what are the impacts?

In the likely event that a system failure will occur at some point, it is necessary that casualty be corrected. To do so, it must be understood what the failure is, what contributing factors led to the failure, what did the failure affect, and what is required to correct the failure. Collectively, all of the steps take time; however, as each may be important to specific individuals analyzing the problem, in general the metric used is mean corrective time, or $\bar{M}ct$. The equation for calculating $\bar{M}ct$ for a system incorporates failure rates of the components and their respective $\bar{M}ct$. The following equation is utilized:

$$\bar{M}ct = \frac{\sum(\lambda_i)(Mct_i)}{\sum \lambda_i} \qquad (1.5)$$

The author cautions that this is a general equation, and that the maintainer must have an understanding, or expectation, of what the repair time distribution is as that there are additional means for calculating to a higher degree of precision. For purposes of this research, this general equation is used.

Just like there is a measurement for the length of a corrective maintenance action, the length of time associated with a preventive maintenance action is also calculable. This is referred to as mean preventive maintenance time ($\bar{M}pt$), and is a function of the frequency of the action (*fpt*) and the time necessary to perform an individual maintenance activity (*Mpt*). Mathematically, it is expressed using the following equation:

$$\bar{M}pt = \frac{\sum(fpt_i)(Mpt_i)}{\sum fpt_i} \tag{1.6}$$

An important consideration of this calculation is it only includes active maintenance times, and not those that are impacted by administrative or logistical delays. For instance, the time assumes that the appropriate number of maintainers are present, they are adequately trained, have the correct tools, and all hardware necessary to perform a task.

If the mean corrective and preventive maintenance times are known, it is possible to combine these into a mean active maintenance time or $\bar{M}$. This is a mathematical computation that includes the two categories as well as the failure rate, λ, and *fpt*. This is also exclusive of logistics or administrative delay time, and is one of the components included in calculating the overall maintenance downtime (MDT). The formula is as follows:

$$\bar{M} = \frac{(\lambda)(\bar{M}ct)+(fpt)(\overline{Mpt})}{\lambda+fpt} \tag{1.7}$$

A final measure with regard to maintainability is mean time between maintenance, MTBM. This incorporates both planned and unplanned maintenance into a single measure, and will be a primary variable for calculating system availability. Essentially, this measures bridges a gap between reliability and maintainability, further emphasizing the important that integrating both attributes is a necessity for a complete evaluation of system performance. The formula is given as:

$$MTBM = \frac{1}{{}^{1}/_{MTBM_u} + {}^{1}/_{MTBM_s}}, \tag{1.8}$$

where, $MTBM_u$ is the mean period of corrective maintenance and $MTBM_s$ is the mean period of preventive maintenance. For general application, and most approximation, it is feasible to equate $MTBM_s$ with MBTF; thus the integration with reliability.

Maintenance categories are not the only facets affecting a system's maintainability. As stated, these categories do not include administrative or logistics delay time, but those are also important considerations that must be addressed. To better understand the importance of these two metrics, each is described and expressed individually. Logistics delay time (*LDT*) is a measure of the time a system is down due to some area of support. This may include a delay in a specific part being available, a service necessary to perform maintenance, transportation, availability of a facility, and so on. Determining LDT is a simple arithmetic function that includes all of those items associated with the delay. This amount is an additional factor involved in calculating the MDT.

Administrative delay time (*ADT*) refers to the time associated with maintenance not being performed due to some administrative cause such as personnel assignments, organizational constraints, or a problem with the workforce such as a labor strike. This is a delay that is difficult to quantify for a military vessel because of the expectations of the workforce within a military chain of command and streamlined processes. However, it may be included as "other" time that is not easily determined or specified. *ADT* is the final component of maintenance downtime. Thus, *MDT* is calculated in the following fashion:

$$MDT = \bar{M} + LDT + ADT \qquad (1.9)$$

It is important for decision makers to be aware of the different factors that affect *MDT* as this is the combination of different maintainability metrics. As related to shipboard maintenance, this value is a starting point for breaking down individual delay or activity times and allows for optimizing processes so that each variable is minimized. For $\bar{M}$, this may include specifying the periodicity of when maintenance actions would be performed and by whom; for LDT, this may dictate programs for forward deployment of parts and resources as well as contractual measures for expeditious support; and for *ADT*, this may include considerations of individual personnel onboard as well as what competencies shore-side technicians are required to demonstrate.

There are other maintainability metrics that may be considered, but are not necessarily directly applicable for an overarching maintenance philosophy. These would provide more substance with development of individual, and specific, maintenance programs to address the procedural requirements for a system. These other factors include:

- Labor Hour Factors: Important considerations of how many labor hours are expended for different trades including per operating hour, cycle, period (day, week, month), or action.
- Frequency Factors: This is a key factor that relates to how often maintenance should be completed. It is a pivotal balance of doing what is needed at the right times and not performing to much as that may have a degraded effect on the system.
- Cost Factors: Everything has some cost value associated with it. For the application of a military ship, one that is subject to taxpayer dollars, the desire is to complete necessary maintenance at a minimal cost. These include costs per action, per operating hour, per period, and per mission. In addition, to gain a perspective of the overall impact, one may consider a ratio of the maintenance costs to the overall system life cycle cost.

Planning for, and executing, a sound maintainability strategy is requisite for any system to achieve success.

3. Availability

With system reliability and maintainability known, the next suitability trait to determine is availability. Availability refers to the ability of a system to operate when desired. There are three general conditions that may apply: inherent, achieved, and operational. Inherent and achieved focus on availability given ideal settings, and so they will not be further discussed. Operational availability, however, is the “probability that a system or equipment, when used under stated conditions in an actual operational environment, will operate satisfactorily when called upon.” To calculate A_O, the following equation is used:

$$A_O = \frac{MTBM}{MTBM+MDT}, \qquad (1.10)$$

where *MTBM* is the mean time between maintenance and *MDT* is maintenance downtime. This metric is one that operational commanders most often focus on as it relates directly to readiness and their ability to initiate, or respond to, a mission set.

