NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

AN ANALYSIS OF MAINTENANCE PERIODICITY EFFECTS ON THE AVAILABILITY OF COAST GUARD'S MEDIUM ENDURANCE CUTTER BOAT LAUNCH SYSTEMS

by

Paul R. Alexander

June 2020

Thesis Advisor:	Alejandro S. Hernandez
Co-Advisor:	Bryan M. O'Halloran
Second Reader:	Paul T. Beery

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** June 2020	**3. REPORT TYPE AND DATES COVERED** Master's thesis

4. TITLE AND SUBTITLE
AN ANALYSIS OF MAINTENANCE PERIODICITY EFFECTS ON THE AVAILABILITY OF COAST GUARD'S MEDIUM ENDURANCE CUTTER BOAT LAUNCH SYSTEMS

5. FUNDING NUMBERS

6. AUTHOR(S) Paul R. Alexander

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release. Distribution is unlimited.

12b. DISTRIBUTION CODE
A

13. ABSTRACT (maximum 200 words)

This thesis explores the periodicity of planned depot maintenance and its effects on failure rates for U.S. Coast Guard shipboard davit systems. Davits are used on Coast Guard cutters to launch small boats, which are needed to accomplish a range of missions. The operational availability of these davit systems is important in keeping Coast Guard cutters fully mission capable. This study collected davit failure and maintenance data from nearly eight years of archived records for two cutter classes, which served as a sample of Welin Lambie davit systems that are widely used in the fleet. Concepts of reliability, availability, and maintainability were applied to calculate failure rates, mean time between maintenance, and mean time between failures. From this information, statistical hypothesis testing was used to determine what factors influence the system failure rate. It also addresses whether the historical data on these systems can be used to develop experimental models and whether those models can be used to influence decisions on maintenance periodicity.

14. SUBJECT TERMS
U.S. Coast Guard, preventative maintenance, system reliability, boat davit

15. NUMBER OF PAGES
75

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release. Distribution is unlimited.

AN ANALYSIS OF MAINTENANCE PERIODICITY IMPACTS ON THE AVAILABILITY OF COAST GUARD'S MEDIUM ENDURANCE CUTTER BOAT LAUNCH SYSTEMS

Paul R. Alexander
Lieutenant Commander, United States Coast Guard
BS, U.S. Coast Guard Academy, 2006

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 2020

Approved by: Alejandro S. Hernandez
Advisor

Bryan M. O'Halloran
Co-Advisor

Paul T. Beery
Second Reader

Ronald E. Giachetti
Chair, Department of Systems Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

This thesis explores the periodicity of planned depot maintenance and its effects on failure rates for U.S. Coast Guard shipboard davit systems. Davits are used on Coast Guard cutters to launch small boats, which are needed to accomplish a range of missions. The operational availability of these davit systems is important in keeping Coast Guard cutters fully mission capable. This study collected davit failure and maintenance data from nearly eight years of archived records for two cutter classes, which served as a sample of Welin Lambie davit systems that are widely used in the fleet. Concepts of reliability, availability, and maintainability were applied to calculate failure rates, mean time between maintenance, and mean time between failures. From this information, statistical hypothesis testing was used to determine what factors influence the system failure rate. It also addresses whether the historical data on these systems can be used to develop experimental models and whether those models can be used to influence decisions on maintenance periodicity.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

CASREP	casualty report
CB-OTH	over-the-horizon cutter boat
DCMS	Deputy Commandant for Mission Support
EAL	Electronic Asset Logbook
EO	Engineer Officer
ESD	Engineering Services Division
M&S	modeling and simulation
MAM	Mobile Asset Manager
MDT	maintenance down time
MEC	Medium Endurance Cutter
MECPL	Medium Endurance Cutter Product Line
MTBF	mean time between failure
MTBM	mean time between maintenance
$MTBM_S$	mean time between scheduled maintenance
$MTBM_U$	mean time between unscheduled maintenance
NCWR	non-casualty work request
RCM	reliability centered maintenance
SE	systems engineering
SFLC	Surface Forces Logistics Center

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

The U.S. Coast Guard's cutter fleet has a broad array of missions including search and rescue, environmental protection, aids to navigation, homeland security, and drug interdiction. Most cutters conduct their operations with the use of small boats that are deployed using shipboard davit or crane systems. These boat launch systems are vitally important to maintaining mission readiness, yet they consist of many integrated mechanical, hydraulic, electrical, and electronic components that have a potential for failure. The Welin Lambie model TW.PIV 5.0B dual-point davit is one such system that is used on numerous classes of cutter. The Coast Guard collects maintenance and failure records for these systems, which make it possible to conduct analyses that may help inform maintenance programs.

The Coast Guard's Surface Forces Logistics Center (SFLC) provides technical, logistics, and maintenance support to the cutter and small boat fleet. SFLC is comprised of seven Shared Services Divisions and five Product Lines, which generate the policy and procedures for maintenance and repair management. The SFLC dictates a bi-level maintenance program; organizational-level maintenance is the responsibility of the cutter crews whereas depot-level maintenance is supported by a platform's respective Product Line. The Welin Lambie davits onboard the Reliance Class (WMEC-210) and Famous Class (WMEC-270) cutters have planned depot maintenance that consists of overhauls and renewals. Davit overhauls occur after four years of operation, with a renewal occurring after the following four years. This periodicity is based on many considerations including manufacturer recommendations, funding levels, and historic conditional needs. An analysis into the relationship between depot maintenance periodicity and the failure rates may provide additional quantifiable guidance on improving overhaul and renewal schedules.

This study began by collecting davit discrepancy reports and planned depot maintenance records from January 1, 2011, to December 14, 2018. A series of assumptions and definitions were applied to the data to extrapolate only the discrepancies that directly impacted the operational availability of each davit. As davits were renewed instead of overhauled, they were treated as a separate davit from the one they replaced, which

generated 45 individual units. Then the duration between scheduled maintenance actions and number of failures within those periods were used to calculate the mean time between maintenance (MTBM) and mean time between failure (MTBF) associated with each davit. Statistical methods were used to conduct hypothesis testing and analysis of variance (ANOVA) testing, which examined what factors had influence on the failure rates. Finally, a model was created in ExtendSim that would simulate davit maintenance life cycles and permit exploration of influential factors.

The statistical analysis first revealed that maintenance periods containing left or right censored data were statistically different than maintenance periods containing uncensored data. The censored data was removed, leaving 18 complete davit maintenance periods for the follow-on factor assessments. A comparison between overhauled davits to renewed davits revealed no clear impact that the type of depot maintenance had on the subsequent MTBF. The maintenance period durations were also broken into four groups of 500 days each, ranging from 0 to 2000 days. An ANOVA was used to compare the impacts the MTBM had on the failure rates, which also produced no significant difference. Next, ANOVAs were used to determine the impact that each cutter’s geographic region of homeport had on the davit MTBM and on MTBF. Again, the analysis revealed no influence that this factor had on either variable. Finally, experimentation with the ExtendSim model revealed that maintaining a desired level of MTBF would theoretically be more influential on davit availability than changing the depot maintenance periodicity.

The statistical analysis resulted in identifying no clear influence that the various factors had on the davit failure rates. The absence of a trend between the scheduled MTBM and the MTBF indicated that the davit failures were mostly random and did not follow a wear-out distribution. The results of the modeling and simulation indicated that other methods of controlling MTBF beside planned maintenance periodicity should be explored. The Coast Guard may improve the ability to perform future analyses by tracking davit operating hours, similar to the way main diesel engines and generators are tracked. The results of this analysis, if accurate, may also indicate that the periodicity between costly depot maintenance actions could be extended without necessarily reducing the operational availability of the davit systems.

ACKNOWLEDGMENTS

I would first like to thank my wife, Kate, and my children, Bridget, Ellie, and Abigail, for being supportive, loving, and patient throughout my Coast Guard career and my graduate education. You have sacrificed so much, including our time apart from each other, and this thesis development has been no exception. I would also like to thank my parents for all the love and encouragement throughout my life to keep learning and expanding my education.

I would also like to thank my thesis advisory team, Dr. Alejandro Hernandez, Dr. Bryan O'Halloran, and Dr. Paul Beery, who provided endless guidance throughout this process. Professor Hernandez, thank you for your time keeping me focused and progressing through the data collection and analysis. Professors O'Halloran and Beery, thank you for the in-depth discussions and guidance on reliability and modeling methods. Finally, thanks to all the NPS faculty I have worked with over the past two years for providing me with the tools and knowledge to conduct this study.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. PURPOSE

The purpose of this study is to examine the effects of maintenance periodicity on the operational availability of Coast Guard cutter systems. The results of the study are intended to inform policy for intervals between scheduled depot maintenance. It will also demonstrate the ability to use modeling and simulation (M&S) to establish maintenance and repair intervals for shipboard equipment.

B. BACKGROUND

Military ships such as Coast Guard cutters operate in a wide variety of unforgiving environments. Exterior equipment onboard these vessels are often exposed to extreme temperatures, corrosive seawater, salt air, sun radiation, rain and ice, and physical vibrations. These environmental factors cause wear on machinery over time even when the equipment is not in use. Protective coatings break down, metal corrodes, electrical connections fail, and gaskets crack.

In addition to the environmental effects, dynamic systems are also subjected to a wide range of wear and stresses throughout their operation. Mechanical contact surfaces become worn, seals break, fluids leak, and electronics fail. Left unchecked, these conditions gradually increase the probability of total system failure.

These issues necessitate rigorous maintenance programs that are designed to keep all equipment operating as intended. Preserving the availability of equipment is essential to ensuring ship operations can be carried out unhindered. Equipment maintenance includes routine inspections, measurements, repairs, overhauls, and even renewals as needed. This typically requires a great deal of continuous attention from vessel crew members and depot maintenance organizations.

Most U.S. Coast Guard cutters, service vessels at least 65 feet in length, utilize davit or crane systems to store and launch their small boats. This thesis will examine the Welin Lambie davits onboard the 270-foot Famous class (WMEC-270) and 210-foot Reliance class (WMEC-210) cutters as a case study for ship equipment maintenance. There are 13 Famous class cutters and 14 Reliance class cutters in active service, which are classified as Medium Endurance Cutters (MECs). These cutters are used to execute many of the Coast Guard's broad missions that include maritime safety, law enforcement, and homeland security. The first Famous class cutter, CGC BEAR, was placed in service in 1983 while the first Reliance class cutter, CGC RELIANCE, entered service in 1964 (US Coast Guard n.d.).

The MECs each have two small boats with dedicated launch systems. Each MEC has a port-side crane that launches a small boat using a single-point hoisting cable. The other launch system is the starboard-side Welin Lambie model TW.PIV 5.0B dual-point davit system, which launches an over-the-horizon cutter boat (CB-OTH).

Figure 1. Welin Lambie Dual-Point Davit on a 270-foot MEC, Shown with Cutter Boat Cradled. Source: Welin Lambie (n.d.).

While all launch systems are operationally important, the CB-OTH is the cutter's primary response boat for many missions including counter-narcotics and migrant interdictions, rescue-and-assistance, safety inspection boardings, helicopter operations, and man overboard emergencies. The ability of a cutter to utilize its small boats depends not only on the boat conditions but also the operational availability of the respective launching system. Therefore, the Welin Lambie dual-point davit systems onboard the cutters are vital to maintaining the mission capabilities of each ship.

Unfortunately, these davit systems can be prone to failure. In 2018, Cutter Engineering Reports submitted from the 270-foot MEC commands listed the Welin Lambie davit failures and maintenance difficulties as one of their top engineering concerns (Keane 2019). Although the reliability of the davit systems overall is generally high, the consequences of a davit that is no longer fully operational can be significant. Any casualty that hinders the ability to quickly and safely launch the CB-OTH will degrade a cutter's ability to carry out most of its operational missions.

The davits are maintained by the cutter crews and depot-level resources. The Welin Lambie davits are part of a rotating pool program in which each cutter's davit is replaced with a fully refurbished one approximately every eight years, with a depot-level in-place overhaul performed four years after each renewal. This program is costly but is intended to keep the davits in a state that is maintainable by the ship crew. It is also intended to reset the clock on the davit life cycle every eight years to prevent cascading component failures due to excessive age, corrosion, and wear. There is a good deal of interest in whether that time-based work is warranted.