4. Supportability

Supportability is a reference to the logistical support mechanisms available to render aid and assistance in all manner of things related to the system. With respect to this research, the primary application is that of shore-side support. As stated, the USCG utilizes multiple product lines within SFLC’s organization. The product lines are separated to support the different classes of cutters, and each is primarily composed of three branches: supply, programmed depot maintenance, and engineering. An expectation is that the cutter is the customer, and so any need must be responded to in a timely fashion. Often, the support from the product line is to provide spare parts, coordinate a service for repair, plan extensive maintenance periods, or coordinate advanced technical engineering support. This shore-side support is critical to meeting the operational and maintainability requirements for stakeholders.

5. Usability

A final design for suitability is that of usability, or as it is commonly referred to, human factors integration. Just as much as hardware, software, machinery, and equipment are a part of the system, so is the human that is completing an aspect of the system’s functions. In essence, this is an understanding of how the human and various components of the physical system interface with one another. It may be pertinent to ask why consider human factors in the design of a system. The rationale is a system, that is operated or maintained through human interface, is only as strong as the components from which it is derived. If all parts are not functioning correctly, like a well-oiled gear, then there is an increasing probability of casualty or failure. In addition, when considering this characteristic with the goal of developing a sound, and useful system, it is important to recognize that safeguards must also be established to prevent incorrect or misuse as that could also result in system failure.

When developing a maintenance philosophy, there are several tenants of usability to consider. These tenants include:

- Who will perform maintenance and with what skillset?
- When and where will maintenance be performed?

- How long will the maintenance take and what fatigue limits must be identified and imposed?

To aid in answering these questions, Blanchard and Fabrycky (2011) provide a breakdown of human factors elements. The following definitions and examples are provided verbatim from their *Systems Engineering and Analysis, Fifth Edition* (469–470).

- *Job Operation*: Completion of a function normally includes a combination of duties and task. A job operation may involve one or more related groups of duties, and may require one or more individuals in its accomplishment. An example is operating a motor vehicle or accomplishing a maintenance requirement.
- *Duty*: Defined as a set of related tasks within a given job operation. For instance, when considering the operation of a motor vehicle, a set of related tasks may include driving the motor vehicle in traffic on a daily basis, registering the motor vehicle yearly, servicing the motor vehicle as required, and accomplishing vehicle preventive maintenance on a periodic basis.
- *Task*: Constitutes a composite of related activities performed by an individual in accomplishing a prescribed amount of work in a specified environment. A task may include a series of closely associated operations, maintenance inspections, and so on.
- *Subtask*: Depending on the complexity of the situation, a task may be broken down into subtasks to cover discrete actions of a limited nature. A subtask may constitute the shifting of gears from first to second, a machine adjustment, or a similar act.
- *Task Element*: Task elements may be categorized as per the smallest logically definable facet of activity that requires individual behavioral responses in completing a task or subtask. For example, the identification of a specific signal level on a display, the actuation of a switch on a control panel, and the interpretation of a go/no-go signal. This is the lowest category of activity where job behavioral characteristics are identified and evaluated.

These five tasks, in order of succession, provide an allocation of functions from top-level overarching to the smallest human activity associated.

With these elements outlined, one may now return to the questions regarding the maintenance philosophy and human factors. The first is one that may have a broad answer, but a review of the vessel’s requirements aids in its answer. In general, the “who” in who should perform the maintenance is a cognizant member of the crew assigned into a particular billet code, with a specified background commensurate with the equipment to be maintained, and is suitably trained to perform the maintenance task. The billets assigned to a vessel are based on competency and expected experience from a desired level of leadership. For example, a machinery technician, first class, is typically placed in a leadership position for maintenance over complex systems including main diesel engines or hydraulic systems. This individual is highly trained for these systems; unlike junior personnel, this individual has an advanced skillset for diagnosing casualties and affecting repairs, but unlike senior personnel, is not yet removed from the physical maintenance element to more of an administrative and leadership role.

The second may have many different answers, but in general it refers to what is a suitable location for completing maintenance and when, during the day, it would take place. It would not be prudent to complete maintenance on a piece of machinery outside and in adverse weather conditions. Nor would it be satisfactory to complete maintenance at midnight when extreme fatigue may be occurring. While it may be difficult to specify when a maintenance task occurs, and there may be unique cases that require specific conditions (such as sea conditions for conducting a full power trial or checking clearances for a propeller shaft thrust bearing), management of when these maintenance actions take place is left to leadership to manage. One caveat, which will be discussed in chapter four, is a reference to the amount of maintenance conducted.

Lastly, and following with the second, is the length of time that a maintenance action may take and what fatigue limits to consider. An important aspect of human factors is safety. Considering safety is important not only from the perspective of the maintainer, but the system itself. Safety may be an assurance that the maintainer is well rested, nourished, and not in an adverse climate for an extended time (i.e., 100+ temperatures in an engine room for longer than 30 minutes). If any of these elements exist, it is possible the maintainer may inadvertently cause harm to himself or a shipmate, or may cause damage to the equipment due to carelessness or complacency. Once more, this is a leadership challenge, but the statistically accurate length of time to complete the tasks aid in planning and ensuring the task is not becoming overly burdensome.

A final though on usability is with regard to the physical design of the system, in this case the machinery and equipment installed aboard an OPC that will require maintenance. Ideally, everything would be accessible from an average height individual at an average arm's length distance without the need to bend over, peer around, or reach for. Is this realistic? Most likely it is not, but there is a study of Anthropometric Factors, that considers the physical dimensions of the human body. The results of surveys that develop these factors provide the designer with a 5th and 95th percentile of statistics with regard to the dimensions. However, not everything is addressed such as the circumference of a screwdriver or the weight of a special tool, and so that must be addressed with the development of the maintenance action, including the number of people recommended to perform such action.

6. Analysis of Metrics

With the various suitability metrics defined and quantitatively represented, conducting an analysis that captures how they integrate and impact each other is necessary. By doing so, this presents the designer, user, and stakeholders with trade space so as to determine means of optimizing the maintenance approach. For instance, knowing that reliability and maintainability have some degree of inclusion for operational availability, there would be an impetus to maximize these values so as to achieve a maximum A_o. As well, the analysis would provide the maintainer, through the iterative approach, trends in system functionality so as to forecast future major maintenance activities or events.

A systems engineering tool that is incredibly useful in analyzing how well a system is performing, or more importantly to ascertain what concepts of the design to influence for optimization is model-based systems engineering (MBSE). To break down what this tool is, it is first important to examine a model as a stand-alone feature. A model, as described by IEEE 610.12-1990, is "an approximation, representation, or idealization of selected aspects of the structure, behavior, operation, or other characteristics of a real-world process, concept, or system" (Miller 2017). Models may be qualitative, physical, functional, or virtual, meaning they may be in the form of software. Often, software models are beneficial by introducing raw data and, through careful manipulation, deciphering end results. Simply inserting values and running scripts is only part of the process, which is where the systems engineering element is introduced.

As described in Chapter II, Section D, systems engineering is a field used to develop system requirements, design, analyze, verify, and validate. Through the application of a model, it is possible for the system designers to translate ideas and ideals from paper to something of substance so as to further enhance the system's capability. It is in this manner that MBSE is realized, and further focuses the efforts of the design through iteration. An important consideration is that when developing models, there are an innumerable number of perspectives, simply from different experiences and backgrounds. Leveraging these different perspectives will enable a better wholly-understand model that will ensure sound understanding to all involved. Furthermore, a supportive element relating to the use of MBSE is this allows all an opportunity to determine the abilities of the system without actually creating a physical specimen, thus reducing potential schedule and cost impacts.

For this research, there are many different software programs available that can provide the desired data and metrics. These include the ability to augment input data so as to determine the overall effect on the metrics; essentially determine what input data is needed to achieve desired results. It may also indicate that the desired results are unachievable, prompting a follow-on discussion with stakeholders to revisit system requirements. As well, for quick "back-of-the-envelope" calculations, there are simple processing applications such as Microsoft Excel or Mathworks' MATLAB which a basically trained user can use to develop a rudimentary model. In summary, exploring different modeling techniques and developing a suitable one for analyzing the system is highly recommended. This will provide the best indicators for understanding system behavior and observe relationships with system components.

The methodology is intended as a framework for a user to follow in the design and development of a maintenance philosophy. To provide an indicator of its usefulness, the next chapter will provide a use case of the OPC using the requirements for operation and maintenance as well as faux data of systems that will be installed. Analysis of this data, and the resultant suitability metrics, will be interpreted and recommendations provided as considerations for improvement. This, in turn, is useful in understanding how RCM can overall improve system effectiveness.

E. STEP 5: CONDUCT MAINTENANCE

The final step in the framework is to conduct maintenance. In theory, this is the pinnacle of effort and results in the maintenance philosophy. This is also where validation of the system occurs and so those involved in operation and maintenance of a system are able to present the results of the philosophy to stakeholders, ensuring their requirements are met. Figure 13 is an enhance view of this step in developing a maintenance philosophy.

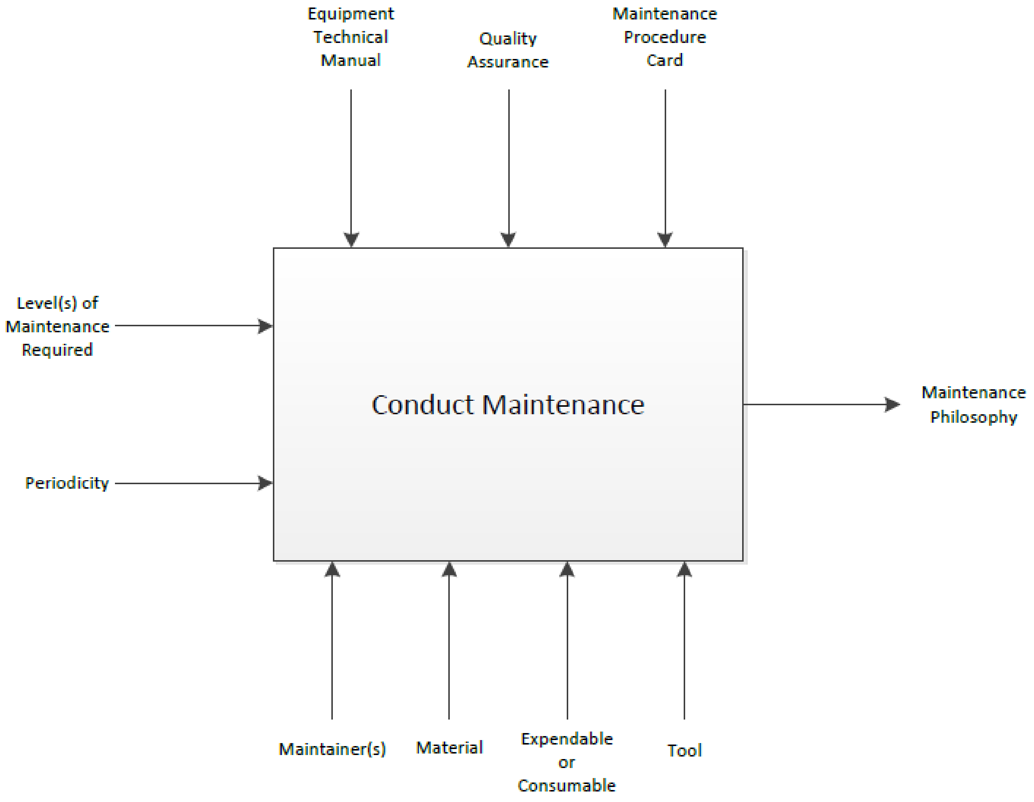

Figure 13. Step 5 in Developing a Maintenance Philosophy

Similar to the previous steps, the inputs for conducting maintenance are the outputs from the previous step. Having an understanding of the periodicity of maintenance as well as knowing what level of maintenance is required is a necessity for enabling this step. There are several controls and mechanisms to discuss. The controls are equipment technical manual, maintenance procedure care (MPC), and quality assurance. These should not be unexpected, and should all be leveraged to their maximum so as to ensure that maintenance is completed correctly. The MPC will provide the maintainer with step-by-step instructions regarding how to complete maintenance along with the tools and materials needed. For USCG MPCs, the grade of maintainer is specified, such as MK2 or EM1, as well as the expected time to complete the task. The next reference above MPC is the technical manual related to the equipment. The information in the MPC should, and most likely will, refer to the respective manual, which will also have amplifying information that provides additional background and instruction for performing a task. Finally, some level of oversight, often in the form of a designated quality assurance supervisor, is required to act as a cognizant authority that the maintenance was performed correctly. It is imperative that the quality assurance be conducted by an independent individual and not the maintainer who completed the tasks.