The Coast Guard maintenance program currently tracks certain failure data as well as the maintenance activities that are performed on the equipment. In theory, this information can be analyzed to determine the failure rates of these davit systems. A systems engineering (SE) approach can be implemented to analyze historic failure data, model the system life cycle, and predict failure probabilities to determine when the major maintenance overhauls should be conducted.

C. OBJECTIVES OF THE STUDY

The Coast Guard must continue to seek ways to improve its maintenance management to minimize the frequency of equipment failures that impact mission readiness. The objective of this study is to use the Welin Lambie davit system onboard the 270-foot and 210-foot MECs to model failure patterns and identify ways to adjust the depot maintenance schedule that will improve davit availability. To achieve this objective, this thesis will answer the following research questions:

1) How can the failure and maintenance data that the Coast Guard currently collects be used to generate system failure models?

2) How can the frequency of depot-level overhauls and renewals be modified to improve the operational availability of the MEC davits?

D. BENEFITS OF THE STUDY

This study can directly benefit the Coast Guard's maintenance of the davit systems onboard the EMC fleet. Other cutter classes that have similar Welin Lambie davits such as the 225-foot Seagoing Buoy Tenders can also benefit from the findings of this study. Additionally, the methodology can potentially be extended to analyze periodic maintenance on many other types of engineering equipment throughout the Coast Guard and Department of Defense (DOD) platforms.

E. ORGANIZATION

This study is divided into five chapters. Chapter II provides the context of this topic by detailing the literature review of Coast Guard's maintenance policies, commercial davit maintenance practices, and previous availability modeling techniques. Chapter III discusses the approach used to collect and interpret the data as well as the methodology applied in analyzing data and developing a model. Chapter IV provides the results of the analysis that was performed, and Chapter V provides the conclusions and recommendations based on those findings.

II. LITERATURE REVIEW

A. OVERVIEW

The topics of maintenance and reliability are heavily studied within industry and the military. However, there seem to be limited published studies that apply specifically to shipboard davit systems. Therefore, the literature review explores how maintenance is managed for critical systems onboard Coast Guard cutters in order to maintain the availability of the system.

B. U.S. COAST GUARD MAINTENANCE ORGANIZATION

Ship maintenance in the United States Coast Guard is managed within the Deputy Commandant for Mission Support (DCMS), which commands the Assistant Commandant for Engineering and Logistics (CG-4). This directorate consists of six program offices including the Office of Aeronautical Engineering (CG-41), Office of Civil Engineering (CG-43), Office of Logistics (CG-44), Office of Naval Engineering (CG-45), Office of Energy Management (CG-46), and the Office of Environmental Management (CG-47). The Office of Naval Engineering commands the Surface Forces Logistics Center (SFLC), which manages the maintenance, repair, logistics, and technical information of the Coast Guard's surface vessel fleet.

The SFLC is comprised of five product lines, each of which manages engineering and logistics support for several classes of cutters or small boats regardless of geographic location of the assets. These are the Small Boat Product Line, Patrol Boat Product Line, Medium Endurance Cutter Product Line, Long Range Enforcer Product Line, and Icebreaker, Buoy, and Construction Tender Product Line. Each product line is responsible for providing constant mission support to their respective assets and are the primary conduit between naval engineering staff and the fleet Commanding Officers (DCMS n.d.).

The SFLC also consists of seven Shared Service Divisions, which provide support to all product lines for "engineering, supply, contracting, industrial services, and logistics management" (DCMS n.d.). These shared divisions consist of the subject matter experts that establish the technical engineering processes used by all product lines. One of these divisions is the Engineering Services Division (ESD), which "provides engineering services, technical publications, engineering technical authority, maintenance procedure card (MPC) development…, and reliability centered maintenance (RCM) support services" (DCMS n.d.). Each product line works with the ESD to establish the maintenance definitions and schedules for all equipment onboard its respective platforms.

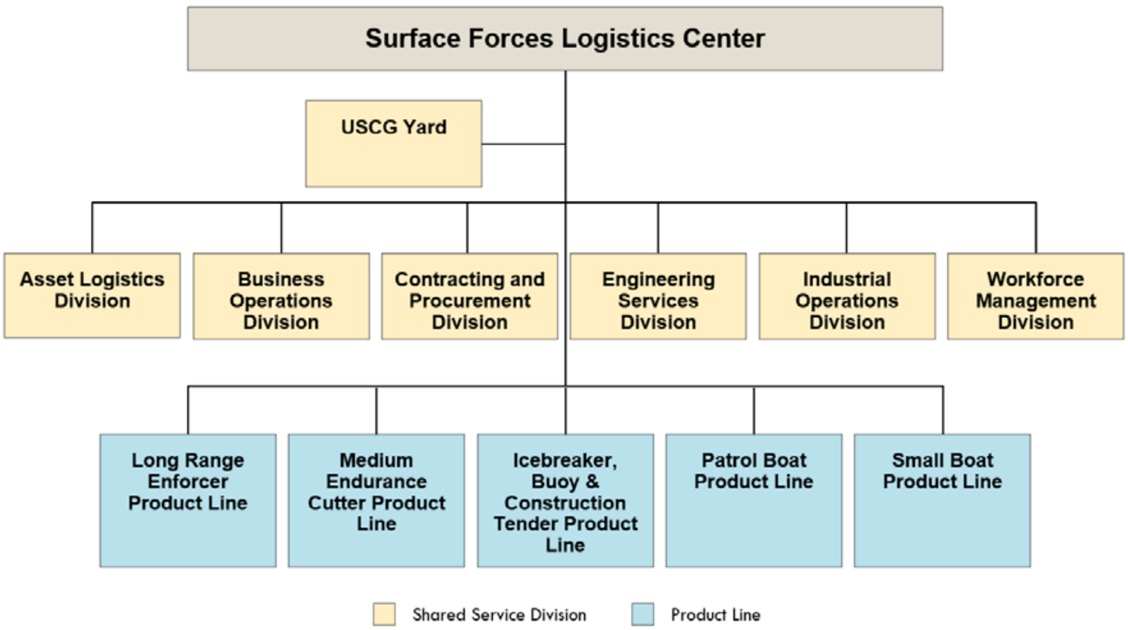


Figure 2. SFLC Organizational Chart

This study will focus on a shipboard davit system that is installed on several classes of cutter; however, the analysis will be performed specifically on the davits installed on the WMEC 270-foot and the WMEC 210-foot Medium Endurance Cutters. Maintenance of these ships falls under the purview of the Medium Endurance Cutter Product Line (MECPL), which works closely with each cutter command to ensure the vessels are properly maintained and repaired to meet operational requirements. The MECPL is divided into three branches, the Engineering Branch, the Program Depot Maintenance (PDM) Branch, and the Supply Branch. The Engineering Branch is the asset manager and subject matter expert for the equipment on the MECs, and it regulates the periodicity of maintenance. It also works closely with cutter Engineer Officers (EO) to ensure maintenance and repairs are properly monitored and recorded. The PDM Branch schedules, plans, and executes contracts for depot-level maintenance and repairs including all major dockside and dry dock availabilities.

C. U.S. COAST GUARD MAINTENANCE POLICY

The Coast Guard's Mission Support Business Model establishes the requirement for a bi-level maintenance program that is divided into organizational-level (O-Level) and depot-level (D-Level) services. Generally, the completion of O-Level maintenance is the responsibility of the individual cutter crews, while the scheduling and execution of D-Level maintenance is the responsibility of the respective product line in conjunction with the crews. Both levels of maintenance consist of planned and corrective actions.

Planned or preventative maintenance is performed on a scheduled basis in order to maintain the operation of equipment and prevent unexpected failures. Operational units complete planned O-Level maintenance through the Planned Maintenance System (PMS), which defines the periodicity and scope of all planned maintenance actions that need to be completed by the crews. Each maintenance action is described in step-by-step detail in Maintenance Procedure Cards (MPCs). The periodicity of maintenance has a broad range of frequency from daily to annual actions, including condition-based and operational hour-based actions. The cutter crews record all completed planned maintenance within a computer program called the Mobile Asset Manager (MAM), which feeds information to a maintenance database called the Fleet Logistics System (FLS). Planned D-Level maintenance is scheduled by the responsible product line and typically involves extensive inspections and overhauls performed by a contractor during maintenance availabilities. When D-level maintenance is completed, the responsible Product Line records the information in FLS.

Corrective, or unplanned, maintenance is performed as necessary in response to equipment failures or unanticipated repairs. Unplanned O-Level maintenance frequently occurs when equipment fails or any time a ship crew identifies a discrepancy while monitoring equipment operation or while conducting planned maintenance. At the unit level, the unplanned maintenance typically involves troubleshooting, parts replacements, and limited-resource repairs. As the crew completes corrective maintenance actions, those actions are supposed to be recorded in the MAM tracking system (SFLC 2019).

If an equipment failure is severe enough to require resources beyond the crews' capabilities, the D-Level corrective maintenance will be supported by the SFLC Product Line using either Coast Guard support personnel or contracted services. If the failure does not impact cutter operations but requires non-urgent D-Level assistance, then the cutter crew enters a Non-Casualty Work Request (NCWR) in MAM (SFLC 2019). However, if the casualty has an impact on operations and/or requires urgent assistance from the Product Line, then the cutter creates a maintenance record in the Electronic Asset Logbook (EAL) (SFLC 2019). These unplanned maintenance records are called discrepancies (discreps), which replaced the Coast Guard's use of the Navy's casualty reports (CASREPs) system. The EAL tool is an electronic system that communicates discrep statuses to the Product Line and provides operational status visibility for Coast Guard assets (SFLC 2019).

D. MAINTENANCE PROGRAMS FOR MEC DAVIT SYSTEMS

The Welin Lambie davits have a broad array of O-Level inspections and repairs that follow the Coast Guard's maintenance policies. These actions are intended to routinely identify and prevent davit problems before a system failure occurs. This maintenance by the cutter crews cannot resolve all issues, especially certain age-related failures that do not present clear physical indicators. Therefore, the Coast Guard has adopted a time-based D-Level maintenance model for the davit systems. This includes scheduled in-place overhauls and renewals of the davit systems for each cutter. Each event is intended to reset the reliability and life cycle of each davit, though the full renewal addresses more corrosion and cosmetic issues than the overhaul does.

The schedules for davit depot overhauls and renewals have evolved over time; however, the current standard is an in-place overhaul every four years and a full replacement every eight years. The MEC Product Line also has contracts in place for Welin Lambie technical representative (tech rep) assistance, which is used to assist the crews in correcting davit casualties as they occur. These costly programs are driven by many factors including the reliability of the davit systems, the effectiveness of the periodic maintenance, the time needed to renovate davits and obtain parts, and the money that can be allocated to the davit systems.

The four-year overhaul is conducted by a contractor whose work is overseen by a certified Welin Lambie tech rep. The project is considered a depot-level inspection, testing, and overhaul which extends the life of the davit another four years until it is renewed again. All major components are cleaned and inspected including structural members, mechanical components, hydraulic reservoirs and valves, electrical cables and wiring, winches, and all foundation welds (Mikedis 2015). The work specification also requires the contractor to overhaul and lubricate all weight lifting mechanical components, replacing any wearing components as needed. The contractor then repaints, tests, and certifies the davit system which places it back in operational service.

The eight-year davit renewal consists of maintaining a rotatable pool of davits. This time-based renewal process allows the MEC Product Line to effectively budget funds and manage the depot projects around cutter operational schedules. The Product Line works with Welin Lambie to maintain a few spare davits that supplement the rotating pool (Welin Lambie 2016). When a cutter is scheduled for renewal, its davit is removed and a replacement is installed by a commercial contractor under the supervision of a certified Welin Lambie tech rep. The removed davit is sent to Welin Lambie's facilities for a full OEM refurbishment, after which it is placed back into the pool as an available spare.