For the mechanisms, the crew continues to be the first contributing factor. Though there is ever improving and changing levels of technology and automation, most tasks require the *human element* to interface with the system for performing maintenance satisfactorily. Tools are also required; as stated in Chapter II, Section D: ensure that the correct tool is used to perform tasks. The last two mechanisms, materials and expendables or consumables, could be combined, but are intentionally left separate. The reason for the separation refers to levels of responsibility within the supply chain. Materials are a reference to spare or replacement parts that may, or may not, be needed to perform maintenance. Often, an inspection will yield that a part is worn nearly to failure, such as an oil seal becoming out of tolerance and beginning to weep oil. In this case, a replacement part is required. While not a central focus for this research, SFLC processes provide parts to the cutter fleet based on periodicity of maintenance. In addition, emergency casualty repair parts also tend to be the responsibility of SFLC. Expendables or consumables could be separated, and when considering budgeting often are, but in this context are kept within the same category. These are items such as gaskets, oils, greases, or paints that are expected to wear or fail over time, with a relatively short finite interval. Thus, they may be stocked in bulk and typically procured by the cutter to have as a readily available controlled item.

Finally, the output: maintenance philosophy. The goal of this framework and a necessity for ensuring a system meets life cycle expectations. Recall that a maintenance philosophy is a reference to a mix of strategies that ensure a system or process is functioning as intended when called upon. Throughout this development process, there were many strategies including:

- the use of systems engineering development and decomposition tools
- utilizing standard processes and procedures for operating equipment so that the accumulate raw data clearly relates to the expected functionality of the system
- various analytics that evaluate the data and incorporate into a number of suitability measures for decision makers
- the completion of maintenance that is directly in-response to how the system is functioning without the need for superfluous tasks

Check on the system to apply the validation loop, which will ensure that the maintenance philosophy, when enacted and performed on cutter equipment, meets stakeholder requirements and the bounds of the problem need statement.

A final thought for all involved: one iteration is not sufficient and never enough. As the system operates, there will be different periods where it will function differently, along with indicators of pending failure. As with the discussion of the reliability bathtub curve, as the cutter ages and undergoes maintenance availabilities, there will be increases and decreases in the expected measures of suitability. In addition, this framework can apply to every system, and subsystem, aboard the cutter and so an additional part of step four would be to integrate them all and determine overall trends for the cutter performance. Repeating the process over and again, along with verifying and validating the end result, ensures that the desired goal is achieved.

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IV. OPC USE CASE

With a methodology for developing a maintenance philosophy presented, an application of this process will now be presented. This application will follow the five steps of the framework development process, and highlight those steps that should be considered most important for those involved in its development. The data provided as a result of system operation is not actual data, and is not referenced from any particular source. Instead, the data is intended to demonstrate the methodology. In addition, only a sample of the entire ship systems will be presented. This data is provided to illustrate how the suitability measures interact. In addition, a simple Microsoft Excel model will be presented with indicators of how operational availability may decrease or increase depending on maintenance needs and system performance. With respect to the quantitative results of this study, the reader is reminded that the results are irrelevant as this is for demonstration purposes of using the methodology. The primary goal of this case study is proof-of-concept that optimizing maintenance processes results in improved system performance.

A. CASE STUDY DATA AND ASSUMPTIONS

Table 3 is provided as raw data used in developing a maintenance philosophy.

Table 3. Baseline Data for Maintenance Philosophy Application Case Study

	Op Hours	Tasks	MTBF	λ	Mpt	Mct	fpt	$MTBM_s$
Port Propulsion	400	10	2500	0.0004	2.0	8.0	0.0250	24
Starboard Propulsion	375	10	2530	0.0004	2.0	8.0	0.0267	24
#1 Generator	250	15	2000	0.0005	1.5	4.0	0.0600	48
#2 Generator	250	15	1500	0.0007	1.5	4.0	0.0600	48
Habitability Auxiliaries	150	8	500	0.0020	4.0	3.5	0.0533	20
Propulsion Auxiliaries	400	8	500	0.0020	4.0	3.5	0.0200	40
Combat Systems	500	2	1000	0.0010	2.0	2.0	0.0040	24
Electronics	1500	5	3000	0.0003	3.0	4.0	0.0033	12
Navigation	1000	3	4500	0.0002	1.5	2.0	0.0030	4

With the exception of failure rate (λ), all values are given in hours. In addition, an LDT of three days (72 hours) and an ADT of one workday (8 hours) are used.

Assumptions with regard to the OPC within the context of this use case include:

- Machinery operates continuously until a planned maintenance task is performed or failure occurs; the machinery is not secured for a "lay-up" period.
- All installed equipment functions as-designed and is operated within designed parameters
- Cutter crew has all necessary training enabling their ability to complete maintenance
- All tools, both standard and special, associated with performing organizational maintenance, are onboard and ready for use

B. STEP 1: IDENTIFY AND DEVELOP MAINTENANCE REQUIREMENTS

Refer to Chapter III, Section B that introduced the first step in the maintenance philosophy framework development structure. This section discusses deriving requirements for the maintenance philosophy from stakeholders based on their need and an existing capability gap. There are several documents, typically included in an acquisition program of record, that contain the intent for the requirements for discernment. To recap, the four primary maintenance requirements identified from the OPC ORD and ILSP are outlined in Table 4.

Table 4. OPC Top-Level Maintenance Requirements

The essence of maintenance performed aboard the OPC shall be based on RCM fundamentals
The maintenance necessary for safe and correct operation of the cutter shall be conducted by the crew
The crew will be provided with all tools, training, and material so as to complete maintenance
Shoreside support shall be available to augment the crew's completion of depot and organizational maintenance

As these were presented in-depth earlier, a cursory review is provided for context within this study.

The first requirement is a reference to RCM. As presented throughout this research, RCM is a maintenance program that considers the reliability of a piece of equipment and implements maintenance standards to maximize the reliability. Emphasis of tests, monitoring, and inspections as supplement to required preventive and corrective maintenance programs will act as an enabler for meeting this requirement.

The second requirement is in reference to safe and correct operation of the cutter being conducted by the crew. In essence, while the cutter is at-sea, the primary maintainers are those onboard, and the only maintenance considered is what is necessary to meet mission objectives while ensuring safe operation of systems. This is not intended to minimize any maintenance needs or requirements, but more for the sake of crew fatigue and as assurance that the crew will be available to conduct operational missions including AMIO, counter-narcotics, or SAR.

The third requirement is for all tools, training, and material to be provided. Tools should be a standard set, common to each cutter in the fleet. Though there may be some special tools needed, it should not be an expectation that the cutter crew will continuously purchase tools, unless in response to an individual tool failure or wear. Training should not be unique and available to maintainers as is suitable to their grade. These training sessions shall be, desirably, available prior to the maintainer reporting aboard, and if not then that individual shall be given priority. Lastly, materials may be spare or repair parts or expendable or consumable products. While there is some case-by-case consideration, in the end the requirement is to have the material available so that stagnant time is not introduced into the overall completion of maintenance, thus lengthening the time to restore functionality and creating frustration.

The final requirement refers to shore-side support being readily available. Shore-side support may be in the form of an organic USCG resource such as a MAT or may be contractual. Whichever the case, careful planning and preparation will ensure success for utilizing this support mechanism. In addition to completing depot maintenance, it is also desired that the shore-side support aid in completing any deferred organizational maintenance items to ensure that everything is up-to-date and the equipment is operating satisfactorily.

With the top-level requirements identified, it is possible to draft a problem-need statement to aid in further refinement and decomposition of the problem. With buy-in from stakeholders, the problem statement serves as a reference when the time comes for verification and validation of the end result. This leads directly into step two, which uses Systems Engineering tools to develop measures of effectiveness, performance, or suitability and identify those suitability needs to ensure the system is supported.

C. STEP 2: APPLY SYSTEMS ENGINEERING PROCESS

Systems engineering provides expanded detail regarding the systems functions, requirements, and abilities. In doing so, it enables decision makers to produce measures that indicate how well the system is operating. These measures will be beneficial in later steps as data is collected and analyzed; the analysis will include a comparison to the original measures so that the operational commander can determine whether or not the system is meeting expectations. Part of meeting the expectation includes the outputs from step four regarding periodicity and levels of maintenance. Thus, it is clear that the iterative approach of systems engineering is beneficial in ensuring that the desired output is achieved. As well, the analysis provides an opportunity to incorporate MBSE to analyze capability improvements and thus optimize the performance of the system.

Of the innumerable list of measures that could be derived for the OPC, a list of seven have been selected. These measures were chosen because they best illustrate fundamental performance indicators relating to the system's readiness and ability to operate when desired, thus addressing stakeholder requirements for operational availability. For this study, the following measures of suitability (MOS) are presented:

- subsystem reliability
- cutter reliability
- cutter mean corrective time
- cutter mean preventive maintenance time
- cutter mean time between maintenance
- cutter mean downtime

- cutter operational availability

There are additional suitability needs as well that must be determined. These include considerations of supportability, which will have an impact on the mean downtime of the cutter, and follow-on the operational availability, as well as usability, or human-systems integration. For supportability, a primary element is that of spares to have onboard which is a primary factor of the LDT.

The facets of usability are not as easily determined as there is more subjectivity involved. Usability is a consideration that should be included early in the design, and continuously reviewed throughout the design process and then throughout the system's life cycle. However, there are some measures to consider including (these measures are derived directly from the aforementioned reference and presented verbatim):

- Quantity of personnel required for the maintenance of the system in a designated period of time
- Time it takes to accomplish a maintenance function
- The number of errors committee by the maintainer per maintenance action, function, or period of time

Table 5 provides a first-iteration estimate for each measure listed; the measures of usability will not be quantified, but revisited as a qualitative talking point.

Table 5. Sample Measures of Suitability

Subsystem Reliability	0.95
Cutter Reliability	0.90
Cutter Mct	< 4 hours
Cutter Mpt	< 2 hours
Cutter MTBM	> 24 hours
Cutter MDT	< 12 hours
Cutter Ao	0.85

D. STEP 3: OPERATE SYSTEM

For this analysis, step three is arguably the easiest as it does not directly relate to the actual performance of maintenance. This is the operation of the system which is assumed to occur using published procedures and within parameters. The output for this step is an accumulation of operational data that is subsequently used for data analysis. There will not be any further explanation for this step.

E. STEP 4: PERFORM ANALYSIS USING DATA FROM INSPECTION, TEST, OR MONITORING

With the raw data collected from the operation of the system, analysis can now occur to determine values to correlate with the established measures and determine if the system is meeting expectations. As well, through a simplistic Microsoft Excel model, the manipulation of the data is presented so as to provide information of how some elements can have great influence.

1. Calculations

The following calculations are provided to translate the raw data into useable metrics.

a. Subsystem Reliability

The reliability of each subsystem is important as that will have an impact on the overall cutter reliability. Using the raw data listed in Table 3 and assumption that the reliability function uses an exponential distribution, which is characteristic in implying that failures occur randomly. Thus, application of equations 1.2 – 1.4 are required. A sample reliability calculation for the port propulsion system is provided.

Operational time: 400 hours

MTBF: 2500 hours

$$\textit{Failure Rate } (\lambda) = \frac{1}{MTBF} = \frac{1}{2500\ hours} = 0.0004$$

$$\textit{Reliability} = e^{-(0.0004)(400\ hours)} = 85.2\%$$

Thus, the reliability of the port propulsion system is 85.2%. Table 6 is a summary of individual subsystem reliabilities.