E. PRINCIPLES OF RELIABILITY, AVAILABILITY, AND MAINTAINABILITY

This study relies heavily on the concepts of reliability, availability, and maintainability (RAM). These concepts help build the groundwork for the primary focus, which is the operational availability of the Welin Lambie davit systems. In order to determine the operational availability, there must be an understanding of how reliable the systems are throughout their life cycle. Likewise, the system maintainability must be well understood in order to assess the impacts that maintenance has on availability.

Reliability is the probability that a system will perform its intended function for a given period of time in a given operating environment (Blanchard and Fabrycky 2014, 410). For a system such as the davit, it is important to have good reliability especially considering the impact the equipment status can have on the cutter's capabilities. Reliability is an "inherent characteristic of design," therefore it should theoretically be the same from one davit to the next assuming each davit is configured the same and is operated in the same environments (Blanchard and Fabrycky 2014, 412). However, since the expected design reliability is not known for the Welin Lambie davits, it must be calculated from existing archival data.

A key measure of reliability is the reliability function or survival function. Blanchard and Fabrycky define this as the "probability that a system (or product) will be successful for at least some specified time *t*," which is given by the formula:

$$R(t) = 1 - F(t) \tag{1.1}$$

The function *F(t)* is the failure distribution function, or the probability that a system will fail by a given amount of time. The way this function is calculated depends on the failure characteristics of a piece of equipment, namely the type of probability distribution that the failures generally follow. Common failure distributions are exponential, normal, Poisson, and Weibull, though the distribution would be derived from a system's specific failure profile (Blanchard and Fabrycky 2014, 413).

If using archival failure data, an effective way to determine the reliability and availability of a system is to calculate its failure rate λ and the mean time between failures (MTBF). Meantime between failure is the average time that occurs between consecutive failures in a system. Figure 3 displays a generic system operating cycle that includes operating (up) times and non-operational maintenance (down) times. The MTBF would be the mean of all up times t_n. The MTBF can be used as a measure of reliability, but it must not be used as the measure of a system's average life or expected life (MTL Instruments 2010).

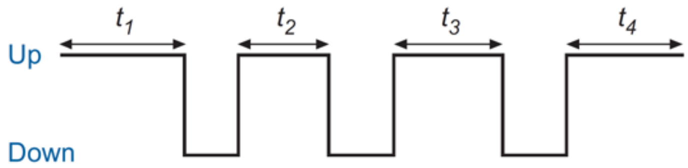


Figure 3. Diagram of a System Operating Cycle. Source: MTL Instruments (2010).

Failure rate is the number of failures that occur over a given interval of time. For example, the failure rate per hour is (Blanchard and Fabrycky 2014, 414):

$$\lambda = \frac{number\ of\ \ failures}{total\ hours} \tag{1.2}$$

The failure rate can be related to the MTBF for a given period of evaluation. If the failure rate does not change over time, indicating an exponential failure distribution, then MTBF can be expressed as the inverse of the failure rate (Blanchard and Fabrycky 2014, 414):

$$MTBF = \frac{1}{\lambda} \tag{1.3}$$

Since reliability is a function of time, its value is dependent on the time scale being analyzed. The time scale can vary depending on the intended purpose of the analysis and the type of data available. Meeker and Escobar (1998) use the example of automobile components stating that some can be assessed based on the miles driven while others may be more appropriately assessed by calendar age. A component whose failure mode is largely a result of use-rate would be relevant for a time scale using hours of operation. Conversely, a component whose failure mode is impacted by its time in service regardless of usage would be suited for a calendar age time scale. These concepts, along with the type of data available, will be applied when considering the form of reliability analysis performed for the Coast Guard davits.

Another important concept of RAM is a system's maintainability, which is the "ability of a system to be maintained" (INCOSE 2015, 228). Maintenance is simply the actions that are performed on a system to keep it operating or to return it to operation. The Coast Guard's approach to preventative and corrective maintenance has previously been discussed, and those actions vary based on each system's maintainability. This is because maintainability is an intrinsic property of a given system's design (INCOSE 2015, 228).

Maintainability is often represented in terms of maintenance times or maintenance frequency. Both are dependent on factors of a system's uptime and downtime. The downtime consists of active corrective and preventative maintenance, administrative delay time, and logistics delay time (Blanchard and Fabrycky 2014, 478). The active maintenance time can be expressed as mean active maintenance time ($\overline{\mathrm{M}}$), which is the average time needed for corrective and preventative actions (2014, 487). However, the full downtime including administrative and logistics delays is typically expressed simply as maintenance downtime (MDT). Like the active maintenance time, this is usually expressed as an average of all associated time requirements (Blanchard and Fabrycky 2014, 488). Figure 4 illustrates the time domain of a system and shows the breakdown of uptime and downtime factors.

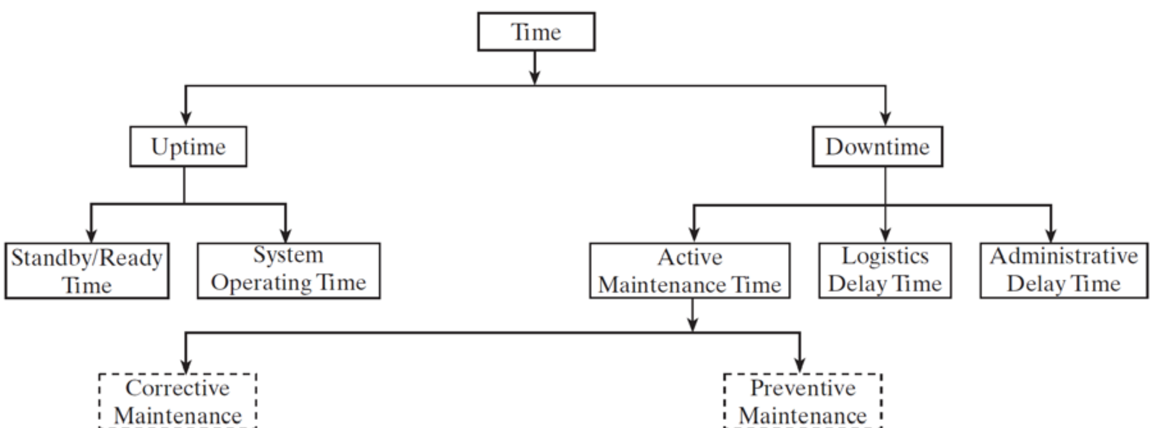


Figure 4. System Uptime and Downtime Factors. Adapted from Blanchard and Fabrycky (2014).

Maintenance frequency is commonly expressed as the mean time between maintenance (MTBM), which includes both preventative and corrective actions (Blanchard and Fabrycky 2014, 490). Blanchard and Fabrycky express MTBM as:

$$MTBM = \frac{1}{1/MTBM_u + 1/MTBM_s} \tag{1.4}$$

where $MTBM_U$ is the mean time between unscheduled maintenance and $MTBM_S$ is the mean time between scheduled maintenance (2014, 490). Since $MTBM_U$ consists of unscheduled downtimes, typically due to failures, it can be used as an approximation of MTBF. The reciprocal of $MTBM_U$ can also be used as an approximation for the failure rate. Likewise, the reciprocal of $MTBM_S$ can be considered the rate at which planned maintenance is conducted.

While reliability is a probability that a system will perform as intended, availability is the percentage of time that a system is available for use under specified circumstances. In relation to the other concepts of RAM, a system's availability is dependent on its reliability and maintainability (INCOSE 2015, 228). There are three primary availability definitions: inherent availability (A_i), achieved availability (A_a), and operational availability (A_o). These definitions vary by the environment in which the system is operating as well as the type of support that is being considered.

Blanchard and Fabrycky define inherent availability as "the probability that a system or equipment, when used under stated conditions in an *ideal* support environment (i.e., readily available tools, spares, maintenance personnel, etc.), will operate satisfactorily at any point in time as required" (2014, 492). They define achieved availability as "the probability that a system or equipment, when used under stated conditions in an *ideal* support environment, will operate satisfactorily at any point in time" (2014, 493). The difference between these two definitions is that A_i does not factor in time for preventive maintenance, logistics delays, and administrative delays, whereas A_a only excludes time for logistics and administrative delays (Blanchard and Fabrycky 2014, 493). An important note for these availability metrics is that they consider the system in an ideal support environment and not a realistic operating environment.

Operational availability is defined as the "probability that a system or equipment, when used under stated conditions in an *actual* operational environment, will operate satisfactorily when called upon" (Blanchard and Fabrycky 2014, 493). Therefore, A_o includes time needed for all maintenance actions, planned and unplanned, as well as time needed for logistics and administrative delays. Blanchard and Fabrycky express operational availability as (2014, 493):

$$A_o = \frac{MTBM}{MTBM + MDT} \qquad (1.5)$$

where MTBM is the mean time between maintenance and MDT is the mean down time. Because MTBM includes planned and unplanned maintenance, this time can be considered the system's uptime. Likewise, the MDT can be considered the system's downtime. Therefore, A_o can be treated as the ratio of system uptime to the entire time scale of uptime plus downtime.

F. RELATED RESEARCH

While there appear to be few published analyses on shipboard davits, there have been applicable studies performed on other critical Coast Guard cutter systems such as the main diesel engines. In 2004, Milkie and Perakis published the technical paper *Statistical Methods for Planning Diesel Engine Overhauls in the U. S. Coast Guard*. This paper uses casualty report data to help model the failure rates vs operating hour for the diesel engines on Coast Guard Reliance class cutters. A similar approach could be applied to study the failure rates over time for the dual point davit system.

The intent of the Milkie and Perakis study is comparable to the intent of this thesis, which is to use historical failure data to help better inform when depot-level preventative maintenance should be conducted on a system. Their study examined failure rates as they pertained to hours of engine operating time, which each cutter records. This estimated the extent of system operation that would typically result in an expected number of casualties. It was not concerned with the cause of each engine failure, only that each failure had an operational impact (Milkie and Perakis 2004, 31). The data collected by Milkie and Perakis indicated an area of constant failure rate with an increasing rate of failure as the engines neared 24,000 hours of operation. The analysis ultimately found that the engine life cycles experienced failure rates that increased as operating hours increased (Milkie and Perakis 2004, 39). It also indicated that scheduled engine overhauls based on engine hours did not prevent an increase in wear-out failure rates. This ultimately resulted in a recommendation for the Coast Guard to pursue more condition monitoring and reliability-centered maintenance approach to the diesel engine overhaul policy (Milkie and Perakis 2004, 39).

Based on background information regarding shipboard davits, some initial comparisons can be made between this diesel engine study and a study for the davits. Milkie and Perakis were able to use the engine hours of operation since the data was available; the hours for each engine are tracked and can be identified at each engine failure. For Coast Guard's shipboard davits, however, hours of system operation are not recorded so that data is unavailable.

Additionally, the diesel engines are interior systems that operate in the controlled environment of an engine room, so their failure rates could be expected to correlate primarily to engine wear. This makes the engine hours much more important to that failure analysis. On the other hand, davits are external systems that are constantly exposed to harsh environments regardless of whether they are operating. This includes extreme temperature ranges, precipitation, ice, sun radiation, and high salinity sea spray. Because of this, the expectation is that davit failure rates would not depend so much on operating hours as they would on time in service. Hence, time in service would be a desired time period for use in an assessment of davit failures.

There are other related works that have applied Systems Engineering concepts to Coast Guard systems in various ways. Koski studied the impacts that the Coast Guard's reliability-centered maintenance approach, relatively new at the time, had on the operational availability of the cutter fleet (2011). Koski implemented a "Soft Systems Methodology" for the analysis, which was more an investigative than a quantitative systems engineering approach to reliability analysis. Another related study by Marino used systems and business model approaches to examine Coast Guard cutter maintenance requirements and life cycle resource requirements (2018). Additionally, Pritchett used traditional system engineering and reliability-centered maintenance methodologies to explore how to better inform maintenance policies for current and future Coast Guard cutters (2018). In one form or another, each of these studies applied the concepts of reliability, availability, and life cycle maintenance to help manage Coast Guard assets.

Finally, another valuable reference for approaching an analysis of davit failures is a Coast Guard maintenance analysis report that was performed on the Welin Lambie model 5.0B davit in 2019. The author, Michael Holz, is a Senior Reliability Engineer at Coast

Guard's SFLC Engineering Services Division. The report's purpose was to analyze system failure data and parts supply-demand rates in order to "improve reliability and update planned maintenance" (Holz 2019, 1). It collected data across all cutter classes that use the model 5.0B davit including configuration data, supply data, maintenance completion data, and maintenance procedure cards for each class (Holz 2019). Recommendations were made for improvements throughout each aspect of the system management for which data was collected. The analysis focused primarily on the O-level maintenance conducted by the ship crews; however, it did not delve into the frequency at which D-level overhauls and renewals were taking place. This thesis attempts to address the D-level maintenance planning using archival failure data for a sample of the Welin Lambie model 5.0B davits.

III. METHODOLOGY

A. OVERVIEW

The research method for this thesis will primarily be statistical analysis based on archived empirical data and a case study of maintenance policies. The research will focus on the dual point davits onboard the WMEC-270 and WMEC-210 cutters as a case study to collect data on davit system failures. Data will also be gathered to determine when the major depot-level periodic maintenance work was done on these davits. The failure rates will be used to calculate the reliability and operational availability of the davit systems. The overall study will determine what effects the planned maintenance frequency has on the system's reliability and availability.

B. DATA COLLECTION

1. Scope

The intent was to obtain a period of data that spans approximately eight to ten years. The thoroughness of the data becomes less reliable the older it is, and the data should all be relevant to SFLC's current modernized organization. The Maintenance Analysis Report by Michael Holz was used as the primary source of failure data since that report had already harvested the FLS and EAL systems for davit failures via CASREPs and discrepancy reports (Holz 2019, 1). Based on the records available, the period of data used in this thesis is from January 1, 2011, to December 14, 2018, just shy of eight years.

The maintenance completion records entered by cutter crews in FLS-MAM only date back to 2013, and there were very limited unscheduled maintenance entries made by crews (Holz 2019, 3). Despite this lack of information, however, the records and this author's personal experience indicate that the cutters were more consistent in recording equipment failures that were not immediately correctable by the crew and impacted operations. These CASREP and discrepancy failures recorded in FLS and EAL are deemed the most important for an availability analysis.

2. Assumptions

There are some assumptions that needed to be made before performing any analysis of the data. These assumptions were intended to simplify the analysis process and focus it on answering the research questions. However, the assumptions were also carefully chosen so they avoid causing changes to the results of any analysis.

The davit casualty reports are considered reasonable accounts of historical failure events. This assumption can be made since the CASREP and discrepancy reports were following prescribed Coast Guard reporting policies that existed when they were created. This does not imply that all casualty records are complete or entirely accurate, but that they are official reports of actual events.

Additionally, cutters and davits are considered homogenous populations. This means that the cutters used in the study are operated and maintained in accordance with the same official Coast Guard policies and procedures. This assumption lead to the selection of the usable data for the study. The davits themselves are homogenous in that they are all the same model and configuration of davit. The davits exist on different geographically dispersed ships that include two different cutter classes. However, the cutters are considered homogenous in that they are medium endurance cutters capable of performing similar Coast Guard missions in accordance with the same directives. Though this assumption of homogeneity guided the selection of data, the analysis will still test the data to ensure it can be statistically considered as part of the same population.

3. Definitions

The following definitions were established for consistency throughout the data collection, interpretation, and analysis. These definitions were influenced by Coast Guard or industry standards but were ultimately formulated by the author for the purposes of this study.

<u>Davit failure / inoperable</u> – A condition that prevents the davit from being used to its designed operating capacity. This includes cases where standard operating procedures must be modified or by-passed in order to use the davit. For example, if a casualty results in a davit being unusable rough seas, this is deemed a davit failure for the purposes of this

study. The missions and purposes for which the davit is intended to operate in have been limited.

Operable – A condition in which a davit system is fully operational and can be used for any mission as it was designed. An operable davit is fully functional while using the published standard operating procedures.

Failure indicators – The linguistic entries in discrepancy reports that lead to the conclusion that a davit has failed. The existence of one or more failure indicators in a discrepancy report results in the davit being considered inoperable. Examples include discrepancy comments of “unable to use davit”; “unable to launch OTH”; “unable to launch in rough seas”; or an associated cutter readiness classification of “partial mission capable” or “not mission capable.”

Non-system failures – Davit casualty reports that result from damage caused by other-than-normal use or events are not considered davit failures. For example, a davit damaged by shipyard crane operations during the vessel’s drydock is not considered a failure of the Welin Lambie davit system.

Uptime – Any duration of time that a davit system is fully operational and available for use when required. This is not equivalent to hours of operation.

Downtime – Any duration of time that a davit is in a failed or inoperable state, as previously defined.

Time between failure – The duration of time between subsequent failures, starting with the date of a previous failure correction to the next date a failure is reported. Equivalent to the uptime between two failures.

Discrepancy/failure duration – The duration of time that a davit is in a failed or inoperable state for a given failure event. Equivalent to the downtime for a single discrepancy report.

Given the wide variety of verbiage cutters have used in their davit casualty records, many decisions had to be made by the author on how to classify a discrepancy as operable or inoperable. In cases where records were unclear, the definitions were applied as consistently as possible.

For example, a common failure component was the davit accumulator bottles, for which crews gave impact assessments ranging from no impact to an inability to use the davit. Accumulator bottles hold reserve hydraulic pressure that allows the davit arms to temporarily luff outward or inward in the event of a power failure. As long as a cutter still has power to the davit, the davit is fully operational for all missions in accordance with standard operating procedures. For such discrepancy reports, the author's decision for the davit being operable or inoperable was based on any available failure indicators as previously defined.

Another example of applying the definitions to unclear records is when temporary repairs were indicated by the crew. In certain few cases the crew indicated that temporary repairs were made in order to keep the davit operational, but the discrepancy reports were not cleared until official repairs were made. For consistency, the davits were considered down and inoperable until their respective discrepancy reports were cleared.

In rare cases, a davit casualty report was initiated by a cutter due to a component being removed and provided to correct another ship's davit discrepancy. In these cases, the failures of both ship davits were included as inoperable reports, since the failure time of one davit transferred to the other davit as parts were swapped.

4. Data Separation Process

a. Failure Data

The data records for the 2019 Holz Maintenance Analysis Report were reviewed and all failure and unscheduled maintenance reports were pulled from the records. As previously discussed, the unscheduled maintenance reports were few and incomplete for most cutters, so the CASREP and discrepancy reports were selected as the primary source of failure data. To avoid double-counting failures, CASREP reports from FLS were compared to discrepancy reports from EAL, and duplicates between the two systems were removed.

For each davit failure, the following important information was compiled: the failure title, a functional description of the failure component, the date the discrepancy was initially recorded, the date it was reported corrected, the operational or capability impacts, impacts on the cutter's readiness, and the crews' descriptive remarks. Table 1 provides an excerpt from one of the cutter's davit discrepancy records.

Table 1. Excerpt from CGC ACTIVE Discrepancy Data from FLS and EAL.

Title	Discrep Reported	Discrep Corrected	Op Impact	Cutter Readiness	Discrepancy Remarks
Welin Lambie Davit Wire Rope	23-Aug-15	24-Aug-15	OPS LIMITED	PARTIAL MISSION CAPABLE - MAINT	* None given
Dual Point Davit Block Assembly and Cable Damage	24-Oct-17	27-Oct-17	OPS LIMITED	PARTIAL MISSION CAPABLE - SUPPLY	* None given
Discrep: 2018019 Dual Point Davit	25-Apr-18	29-Apr-18	OP IMPACT: Cutter is unable to launch the MKIV OTH. SF is able to launch the OTH MKII using the Single Point Davit.	* None given	REMARKS: SF tagged-out the dual point davit to replace one of the control joysticks. Upon clearing the tags and reenergizing the davit, none of the functions at the control station worked. Power is present at the control station and the PLC receives input data from the davit control joysticks but fails to transmit outputs to the davit machinery…
Discrep: 2018049 Dual Point Davit Tension Pin Damage	29-Oct-18	28-Nov-18	OP IMPACT: Cutter is unable to safely operate the Dual Point Davit due to damage to the aft boat block pin…	* None given	REMARKS: Upon inspection of the Welin Lambie Davit boat blocks in accordance with the Time Critical Maintenance Action TP2090.0 SF discovered the aft boat block tension pin to be bent but not sheared. SF ordered replacement pins and plan to install upon receipt…

This information was collected for all 13 270-foot MECs and all 14 210-foot MECs. The author reviewed each report to determine which of the discrepancies resulted in the davit being inoperable, as previously defined. The failure indicators for this decision were primarily found in the readiness statements, operational or capability impacts, and additional remarks. Each record required a judgment call by the author based on the assumptions and definitions that had been established. Then all reports having sufficient information to make a determination were assigned a designation of *operable* or *inoperable*. Some discrepancy reports lacked enough information to make a severity determination. For example, some reports contained no impact information or did not contain enough remarks for the author to infer a level of impact to davit capabilities. These records were assigned a designation of *unknown*.

Next, all davit discrepancies categorized as operable or unknown were removed from the data pool, while those categorized as inoperable were retained for the failure analysis. This consolidated the records to include only the data samples that had an identifiable negative impact on davit equipment operations. All cutters but one, CGC STEADFAST, had usable collections of failure data. The STEADFAST reports were deemed unreliable as there were only three discrepancies recorded in the sources used for this thesis. Two of those three discrepancies did not have enough information to categorize the davit as inoperable or operable. As a result, no analysis could be made using the STEADFAST davit records and they were removed leaving a total of 26 MEC data sources.

While compiling and categorizing the davit casualty records, some limitations were noted by the author. The duration that each discrepancy report is open, or the downtime of each failure, is not broken into periods of repair time, administrative time, logistics supply time, or other delays. Also, the failure records may not include davit casualties that were easily corrected by the crew in less than four hours, even if a davit was inoperable during that time (Holz 2019, 3). Some discrepancy reports appeared as canceled and incomplete when casualty repairs were rolled into planned maintenance availabilities. Additionally, the inconsistencies with report quality was a major concern; for example, CGC MOHAWK had three years of discrepancies (five reports) with no comments or amplifying remarks. Overall, the subjective nature of the report entries is deemed as a significant limitation since one Engineer Officer may consider a davit issue to be inoperable while another may feel comfortable operating it. The variations in how each cutter treats its equipment casualties depends heavily on the experience, technical knowledge, and level of risk acceptance that each cutter leadership has.

b. Scheduled Depot Maintenance Data

The scheduled depot maintenance data was pulled directly from FLS archive records. Maintenance reports were obtained specifically for the Welin Lambie davits, then those were narrowed down to the planned overhauls and renewals. Any records that indicated they were a result of unplanned repair maintenance were removed. For example, many cutters had maintenance items tied to "CASREP FYXX" projects, which were funds that paid for unplanned depot-level discrepancy repairs. Additionally, any maintenance items that did not constitute overhauls or repairs to existing system components were removed, such as fleetwide upgrades to pad eye and bracket components.

The resulting records for the two classes of cutters then had to be further cleaned up by removing glaring data entry anomalies. For example, each WMEC-270 had a davit renewal record—Welin Lambie Davit Renew, CMP41247 – entered with the same date of Oct 20, 2011. Based on the author's experience, this was likely a mass entry made by the Product Line in order to establish or reestablish a class-wide baseline for the timeline of renewals. These October data points were removed from each cutter since they were an administrative artifact and not reflective of actual davit renewals. Similarly, six of the WMEC-210s had Aug 4, 2011 davit renewal entries with no associated project name or cost data, and these entries were removed.

Furthermore, maintenance items that were obvious duplicates were removed. For example, several cutters had maintenance items that repeated only a few months apart within the same year, one showing no *actual cost* record followed by another showing an *actual cost* value. In these cases, the entries lacking associated costs or project connections were removed as duplicates.