Table 6. Subsystem Reliabilities

Subsystem	**Reliability**
Port Propulsion	85.2%
Starboard Propulsion	86.2%
#1 Generator	88.2%
#2 Generator	84.7%
Habitability Auxiliaries	74.1%
Propulsion Auxiliaries	44.9%
Combat Systems	60.7%
Electronics	60.7%
Navigation	80.1%

b. Cutter Reliability

Cutter reliability incorporates the subsystem reliabilities provided in Table 6. An important step in calculating this overall reliability is that some systems, including the propulsion and generators, have parallel features and so their combination follows equation 1.4 versus 1.3. The following calculations determine the cutter's reliability.

$$\textit{Propulsion reliability } (R_P)\text{: } 1-(1-R_P)(1-R_S)=1-(1-0.852)(1-0.862)$$

$$R_P = 98.0\%$$

$$\textit{Generator reliability } (R_G)\text{:} 1-(1-G_1)(1-G_2)=1-(1-0.882)(1-0.847)$$

$$R_G = 98.2\%$$

$$\textit{Cutter reliability: } R_P * R_G * R_{HA} * R_{PA} * R_{CS} * R_E * R_N$$

$$\textit{Cutter reliability} = 0.980 * 0.982 * 0.741 * 0.449 * 0.607 * 0.607 * 0.801 = 0.095$$

Thus, the calculated cutter reliability is only 9.5%, far removed from the desired 90.0%. However, this calculation immediately provides decision makers with information regarding the maintenance needs. From Table 6, notice that there are not any subsystems that have a reliability above the desired 95%. The propulsion and generator systems, when operated in parallel, result in a value above that. However, the greatest impact to overall system reliability are the three lowest values associated with propulsion auxiliaries, combat systems, and electronics. If each of these systems were improved, either through corrective or preventive maintenance, to 0.75, the overall cutter reliability would improve to 24.0%, more than a 200% increase.

c. *Cutter Mean Corrective Time*

The cutter's mean corrective time takes into account the *Mct* for each subsystem along with its associated failure rate. Using the given *Mct* for each system, and applying equation 1.5, the overall rate is calculated. Table 7 is a summary of results using this equation.

Table 7. Summarized Results of Subsystem *Mct* Calculations

Subsystem	**Subsystem *Mct* (hrs)**	**Subsystem Failure Rate (λ)**	***Mct**λ**
Port Propulsion	8.0	0.0004	0.0032
Starboard Propulsion	8.0	0.0004	0.0032
#1 Generator	4.0	0.0005	0.0020
#2 Generator	4.0	0.0007	0.0027
Habitability Auxiliaries	3.5	0.0020	0.0070
Propulsion Auxiliaries	3.5	0.0020	0.0070
Combat Systems	2.0	0.0010	0.0020
Electronics	4.0	0.0003	0.0013
Navigation	2.0	0.0002	0.0004
Total	N/A	0.0075	0.0288

$$\sum Mct_i \lambda_i = 0.0288$$

$$\bar{M}ct = \frac{\sum Mct_i \lambda_i}{\sum \lambda_i} = \frac{0.0288}{0.0075} = 3.8319\ hours$$

Thus, the mean corrective time for the cutter is calculated to be 3.83 hours or just under 4.0 hours. It remains to be seen if this is acceptable or not, and that may be more of a decision for the operational commander on a case-by-case basis depending on the mission and impacts of the delay. A general precept is that the overall desire is to minimize this value, but not at the expense of faulty or incorrect repairs.

d. Cutter Mean Preventive Maintenance Time

The OPCs mean preventive maintenance time is calculated in a similar fashion as the corrective time. This incorporates the *Mpt* for each subsystem along with its frequency of action through the use of equation 1.6. Table 8 is a summary of results using this equation.

Table 8. Summarized Results of Subsystem *Mpt* Calculations

Subsystem	**Subsystem *Mpt* (hrs)**	**Subsystem Frequency Rate (*fpt*)**	***Mpt*fpt***
Port Propulsion	2.0	0.0250	0.0500
Starboard Propulsion	2.0	0.0267	0.0533
#1 Generator	1.5	0.0600	0.0900
#2 Generator	1.5	0.0600	0.0900
Habitability Auxiliaries	4.0	0.0533	0.2133
Propulsion Auxiliaries	4.0	0.0200	0.0800
Combat Systems	2.0	0.0040	0.0080
Electronics	3.0	0.0033	0.0100
Navigation	1.5	0.0030	0.0045
Total	N/A	0.2553	0.5992

$$\sum Mpt_i fpt_i = 0.5992$$

$$\bar{M}pt = \frac{\sum Mpt_i fpt_i}{\sum fpt_i} = \frac{0.5992}{0.2553} = 2.3460\ hours$$

Thus, the mean preventive maintenance time for the OPC is 2.3460 hours or approximately 2 hours 15 minutes. As with $\bar{M}ct$, it remains to be seen if this is acceptable or not, and will most likely be influenced based on operations or mission requirements.

e. Cutter Mean Time Between Maintenance

While the mean corrective and preventive maintenance times are important, of more interest are the remaining three metrics that are presented: *MTBM*, *MDT*, and A_o. The first, mean time between maintenance, is calculated first for each subsystem and then averaged to determine a rudimentary value for the cutter as a whole. The calculation uses both the mean time between failure, a reliability metric, and mean interval of scheduled, or preventive, maintenance, a maintainability metric. The combination of these two metrics further illustrates the integratability aspects of suitability measures. To demonstrate this calculation, the *MTBM* for the #1 generator follows.

$$MTBM_{\#1\ Gen} = \frac{1}{{}^{1}\!/_{MTBF_{\#1\ Gen}} + {}^{1}\!/_{MTBM_{S,\#1\ Gen}}}$$

$$MTBM_{\#1\ Gen} = \frac{1}{{}^{1}\!/_{2000\ hrs} + {}^{1}\!/_{48\ hrs}} = 23.77\ hrs$$

Thus, the mean time between maintenance for the #1 generator is 23.77 hrs or approximately daily. For discussion purposes, maintenance is prescribe as a general procedure and may be one of the RCM-type activities or may be a response to that such as an oil change on the prime mover or cleaning of the generator windings. The importance, with regard to this calculation, is not so much what the maintenance is, but when the maintenance occurs. Following this method and calculating for the remainder of the subsystems yields the information documented in Table 9.