Like the failure records, the maintenance records had limitations that must be acknowledged. The decisions to remove duplicates and baseline entries reflected a larger concern over the reliability of the data to be taken on face value. The inconsistencies made it difficult to tell for sure if entries were accurate. For example, if a depot project was deferred to another time, but the entry was marked in FLS as complete instead of canceled, then it will show up as a completed overhaul or renewal even if no work took place. Additionally, the records obtained by the author did not provide the start and end dates of each davit planned maintenance event. Therefore, the downtime for planned maintenance is not included in future calculations, and each davit overhaul or renewal completion is treated as a point in time.

c. Combining Failure and Maintenance Data

Once the failure and planned maintenance data were collected and scrubbed for each cutter, the next step was to combine the information for each davit system. Combining the data resulted in breaking the full period of interest, January 1, 2011, to December 14, 2018, into a series of smaller periods of maintenance and failure events. This made it possible to calculate the amount of davit uptime and downtime for each cutter, as well as the number of failures that occurred between planned maintenance actions. Table 2 provides an example of the resulting combined information.

Table 2. Consolidated Failure and Planned Depot Maintenance Data for CGC ACTIVE.

Period Event		**Period Dates**		**Period Duration**		**Uptime between Maint**	**Downtime between Maint**	**Total Days**
From	**To**	**Start**	**End**	**Uptime**	**Down time**			
Data start	Overhaul	01-Jan-11	01-Oct-11	273		273	0	273
Overhaul	Failure start	01-Oct-11	23-Aug-15	1422		1471	1	1472
Failure start	Failure correction	23-Aug-15	24-Aug-15		1			
Failure correction	Renewal	24-Aug-15	12-Oct-15	49				
Renewal	Failure start	12-Oct-15	24-Oct-17	743		1122	37	1159
Failure start	Failure correction	24-Oct-17	27-Oct-17		3			
Failure correction	Failure start	27-Oct-17	25-Apr-18	180				
Failure start	Failure correction	25-Apr-18	29-Apr-18		4			
Failure correction	Failure Start	29-Apr-18	29-Oct-18	184				
Failure start	Failure correction	29-Oct-18	28-Nov-18		30			
Failure correction	Data end	28-Nov-18	14-Dec-18	15				

The information illustrated in Table 2 was then used to further consolidate the data into periods between maintenance actions and separate davit systems from one another. In order to gain an understanding of the availability of each davit, the data taken from each cutter had to be reorganized. When a davit is overhauled, it may be considered to have a refresh on its life cycle, but it is still the same unit. However, when a davit is renewed, that cutter receives a different davit with a different serial number. Therefore, a cutter that has a recorded davit renewal will have at least two davit units each with its own set of failure data. This data needed to be separated accordingly.

The result was a list of 45 davits that each were divided up by periods between scheduled depot maintenance actions. This permitted the uptime, downtime, number of failures, and time between maintenance actions to be determined for each davit. If a davit was renewed, then each davit was indicated as “CUTTER NAME-1”; “CUTTER NAME-2” and so on. Table 3 provides an excerpt from the full table of davits.

Table 3. Consolidated Failure and Maintenance Data per Davit Unit.

Davit Unit	Period	Start	End	Days Up	Days Down	Total Days	No. of Failures	No. of Maint Actions
ACTIVE-1	Before Overhaul	01-Jan-11	01-Oct-11	273	0	273	0	1
	After Overhaul	01-Oct-11	12-Oct-15	1471	1	1472	1	1
ACTIVE-2	After Renewal	12-Oct-15	14-Dec-18	1122	37	1159	3	0
ALERT-1	Before Overhaul	01-Jan-11	15-Feb-13	776	0	776	0	1
	After Overhaul	15-Feb-13	13-Aug-17	1546	94	1640	5	1
ALERT-2	After Renewal	13-Aug-17	14-Dec-18	256	232	488	1	0
CONFIDENCE-1	Before Renewal	01-Jan-11	25-Jan-14	868	252	1120	4	1
CONFIDENCE-2	Before Overhaul	25-Jan-14	29-Jul-18	1646	0	1646	0	1
	After Overhaul	29-Jul-18	14-Dec-18	138	0	138	0	0
DAUNTLESS-1	Before Renewal	01-Jan-11	12-Jan-15	1336	136	1472	6	1

Davit Unit	Period	Start	End	Days Up	Days Down	Total Days	No. of Failures	No. of Maint Actions
DAUNTLESS-2	After Renewal	12-Jan-15	14-Dec-18	1309	123	1432	3	0

As shown in Table 3, the overall data available for each cutter begins with January 1, 2011, and ends with December 14, 2018. These dates generated left-censored data for each cutter's first davit and right-censored data for each cutter's last davit. The censoring included the unknown previous or future failures and maintenance actions. The second to last column includes the number of known failures that occurred within each period recorded, and the last column shows the number of known maintenance actions that occurred in that period. For consistency, if a period ended in an overhaul or renewal, that period was marked as having one known maintenance action. If a period ended with the termination of data collection, then the maintenance is right-censored and there were zero known maintenance actions assigned to that period.

The compiled data for all davits will be used in the analysis to calculate the failure rate that occurred between each subsequent maintenance action, the MTBF within each period, and the MTBM within each period. From there, a more in-depth statistical analysis can be performed.

C. STATISTICAL ANALYSIS

In order to answer the research questions, the data must be analyzed for usable information. The goal in analyzing any of the data shall be to address the research questions. The first question is determining how the failure and maintenance data that the Coast Guard currently collects can be used to generate system failure models. In order to begin answering that question, there needs to be some observations or conclusions that can be made regarding the data. Those observations can then be used to build a model to modify and study, which helps answer the second research question.

1. Analysis Techniques

The analysis techniques chosen will depend on the type and quality of the data available, and how that data can be manipulated to lend useful observations. The primary dependent variable of concern is the operational availability of the davit system, and how that is influenced by scheduled depot maintenance periodicity. It will also be prudent to explore other independent variables besides the maintenance periodicity to fully round out the understanding of the relationships among variables.

a. Exploring Data Relationships

The primary method of exploring the data is to statistically identify relationships, if any, that exist among the independent and dependent variables. A qualitative way to determine relationships is to plot the data and visually look for patterns. The initial approach will be to perform basic plots of each variable of interest such as failure rate and mean time between failures against the mean time between maintenance. This allows for a rudimentary identification of any trends that appear between the variables. While this is helpful to target the most obvious relationships, there would need to be a quantitative statistical analysis to identify the more obscure relationships.

b. Paired t-tests

A quantitative analysis can be performed in several ways and choosing a method can be determined by the variety of factors that may exist in the data. One simple method is to perform a *t*-test, which will help determine if two sets of samples are statistically different. A null and alternative hypothesis are each made as to whether the population means are equal or unequal. Then the *t*-test looks at the mean and variance of each set of sample data and makes it possible to reject or fail to reject the null hypothesis.

Regarding the davit information, a *t*-test can accomplish several important comparisons. First, a *t*-test will be needed to ensure the failure data collected from the two pools of samples – 210-foot MEC davits and 270-foot MEC davits – can be treated as being from the same population. Another test can be used to determine if censored data has a significant effect on the overall samples. If a test cannot reject a null hypothesis that the mean of the censored data is the same as the mean of the uncensored data, then the data from both sets can be treated equally. A *t*-test can also be used to determine whether the type of planned depot maintenance, overhaul or renewal, has a statistically discernable effect on failure rate.

c. Single-factor ANOVA

Another way to assess a set of data is to perform an analysis of variance (ANOVA), which makes it possible to compare the means of three or more groups of data (Montgomery and Runger 2014, 539). If there are multiple groups, or levels, of one factor then a single-factor ANOVA can be performed to identify the variability between groups and within the groups. Like the *t*-test, a null and alternative hypothesis will be made as to whether the population means are equal or unequal. An *F*-test is performed which compares the mean square for the treatments (MS_T), or variance between groups, to the mean square for error (MS_E), the variance within the groups. This ratio generates an *F* statistic F_0 as shown in (Montgomery and Runger 2014, 545):

$$F_0 = \frac{MS_T}{MS_E} \tag{1.6}$$

As shown by Montgomery and Runger, F_0 has an *F*-distribution with a critical value of $f_{\alpha,a-1,a(n-1)}$. If the calculated F_0 is greater than the critical *F* value, then it indicates there is greater variance between the groups than there is within the groups, thereby rejecting a null hypothesis that the group means are all the same (Montgomery and Runger 2014, 545).

There are several ways that the data for davit failures can be broken down into bins for one factor. These can be used to identify levels of influence that the factor has on the failure rates and ultimately the operational availability. For example, the mean time between scheduled maintenance can be separated into multiple groups of equal sizes such as 0–500 days, 500–1000 days, 1000–1500 days, and 1500–2000 days. The single factor is the MTBM values, but there are four levels chosen for that factor. Another factor that can be considered is the location or region in which each davit is primarily located. Since each cutter can patrol in a broad array of climates, the most dependable treatment for a location would be the homeport where the cutters spend up to half each year.

d. Two-factor ANOVA

If the single-factor ANOVA identify relationships, then performing two-factor ANOVA tests may be useful for identifying more discrete relationships among the davit failure data. Like the one-way ANOVA, the two-way ANOVA compares the variance within and among groups of a factor. However, the two-way process also allows for the identification of interactions between variables (Montgomery and Runger 2014, 581). By using this method, the *F* statistics, the resulting *P*-values for each factor, and their combinations can be used to identify the level of influence that exists. A small *P*-value would indicate a greater significance to the level of influence.

This can be a useful tool to identify variables, or combinations of variables, that influence the davit failure rates. Specifically, the two-factor ANOVA can be used to identify interactions that exist between combinations such as davit geographic location and maintenance type, or between $MTBM_S$ groups and location.

D. DEVELOPING A MODEL

The research questions ask whether the data that is currently collected by the Coast Guard can be used to develop a failure model. Depending on the outcome of the statistical analysis, a model may be developed to experiment with potential impacts on operational availability. One method for doing this is to use ExtendSim, which is a modeling and simulation software that has a broad range of uses including engineering, scheduling, and analysis (ExtendSim n.d.). It implements simple icons and lines that the user can manipulate to provide layers of intricacy to a model. It generates a visual representation similar to a flow-block diagram but consists of many imbedded menus that allow for detailed modification of parameters and information. Once a model is created, it can be run in a time-based simulation that allows the user to collect and analyze resulting data.

For the purposes of the davit failure data, ExtendSim could potentially be used to simulate davits entering a life cycle which applies maintenance actions at an average periodicity determined by the analysis of the data. They will then experience failures and repairs at rates and distributions that are supported by the archived data. The output of the simulation provides calculated expectations of the operational availability of the davit systems. The benefit of this modeling and simulation is the ability to run the scenario multiple times very quickly, as well as the ability to vary the factors based on the historical data.

IV. ANALYSIS

A. OVERVIEW

The intended analysis methodology was applied to the data with some necessary modifications. Much of the analysis evolution was dependent on the quality of the data and the results that were discovered in each previous step of the analysis. The results were less definitive than expected, which may be an indicator as to the quality of the data. Nonetheless, the outcomes still provided useful information for davit maintenance management.

B. ANALYSIS RESULTS

1. Pooling the Samples

The first step of the analysis after compiling all the data was to verify whether the two sources of data were statistically from the same population. Failure and maintenance records were collected from two separate groups of samples: davits on WMEC-210s and davits on WMEC-270s. This report's analysis intended to treat these sets of data as being from the same overall population, that being the Welin Lambie twin pivot arm davit model TW.PIV 5.0B. Therefore, a hypothesis test was performed in order to determine whether these two data sets could be pooled. The factors that were evaluated for each set of data was the number of inoperable davit failures and the MTBF that resulted for each class of cutter. Table 4 and Table 5 present summaries of these values for both cutter classes.

Table 4. WMEC-210 MTBF Summary

Cutter	Location	No. of Failures	MTBF (days)
ACTIVE	Port Angeles, WA	4	385.3
ALERT	Astoria, OR	7	161.9
CONFIDENCE	Port Canaveral, FL	5	148.8
DAUNTLESS	Pensacola, FL	10	250.4
DECISIVE	Pensacola, FL	19	116.4
DEPENDABLE	Little Creek, VA	9	199.6
DILIGENCE	Wilmington, NC	10	234.8
RELIANCE	Kittery, ME	4	57.7
RESOLUTE	St Petersburg, FL	16	138.8

Cutter	Location	No. of Failures	MTBF (days)
VALIANT	Mayport, FL	7	375.3
VENTUROUS	St Petersburg, FL	8	315.6
VIGILANT	Port Canaveral, FL	3	932.3
VIGOROUS	Little Creek, VA	9	293.1

Table 5. WMEC-270 MTBF Summary

Cutter	Location	No. of Failures	MTBF (days)
BEAR	Portsmouth, VA	7	226.8
CAMPBELL	Kittery, ME	9	317.6
ESCANABA	Boston, MA	8	27.1
FORWARD	Portsmouth, VA	9	301.1
HARRIET LANE	Portsmouth, VA	6	283.4
LEGARE	Portsmouth, VA	16	111.5
MOHAWK	Key West, FL	8	294.1
NORTHLAND	Portsmouth, VA	7	435.1
SENECA	Boston, MA	9	295.6
SPENCER	Boston, MA	6	219.6
TAHOMA	Kittery, ME	7	412.6
TAMPA	Portsmouth, VA	14	201.4
THETIS	Key West, FL	10	206.5

Since each sample set had less than 30 data points, a two-sample *t*-test was used as the statistical testing method. From the data available, the following hypothesis was made:

Null hypothesis $H_o : \mu_1 = \mu_2$

Alternative hypothesis $H_a : \mu_1 \neq \mu_2$

Where μ_1 and μ_2 represent the means for the WMEC-210 and WMEC-270 data sets, respectively. Because these davits are all the same model, their population variances were assumed to be the same but are unknown, which required the use of a pooled variance.

Testing the means was a two-sided assessment so the critical limit $t_{\alpha,n1+n2-2}$ with a 95% confidence level was calculated to be 2.06. The null hypothesis would be rejected if the test statistic *T* was greater than the critical limit. Therefore:

Reject H_o if $|T| > 2.06$

Based on the MTBF as the parameter of interest, the test statistic was calculated to be $|T| = 0.312$. Subsequently with the number of failures as the parameter of interest, the test statistic was $|T| = 0.251$. Since both were less than the critical t, both tests failed to reject the null hypothesis indicating that neither the MTBF nor the number of failures are significantly different. Therefore, the data collected from the WMEC-210 and WMEC-270 cutters were pooled together for use in the remaining analyses.

2. Calculating MTBF and MTBM

Determining that both data sources could be treated equally increased the sample size for our analyses. The initial calculations were performed to determine failure rate, MTBF, and MTBM for each individual davit. These calculations were based on the summarized data that was presented in Table 3. First, the failure rate λ between planned maintenance actions was calculated using Equation 1.2, the number of days between maintenance, and the number of failures that occurred in that period. For example, the failure rates between planned depot maintenance for CGC ALERT davit "ALERT-1" were calculated as:

$$\lambda = \frac{number\ of\ \ failures}{total\ days} = \frac{0}{776} = 0 \qquad \text{and} \qquad \lambda = \frac{number\ of\ \ failures}{total\ days} = \frac{5}{1640} = 0.003$$

Since MTBF is just the reciprocal of the failure rate, that was also calculated for each davit using Equation 1.3. For periods where no failures occurred, the failure rate was zero resulting in MTBF being incalculable.

Due to each davit having so few scheduled maintenance actions, the period between each planned depot maintenance was treated as the $MTBM_S$. This was applied to Equation 1.4 along with the calculated MTBF, or $MTBM_U$, to determine the overall MTBM for each period between a davit's planned maintenance. For example, the first maintenance period for davit ALERT-1 had MTBM values equal to the period duration of 273 days since there were no failures in that time. However, the next maintenance period for ALERT-1 had a MTBM of:

$$MTBM = \frac{1}{1/1472 + 1/1472} = 735.5 \text{ days}$$

and davit ACTIVE-2 had a MTBM of:

$$MTBM = \frac{1}{1/386.3 + 1/1159} = 374.0 \text{ days}$$

Additionally, the davit availability between scheduled maintenance actions was calculated using a variation of Equation 1.5. Since the actual days up and days down were known, the availability was calculated as:

$$A_o = \frac{days\ up}{total\ days}$$

For example, ACTIVE-1 had an availability of 1.0 and 0.999 between subsequent maintenance periods, and ACTIVE-2 has an availability of 0.968. These values provided more ways to observe the data.

3. Treatment of Censored Data

One of the intended methods for exploring data relationships was through plotting, followed by paired t-tests if needed. The correlation between censored and uncensored data was one such relationship that needed to be examined before moving further in the analysis. As discussed with Table 3, there are many periods in the data that included left or right censoring.

To get an initial sense of whether censoring had any impact on the data, several plots were made using all the data and then for comparison using only uncensored data. These are shown side-by-side in Figure 5 and Figure 6.

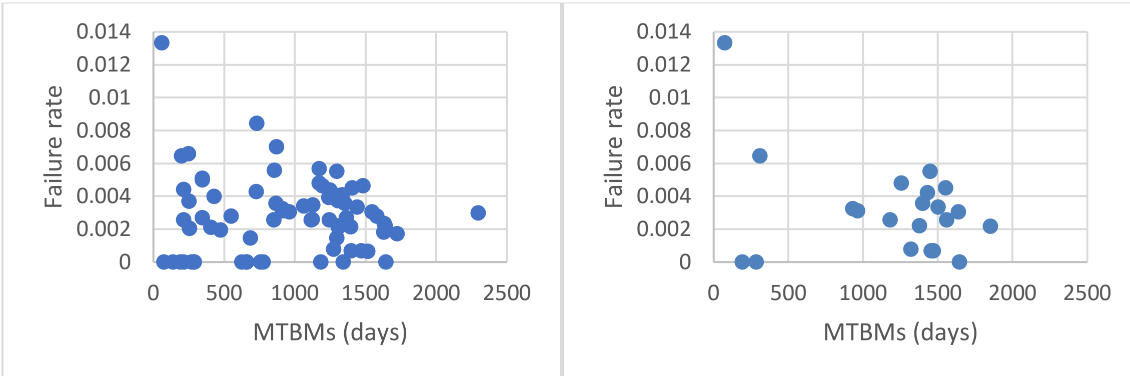


Figure 5. MTBMS versus Failure Rate Using All Data (left) and Only Uncensored Data (right).

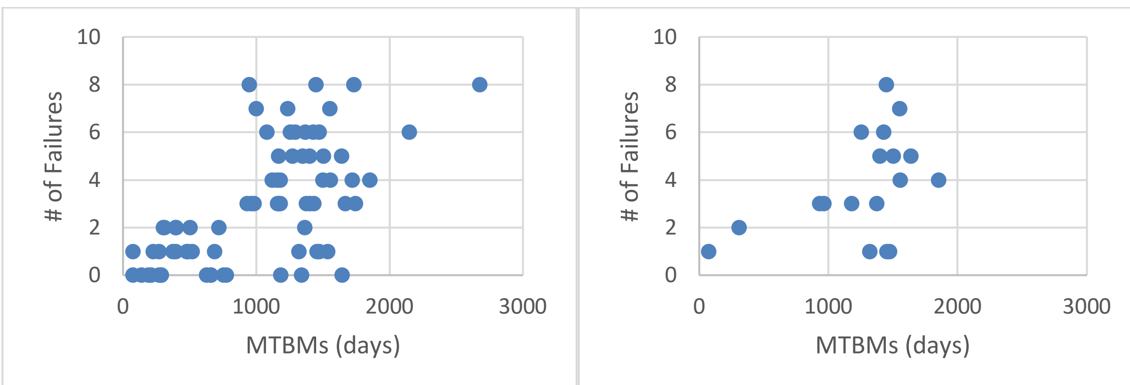


Figure 6. MTBMS versus Number of Failures Using All Data (left) and Only Uncensored Data (right).

As seen in these plot comparisons, there visually appears to be a concentration of uncensored maintenance periods between 1000 to 2000 days, whereas the censored maintenance periods have a greater spread. Since the censored maintenance periods consist of truncated timeframes, it made sense that there could be a higher frequency of censored periods with shorter durations. However, this visual representation only provided an indicator that there could be a significant difference between the data types.

To statistically compare the uncensored data to the censored data, another two-sample *t*-test was performed. The following hypothesis was made:

Null hypothesis $\qquad H_o : \mu_1 = \mu_2$

Alternative hypothesis $H_a : \mu_1 \neq \mu_2$

Where μ_1 and μ_2 represent the means for censored scheduled maintenance periods and uncensored scheduled maintenance periods, respectively. Following the null hypothesis, their population variances were assumed to be the same for the test.

Testing the means was a two-sided assessment so the critical limit $t_{\alpha,n1+n2-2}$ with a 95% confidence level was calculated to be 1.99. The null hypothesis would be rejected if the test statistic T was greater than the critical limit. Therefore:

Reject H_o if $|T| > 1.99$

Based on the time between scheduled maintenance, the test statistic was calculated to be $|T| = 2.05$. Since this was greater than the critical t, the test rejected the null hypothesis, which indicated that the means were significantly different. Therefore, the censored data could not be treated the same as the uncensored data. Because of this significant difference and the fact that censored maintenance periods lacked complete records of failure and maintenance intervals, the censored data was removed from further analysis in favor of only using the uncensored data.

4. Exploring Relationships within Uncensored Data

The next step was to start looking for trends in the remaining data. The simplest methodology was employed first, which was to again plot the information and visually look for patterns and potential relationships. Figure 7 through Figure 9 illustrate several comparisons.

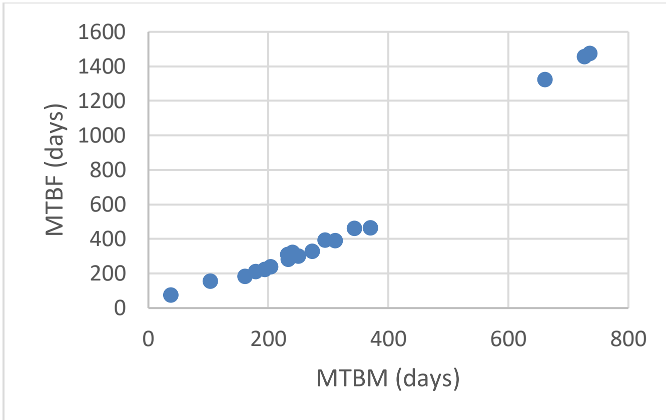


Figure 7. Combined MTBM versus MTBF

The calculated MTBM showed a linear trend when compared with the MTBF. While this looked like a clear trend initially, it was simply an artifact of the way MTBM was calculated within this analysis. The MTBM was calculated between scheduled maintenance actions, so MTBF drove the overall MTBM calculations with little impact resulting from $MTBM_S$.

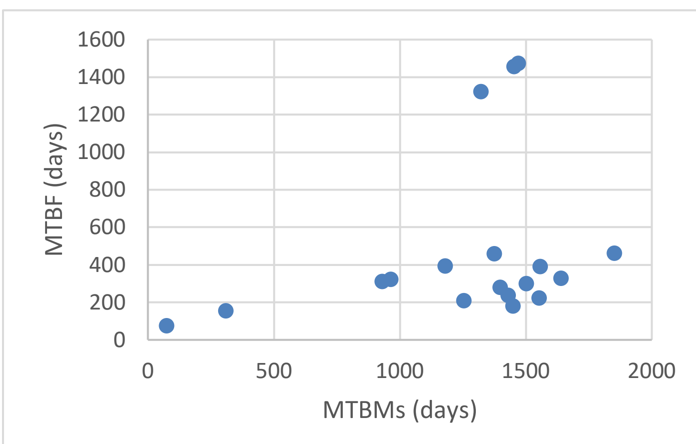


Figure 8. $MTBM_S$ versus MTBF

The scheduled maintenance actions showed little noticeable trending when compared to the MTBF. Due to the two $MTBM_S$ data points under 500 days, there appeared to be a possible trend upward; however, that pattern is less apparent for the rest of the data points.