Table 9. Subsystem *MTBM* Values

Subsystem	***MTBM* (hrs)**
Port Propulsion	23.77
Starboard Propulsion	23.77
#1 Generator	46.88
#2 Generator	46.51
Habitability Auxiliaries	19.23
Propulsion Auxiliaries	37.04
Combat Systems	23.44
Electronics	11.95
Navigation	4.00

Using these calculated values, a rudimentary *MTBM* for the cutter as a whole is calculated. This calculation is simply an arithmetic mean without any weight based on the different systems or consideration that some systems, such as the propulsion, may require more hands-on usage than others, such as electronics. As well, recall the assumption is that these systems are functioning continuously, which is most likely not a realistic expectation for all; this is especially true for combat systems which are usually employed for some degree of combat or training. With this expectation, OPC *MTBM* is calculated as follows:

$$MTBM = \frac{\sum MTBM_i}{n} = \frac{236.59}{9} = 26.29\ hrs$$

Thus, the calculated *MTBM* for the OPC is 26.3 hours. This will be important for decision makers when developing a maintenance schedule and periodicity, especially when considering that it is not realistic that all maintenance activities can feasibly, or physically, be performed at the same time.

f. Cutter Mean Downtime

Mean downtime is a consideration of how long a system will not be functioning and is a combination of mean active maintenance downtime ($\bar{M}$), logistics delay time (LDT), and administrative delay time (*ADT*). The $\bar{M}$ calculation includes the measures associated with preventive and corrective maintenance, so that an overall understanding of how maintenance affects the ability for the system to be operating. As with previous metrics, a sample calculation will be conducted followed by a summary table. The electronics subsystem is used for this calculation, using equation 1.7.

$$\bar{M} = \frac{(\lambda)(\bar{M}ct) + (fpt)(\overline{Mpt})}{\lambda + fpt}$$

$$\bar{M} = \frac{(0.0003)(4.0\ hrs) + (0.0033)(3.0\ hrs)}{0.0003 + 0.0033} = 3.09\ hrs$$

Thus, for electronics, the calculated mean active maintenance downtime is 3.09 hrs, or just over three hours. This is a fairly lengthy time downtime, and would most likely be a targeted value in a maintenance efficiency study. Table 10 is a summary of values for $\bar{M}$ for each subsystem.

Table 10. Subsystem $\bar{M}$ values

Subsystem	**$\bar{M}$ (hrs)**
Port Propulsion	2.09
Starboard Propulsion	2.09
#1 Generator	1.52
#2 Generator	1.53
Habitability Auxiliaries	3.98
Propulsion Auxiliaries	3.95
Combat Systems	2.00
Electronics	3.09
Navigation	1.53

Similarly to the calculation for OPC *MTBM*, OPC $\bar{M}$ is calculated as an arithmetic average. The same considerations apply that this is a rudimentary calculation and does not include any consideration of weighting of the subsystem. Thus, the calculated OPC mean active maintenance downtime is 2.42 hrs. In reality, it is not likely that the entire cutter would be down due to one maintenance task; in fact, it is more likely that multiple tasks can be conducted simultaneously with minimal impact to operations and the crew as a whole.

With $\bar{M}$ calculated, the additional two values for *MDT* are the *LDT* and *ADT*. These values are typically not easily controlled by the cutter themselves as there are entities, offices, and personnel outside of the scope of the OPC that influence them. For the purposes of this study, the assumed values of *LDT* = 72 hours and *ADT* = 8 hours are applied. With all values known, *MDT* is calculated as follows:

$$MDT = \bar{M} + LDT + ADT$$

$$MDT = 2.42\ hrs + 72\ hrs + 8hrs = 82.42\ hrs$$

Thus, the mean downtime for the cutter is 82.42 hrs, or 3.5 days.

g. Cutter Operational Availability

The final metric, but perhaps most telling and important to decision makers, is that of operational availability. The stakeholders and users of a system are typically most concerned with the readiness and availability for which there is system is able to be used.

The inputs for calculating this metric include the mean downtime (*MDT*) and mean time between maintenance (*MTBM*). Notice that this does not directly include consideration of system reliability, but indirectly that is included in earlier calculations that these two measures stem from. From the previous calculations for *MDT* and *MTBM*, A_o is calculated using equation 1.10.

$$A_o = \frac{MTBM}{MTBM + MDT} = \frac{26.29\ hrs}{26.29\ hrs + 82.42\ hrs} = 24.18\% \text{ or } 0.24$$

Thus, the operational availability, based on the given performance of the system and components is 0.24. This is well below the stakeholder's desired value of 0.85.

2. Analysis of Measures

With suitability metrics determined, the decision maker has an initial understanding of how well the system is actually performing. This introduces the opportunity for trade study and various maintenance programs that, when applied at an optimal level, will improve system performance. An important note is recalling that this level of maintenance is not only hands-on repair or manipulation of a faulty system, but also the introduction of components or subsystems that have better reliability. To provide a quick comparison with what was originally desired and what actual occurred, Table 11 is provided.

Table 11. Comparison Between Desired Metrics and Actual Metrics

Suitability Metric	Desired Value	Actual Value
Cutter Reliability	0.90	0.10
Cutter Mct	< 4 hours	3.83 hours
Cutter Mpt	< 2 hours	2.35 hours
Cutter MTBM	> 24 hours	26.29 hours
Cutter MDT	< 12 hours	82.42 hours
Cutter Ao	0.85	0.24

It is clear from this comparison of information that reliability and maintainability measures are outside of desired parameters and subsequently have a negative impact on operational availability.

The analysis portion of this process examines the key components and characteristics that have the greatest impact on the system as a whole. In addition, it is important to consider the feasibility of what efforts are plausible and at what cost. The first step is to consider how each subsystem is functioning on its own and where improvement may occur. Reviewing the individual subsystem reliabilities, the consideration should begin with determining what has the best reliability and what has the worst. The best includes propulsion, generators, and navigation; the worst is propulsion auxiliaries with combat systems and electronics are marginally better.

To analyze how the different subsystems collectively impact the overall cutter performance, a simple Excel model was developed which includes scroll bars for varying the input data to adjust *MTBF* and *MTBM*. Through a simple manipulation of the calculations, it is possible to ascertain how reducing the failure rate, or increasing the *MTBF*, will provide benefit to the individual subsystems and system as a whole. For example, considering the aforementioned "worst" subsystems of propulsion auxiliaries, combat systems, and electronics. If the *MTBF* for each were simple doubled to 1000, 2000, and 6000 hours, respectively, there would be a significant increase in the cutter's reliability. This is computed using the same process for reliability as before, and demonstrated as follows with the bold lettering indicating updated values:

$$\textit{Cutter Reliability:}\ R_P * R_G * R_{HA} * \boldsymbol{R_{PA}} * \boldsymbol{R_{CS}} * \boldsymbol{R_E} * R_N$$

$$\textit{Cutter Reliability} = 0.980 * 0.982 * 0.741 * \mathbf{0.670} * \mathbf{0.780} * \mathbf{0.780} * 0.801 = 0.232$$

Thus, the updated cutter reliability is 23.2%. While this value remains below the desired value, this demonstrates that with the incorporation of timely maintenance using RCM fundamentals, it is possible to improve the overall system reliability.