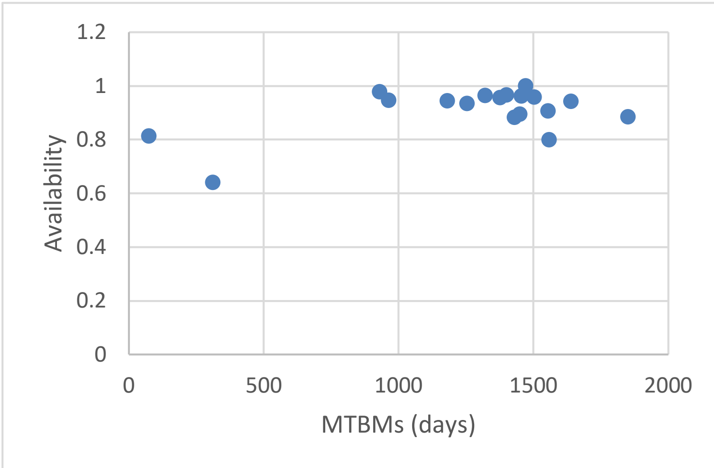


Figure 9. MTBM$_S$ versus Availability

The presentation of MTBM$_S$ compared with davit availability also showed little to no patterns in the data. All plots served as initial assessments of the data in order to begin identifying the most obvious effects between factors. While none of them showed any conclusive trends that were actionable, they did not disprove the existence of relationships. Further statistical analysis was used to better explore the information.

5. Impact of Maintenance Action Type on Failure Rate

One important factor to examine was the effect that the type of maintenance action had on the failure rates. This was determined using another paired *t*-test that compared the MTBF for davits that had most recently been overhauled to those that had most recently been renewed. The null hypothesis was made that their mean MTBF values were equal, with the alternative being that they were unequal. Assuming equal variances, the test statistic was 0.057 while the critical *t* was 2.12. Because the statistic existed within the critical limits, the test failed to reject the null hypothesis. Therefore, there was no statistical difference in the failure rates between davits that had been overhauled and those that had been renewed.

6. Single-Factor ANOVA Tests

Some additional statistical tests compared several groups of data, and therefore required the use of single-factor ANOVA tests. The first was intended to assess the impact that $MTBM_S$ duration had on MTBF. The scheduled maintenance durations were broken into four groups: 0–500 days, 500–1000 days, 1000–1500 days, and 1500–2000 days. Figure 10 shows the summary of the ANOVA results.

Groups	*Count*	*Sum*	*Average*	*Variance*		
0-500	2	230.5	115.25	3240.125		
500-1000	2	631.7	315.8333333	60.5		
1000-1500	9	6010	667.787037	324398.86		
1500-2000	5	1703	340.62	8299.422		
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	734263.976	3	244754.6587	1.3020403	0.312786	3.34389
Within Groups	2631689.16	14	187977.7973			
Total	3365953.14	17				

Figure 10. Summary of ANOVA for $MTBM_S$ Groups

Despite a wide difference in the averages amongst the groups, the variances also widely varied. The F_0 statistic is less than F_{crit}, therefore the variance within the groups was not significantly less than the variance between the groups. This ANOVA failed to statistically show any significant difference in MTBF that resulted from the duration of the $MTBM_S$.

Another factor explored was the geographic location of each davit. This was based on the location that each cutter is homeported. The locations were grouped into four general regions: North-East, Mid-Atlantic, South-East, and Pacific-Northwest. There were two factors that were individually explored with regard to location, the $MTBM_S$ and the MTBF. The $MTBM_S$ was important to first determine whether the maintenance was being conducted the same regardless of the cutter locations. The MTBF was subsequently important to see whether there was a difference in failure rates given specific locations. Figure 11 and Figure 12 present the summaries of the two ANOVA results.

Groups	Count	Sum	Average	Variance		
NorthEast	2	2958	1479	12482		
MidAtlantic	7	9232	1318.857143	238337.14		
SouthEast	7	7427	1061	231957.33		
Pacific NW	2	3112	1556	14112		
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	572476.754	3	190825.5847	0.9379283	0.448527	3.34389
Within Groups	2848360.86	14	203454.3469			
Total	3420837.61	17				

Figure 11. Summary of ANOVA for $MTBM_S$ by Region

Groups	Count	Sum	Average	Variance		
NorthEast	2	669.5	334.75	5995.125		
MidAtlantic	7	3448	492.6333333	193625.66		
SouthEast	7	2657	379.6309524	179573.05		
Pacific NW	2	1800	900	654368		
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	466397.752	3	155465.9172	0.7506402	0.539937	3.34389
Within Groups	2899555.39	14	207111.099			
Total	3365953.14	17				

Figure 12. Summary of ANOVA for MTBF by Region

In both cases, the F_0 statistic existed within the critical limits. Therefore, the geographic region in which the davits were homeported did not have a significant effect on the periodicity of their scheduled depot maintenance nor on their MTBF.

The next level of analysis would normally have included two-factor ANOVAs to determine interactions between the variables. However, due to the lack of statistical influence that was detected in the single-factor ANOVAs, we expected little benefit that would result from conducting two-factor analyses. To confirm this, one example two-factor ANOVA was performed using the program JMP, the results of which are shown in Figure 13.

Source	LogWorth	PValue
MaintAction Type*MTBMs	0.313	0.48697
MTBMs	0.210	0.61657 ^
MaintAction Type	0.030	0.93317 ^

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	424685.4	141562	0.6738
Error	14	2941267.8	210091	Prob > F
C. Total	17	3365953.1		0.5822

Figure 13. Two-Factor Test Results, Effect Summary (top) and ANOVA (bottom).

The individual p-values shown in the Effect Summary indicated that neither the individual variables nor their interaction have a statistically significant impact on the MTBF. Additionally, the ANOVA p-value of 0.58 indicated that the combined effects of each variable do not have a statistically significant impact on the MTBF.

C. THEORETICAL MODELING AND SIMULATION

1. Model Design

The results of the statistical analysis provided little structure to build a model and simulation the way it was initially intended. The lack of interactions between independent and dependent variables yielded few functions that were needed for a traditional experimentation with the archival data. Despite these limitations, a model was designed in ExtendSim that illustrated how one could theoretically conduct simulations if better data or interactions were available.

The model was a discrete-event simulation designed to follow the life cycle of a series of davits through their failures and maintenance actions. The inputs were MTBF, MDT, renewal periodicity, and overhaul periodicity, while the outputs were the number of failures, total uptime, total downtime, and calculated operational availability. Once davits are created, they flow through a decision block that sends them through a renewal or overhaul path of data inputs. A normally distributed random MTBF value is then applied to each davit, which results in a measured uptime, then a normally distributed random MDT is applied, which results in a measured downtime.

Each davit's age is continuously measured throughout the flow, which informs a decision block on what maintenance actions will be performed on each unit. When its age exceeds the renewal periodicity, it reenters the life cycle through the renewal inputs and its age is reset to zero. If a davit's age exceeds the overhaul periodicity but not the renewal periodicity, it reenters the life cycle through the overhaul inputs and retains its age. If a davit's age exceeds neither planned maintenance periodicity, it reenters as a repair unit and continues through the flow until it meets either depot maintenance criteria. An image of the full model is provided in the Appendix.

2. Experimentation

To demonstrate the potential utility of the model, an experiment was performed to examine the theoretical impacts of maintenance periodicity. For the model to provide actionable output information, the number of variables had to be reduced. We decided to look at the relationship that MTBF and renewal periodicity had with davit availability if the overhaul periodicity was kept constant. This simulated a situation in which the overhaul schedule was firmly accepted and had little variability, but maintenance managers wanted to determine whether the renewal periodicity could be adjusted and still achieve an expected level of availability.

Following the modeling approach presented in (MacCalman, Beery, and Paulo 2016), an experimental design strategy for the simulation was defined, resulting in 33 combinations of input variables that were replicated 30 times for a total of 990 model runs. The overhaul periodicity was kept constant at 1460 days to represent the current four-year policy, and the MTBF was held constant at 472 days, which reflected the average seen in the uncensored data. For the overhaul inputs, a nearly orthogonal Latin hypercube was developed based on (Sanchez 2011), which generated the 33 MTBF and periodicity combinations. The MTBF values ranged between 180 days to 730 days, while the overhauls spanned 1460 to 2920 days. For both the overhaul and renewal database inputs, the MDT was held constant at 28 days, which reflected the average downtime seen in past records.

3. Simulation Results and Analysis

A statistical analysis was performed using the results from the model to assess possible interactions among MTBF, renewal periodicity, and availability. The availability was assigned as the dependent variable with MTBF and renewal periodicity assigned as the independent variables. A fit of least squares was applied to the resulting model which had a R^2 value of 0.98. Figure 14 illustrates the closeness of the fit.

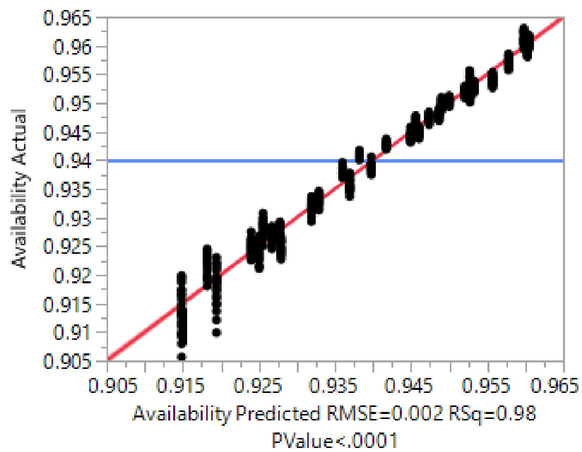


Figure 14. Data Fit Comparing Actual to Predicted Availability

Next, we evaluated the effects that the independent variables had on the dependent variable. The MTBF and renewal periodicity (RenewTime) were evaluated linearly and quadratically, as well as their combined influence. All but the quadratic RenewTime showed significant effects as indicated by their p-values as shown in Figure 15.

Source	LogWorth		PValue	
MTBF	827.193		0.00000	
MTBF*RenewTime	167.070		0.00000	
MTBF*MTBF	95.328		0.00000	
RenewTime	79.507		0.00000	^
RenewTime*RenewTime	1.081		0.08293	

Figure 15. Effects Summary

The effects summary also indicated that MTBF had a greater effect on availability than the RenewTime. A prediction profiler provided an additional visualization of this result as shown in Figure 16. The relative steepness of the curves shows that the changes in MTBF resulted in more drastic change to availability than changes in RenewTime.

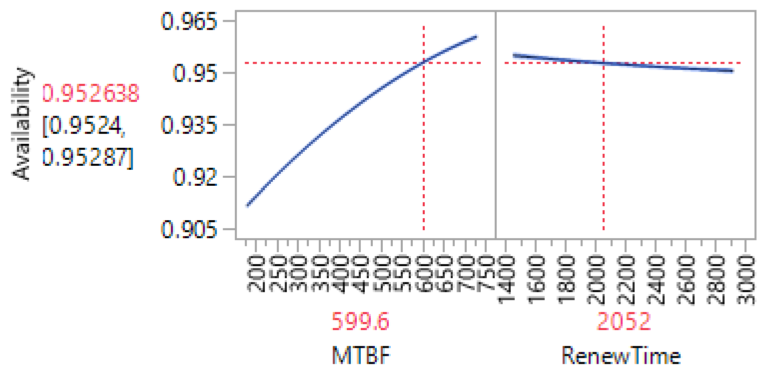


Figure 16. Availability Prediction Profiler for MTBF and RenewTime

One way to make these results actionable was to observe the interactions through contour profilers, as described in (Whitcomb and Beery 2016), which made it possible to adjust the factors and response parameters to desired values. For example, if a specific availability lower limit was required by policy, this tool would make it possible to quickly determine what MTBF would need to be maintained when renewals are happening at a given periodicity. Three contour profile examples are shown in Figure 17 with progressively higher availability limits.

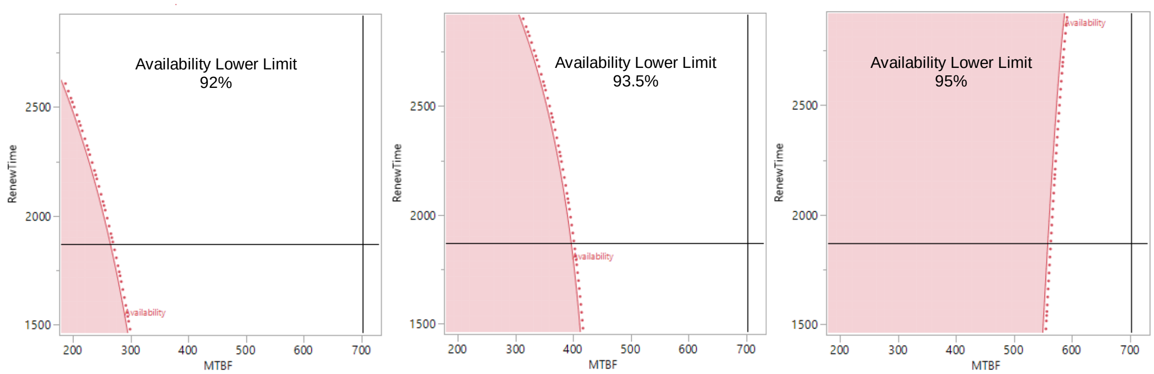


Figure 17. Contour Profiler Showing Requirements to Achieve Three Levels of Availability

The results of this theoretical model exploration show that for the given parameters, the planned davit renewal strategy does not impact the overall availability as much as maintaining a specific level of MTBF. Theoretically, the renewal periodicity could be extended years beyond the current policy without significantly reducing the availability of the davit. However, if the crew, product line, and environmental factors are unable to maintain a minimum level of MTBF, then the availability will slip.

THIS PAGE INTENTIONALLY LEFT BLANK

V. CONCLUSIONS AND RECOMMENDATIONS

Analyzing archived data for the purposes of informing maintenance policies can be an effective tool, but its fidelity is dependent on the quality of the records being kept. This study used system failure reports to determine the influence that planned depot maintenance periodicity has on davit failure rates and operational availability. The results were informative even though they did not present the level of significant relationships expected.

A. CONCLUSIONS

The statistical analysis resulted in a consistent lack of significant influence that independent variables had on the dependent variables. The absence of trends in the davit failure records seem to indicate a random failure rate and no sign of system wear-out over time. This may indicate that the failure rate as it relates to system age should not be a major consideration for the periodicity of planned depot maintenance. Other considerations such as corrosion and an increased rate of organizational maintenance or repairs needed to maintain operations will likely be greater driving factors. However, from a depot maintenance standpoint, there could be room to increase the duration between costly planned depot maintenance without resulting in a higher rate of failures due to a davit's inherent age.

The results of the analyses provided answers to the research questions, even if the outcomes were not as expected. The first question asked how system failure and maintenance data that the Coast Guard currently collects could be used to generate system failure models. A theoretical model was ultimately developed to explore this to some degree, but the crux of this research question is essentially asking how usable the data is that is currently being collected. The Coast Guard cutter discrepancy records contained inconsistent verbiage, missing information, and unclear impact statements which made it difficult to define and categorize the data points. This has great potential to influence the outcome of the analysis if the records are treated differently than they were in this study.

The second research question asked how the frequency of depot-level maintenance can be modified to improve the operational availability of the MEC davits. Initially, the author expected to see some trends that could be applied to a model for experimentation. The statistical analysis however revealed that the davit availability and failure rates did not have a significant dependency on the planned depot maintenance timing. While not the expected result, it is usable in that maintenance planners may have more flexibility in scheduling overhauls and renewals. Other factors aside from system reliability are likely more significant driving factors such as depot maintenance costs, operational schedules, and changes in crew maintenance required to keep the systems operational.

B. RECOMMENDATIONS

The type of analysis presented in this thesis can be used for future maintenance planning once a historic record base is established. However, for the Coast Guard to gain from this methodology, the maintenance policies must continue to enforce discrepancy reporting requirements and improve standardization of the type of information they contain. During the data gathering, it was clear that the recent EAL discrepancy reports were far more thorough and consistent than older FLS CASREPs. This reflected the Coast Guard's efforts over the past years to modernize the reporting systems. The reports effectively serve their purpose of reporting issues, reporting operational status, and requesting logistics aid from the product lines. However, improvements would be needed to effectively be used for maintenance planning via statistical analysis.

The davit system failures and maintenance cannot be analyzed using the same techniques that have been applied to equipment like the diesel engines and generators. If davit operating hours were tracked and logged the way engine hours are, then those techniques could be applied. Without that information however, the methodology used in this report would theoretically be possible given consistent and accurate archived records. Being exterior systems, davit maintenance would expectedly be influenced more by environmental factors than interior engines are, so the operating hours may be less significant than system age.

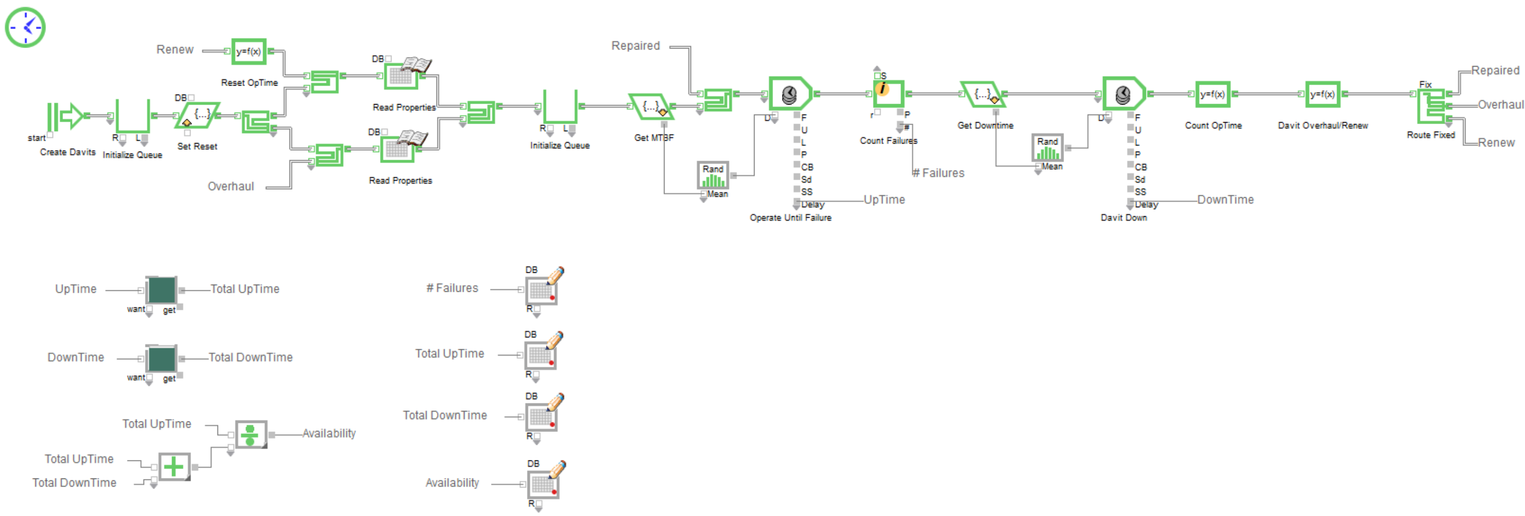
C. FUTURE WORK

It could be beneficial to experiment more with the way assumptions and definitions were applied to the original data to see how that influences the analysis results. For example, what would happen if the discrepancy reports were interpreted differently and therefore classified differently? Would the number and frequency of inoperable davits change? Also, when discrepancy reports lacked enough information to be classified, what would happen if they were treated as inoperable data instead of operable data? These questions could lead to a sensitivity analysis that provides even more insight into the information needed in failure reports.

There is also benefit to further experimentation with the model developed for this study. Chapter IV presented one example of testing the possible effects between maintenance periodicity, MTBF, and availability; however, there are many more "what if" scenarios that can be explored. The model could also be adapted to experiment with failure and maintenance rates on other Coast Guard cutter systems such as fire pumps, buoy handling cranes, and anchor winches.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX. EXTENDSIM MODEL



THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

Blanchard, Benjamin, and Wolter Fabrycky. 2014. *Systems Engineering and Analysis.* 5th ed. London: Pearson Education Limited.

DCMS. n.d. "SFLC Organization." Accessed February 2020. https://www.dcms.uscg.mil/Our-Organization/Assistant-Commandant-for-Engineering-Logistics-CG-4-/Logistic-Centers/Surface-Forces-Logistics-Center/Inside-the-SFLC/.

———. n.d. "SFLC Share Service Divisions." Accessed February 2020. https://www.dcms.uscg.mil/Our-Organization/Assistant-Commandant-for-Engineering-Logistics-CG-4-/Logistic-Centers/Surface-Forces-Logistics-Center/Inside-the-SFLC/SFLC-Shared-Services-Divisions/.

ExtendSim. n.d. "ExtendSim Products." Accessed May 2020. https://extendsim.com/products/line/overview

Holz, Michael. 2019. *Maintenance Analysis: Welin Lambie Boat Davit Model 5.0B System.* Maintenance Analysis Report. Baltimore: SFLC-ESD-SSB-MPS.

INCOSE. 2015. *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities.* 4th ed. Hoboken, NJ: John Wiley & Sons, Inc.

Keane, Daniel. 2019. *Combined WMEC-270 Cutter Engineering Report Response.* Official Memorandum. Norfolk, VA: Surface Forces Logistics Center.

Koski, Heidi L. 2011. "An Analysis of the Coast Guard's Surface Fleet Reliability Program for Medium Endurance Cutters." Master's thesis, University of Maryland. https://drum.lib.umd.edu/handle/1903/11566.

MacCalman, Alex, Paul Beery, and Eugene Paulo. 2016. "A Systems Design Exploration Approach that Illuminates Tradespaces Using Statistical Experimental Designs." *Systems Engineering* 19, no. 5 (September): 409–421. https://doi.org/10.1002/sys.21352.

Marino, Lucas C. 2018. "Level of Repair Analysis for the Enhancement of Maintenance Resources in Vessel Life Cycle Sustainment." D.Eng praxis, George Washington University. ProQuest (10785844).

Meeker, William, and Luis Escobar. 1998. *Statistical Methods for Reliability Data.* New York: John Wiley & Sons, Inc.

Mikedis, Louis. 2015. "Specification for Welin Lambie Dual Point Davit Model TW PIV 5.0B Support." Baltimore: Surface Forces Logistics Center.

Milkie, C. N., and Dr. A. N. Perakis. 2004. “Diesel Engine Overhauls in the U. S. Coast Guard.” *Naval Engineers Journal* (Spring): 31–41.

Montgomery, Douglas C, and George C Runger. 2014. *Applied Statistics and Probability for Engineers.* 6th ed. Hoboken, NJ: John Wiley and Sons, Inc.

MTL Instruments. 2010. “Availability, Reliability, SIL: What’s the Difference?” *AN9030 Rev3 270510.* MTL Instruments.

Pritchett, Andrew. 2018. “A Systematic Approach to Reliability-Centered Maintenance.” Master’s thesis, Naval Postgraduate School. http://hdl.handle.net/10945/59568.

Sanchez, Susan M. 2011. “NOLHdesigns Spreadsheet.” Accessed 21 April 2020. http://harvest.nps.edu.

SFLC. 2019. “SFLC Electronic Asset Logbook Business Rules Process Guide.” *CGTO PG-85-00-1290-S.* Baltimore: SFLC Business Operations Division.

U.S. Coast Guard. n.d. “Atlantic Area Cutters.” Accessed January 2020. https://www.atlanticarea.uscg.mil/AtlanticAreaCutters/.

Welin Lambie. n.d. “Dual Point Pivot Davits.” Accessed September 8, 2019. http://www.welinlambie.com/military/dualpoint.asp.

———. 2016. “During 2015 Welin Lambie Experienced an Increase in Spares and Support Activities Continuing Into 2016.” March 1, 2016. http://welin.mymediaroom.com/pressreleases/viewrelease.aspx?id=4184.

Whitcomb, Clifford, and Paul Beery. 2016. “Exploring the Design Space.” In *Trade Off Analytics: Creating and Exploring the System Tradespace*, edited by Gregory S. Parnell, 405–436. Hoboken, NJ: John Wiley & Sons.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California