This same logic can be applied to improving operational availability. Recall a primary metric in this calculation is the *MTBM*. If this metric can be increased, without causing undue stress or damage to the equipment, it is possible to achieve a greater availability. The desired *MTBM* value for the cutter was greater than 24 hours. While the combined value is greater, there are individual subsystems that are below this threshold, namely habitability auxiliaries, electronics, and navigation. To demonstrate the achieved benefit of a greater availability, the following calculation is completed with these subsystems increased to 24 hours.

$$MTBM = \frac{\sum MTBM_i}{n} = \frac{271.99}{9} = 30.22\ hrs$$

When placed into the equation for calculating A_o, this increase in *MTBM* results in an increase of A_o by only 0.5%. Thus, additional analysis is required.

Suppose the MTBM could be increased to at least 48 hours for all subsystems. This would result in a new cutter *MTBM* of 48 hours and A_o of 36.8%, or a 12% increase. However, increasing the maintenance time is only part of the answer as there are other factors in the A_o equation to consider. In addition, it would be unwise to continue to increase the *MTBM* to reach a desired output as this would most likely eventually have a detrimental effect on reliability metrics, specifically an increased failure rate. Returning to the A_o calculation, it is evident that the primary driver is the *MDT*, which is most effected by *LDT* and *ADT*. This is where a consideration of shore-side support, logistics, and infrastructure is paramount. The ability to quickly provide material and services will decrease the *LDT*. This may include stockpiling parts aboard the cutter as well as forward positioning of material for quick access at various parts. However, as would be expected, it is not possible to have parts available to support worldwide deployments at a moment's notice.

One option, is the previously introduced "Push-Parts" program, utilized by the USCG Surface Forces Logistics Center (SFLC) to monitor the completion rates of each cutter's maintenance programs and delivers maintenance material to the cutter prior to the next expected maintenance period. In this way, the parts are already aboard the cutter for use when the maintenance is due, thereby essentially negating the *LDT*. To illustrate how effective this could be, assume the *LDT* is decreased to 2 hours, the time necessary to retrieve a part from onboard storage, and *ADT* decreased to 0.5 hours, the time necessary to log the request into the ship's computer system. Using the original values for *MTBM*, with the updated *LDT* and *ADT*, results in the following calculated values:

MTBM: 26.3 hours

MDT: 4.9 hours

$$A_o: 84.2\%$$

The operational availability is now approximately four times the original amount; a conclusion from this is that the *MDT* is a more important and easily manipulated metric than *MTBM*. Thus, robust, mature, and proactive support processes are a necessity.

F. STEP 5: CONDUCT MAINTENANCE

The final step is to conduct the maintenance. There are any number of analysis tools, including the rudimentary Excel tool created for this research to support decision makers in the type of maintenance, when to conduct the maintenance, and who should conduct the maintenance. The integration of various programs including RCM fundamentals of observation, testing, and inspection early on will benefit the sustainment of the cutter throughout its life cycle. There are a number of programs in existence within the USCG, as well as some that are considered legacy, but are recommended for renewed use including:

- Push-Parts: A program created by the MECPL to provide maintenance material prior to a maintenance need so as to reduce maintenance down time
- Cutter Boat Pooling (CBP): A program that incorporates standard cutter boats with central overhaul and repair facilities to ensure a boat's safe readiness and operation.
- Diesel Engine Inspection (DEI): Effort using diesel engine SMEs to investigate and evaluate the performance of any type of diesel engine and to provide recommendations regarding regular maintenance, overhaul, or immediate casualty repair.
- Watertight Closure Assessment (WCA): Effort to inspect all watertight hatches, doors, scuttles, and non-tight fasteners for correct operation, structural integrity, maintenance needs, or replacement.
- Vibration Analysis: Effort to inspect and analyze various pumps and motors throughout the cutter for bearing wear, proper balance, and designed output so as to repair or replace before a failure occurs

In addition, it is important to identify exact expectation for crew maintenance while underway to ensure their ability to operate the cutter while at the same time be ready to support various mission requirements including law enforcement and search and rescue.

V. RECOMMENDATIONS

A. APPLICATION

The development and use of the proposed methodology has application across a wide spectrum of uses. While this primarily evolved around a new construction Coast Guard cutter, any system that requires some degree of maintenance could benefit from a structured philosophy best suited to meeting stakeholder requirements while also operating within the intended parameters of the system's design. Furthermore, further evaluation and analysis of suitability metrics better illustrates the overall functionality of the system, as well as forecast burnout rates, potential failures, and enable planning for major system overhauls or replacement.

B. FUTURE WORK

An initial recommendation is to simply apply this process to the OPC once production is completed and an operational cutter is functioning. Until factual raw data is acquired, the performance of the cutter is theoretical and more subjective than objective. Furthermore, a continuance of this analysis to better refine the suitability model, as well as incorporating optimization protocols, perhaps using a different software, would provide more fidelity to the calculated metrics and resultant maintenance programs. Finally, it is recommended the discussion of external maintenance support mechanisms such as the WTA and DEI be expanded for leveraging programs that provide the greatest benefit as well as ascertain if any could be incorporated into existing USCG training programs so as to further reduce maintenance cost without contractual overhead.

C. CONCLUSION

The methodology created in this research was designed to integrated stakeholder requirements and principles of reliability centered maintenance while using the systems engineering process. Maintenance completion is an important facet of operating any system and must be included early and throughout the system's life cycle. A system is going to operate only as well as it is taken care of, and if left to chance, there is an increased likelihood of failure. Applying reliability centered maintenance, especially by means of inspection, tests, and monitoring provides operators and maintainers with indicators of system performance include if the system is beginning to function outside of established tolerances and potentially leading to failure. It is imperative that a clear understanding of stakeholder requirements be the starting point as all follow-on functions will refer to them for verification and validation. Finally, proper analysis and an understanding of the data and calculations associated will enable the development of a sound maintenance philosophy and assure intended life cycle timelines are achievable.

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