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ANALYSIS OF THE INCREASING TREND IN EXPENDED MAN-DAYS FOR SELECTED 688-CLASS SUBMARINE DSRAS AT PEARL HARBOR NAVAL SHIPYARD

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THESIS

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by

Mark Lindle and Ryan Wisz

December 2019

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The purpose of this research is to establish and analyze trends for direct labor man-days charged to selected 688-class submarines at Pearl Harbor Naval Shipyard (PHNSY). Based on recommendations from previous studies, this research is focused on analyzing the 100 Series of maintenance for nine selected submarines undergoing Docking Selected Restricted Availabilities (DSRAs) between 2010 and 2015. The 100 Series includes the hull and tanks, which frequently experience work growth over the availability. Additionally, further analysis was conducted on a possible hull-age correction factor used to explain increased labor trends, and a simple Monte Carlo simulation was used in an attempt to estimate final labor cost of the DSRAs. Our research is aimed at identifying existing trends and attempting to explain why those trends may exist.

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The purpose of this research is to establish and analyze trends for direct labor man-days charged to selected 688-class submarines at Pearl Harbor Naval Shipyard (PHNSY). Based on recommendations from previous studies, this research is focused on analyzing the 100 Series of maintenance for nine selected submarines undergoing Docking Selected Restricted Availabilities (DSRAs) between 2010 and 2015. The 100 Series includes the hull and tanks, which frequently experience work growth over the availability. Additionally, further analysis was conducted on a possible hull-age correction factor used to explain increased labor trends, and a simple Monte Carlo simulation was used in an attempt to estimate final labor cost of the DSRAs. Our research is aimed at identifying existing trends and attempting to explain why those trends may exist.

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LIST OF ACRONYMS AND ABBREVIATIONS

688-class	Los Angeles Class
AWP	Availability Work Package
BQWP	Budgeted Quantity of Work Performed
BQWS	Budgeted Quantity of Work Scheduled
CA	Corporate Cost Assessment
CNO	Chief of Naval Operations
COMSUBPAC	Commander, Submarine Force, U.S. Pacific Fleet
D-level	Depot Level
DoD	Department of Defense
DSRA	Docking Selected Restricted Availability
EOC	Engineer Operating Cycle
FRE	Final Review Estimate
GAO	Government Accountability Office
I-level	Intermediate Level
IMA	Intermediate Maintenance Activities
IMF	Intermediate Maintenance Facility
ISIC	Immediate Superior in Command
JO	Job Order
KO	Key Op
MD	Man-Days
MRC	Maintenance Record Card
NAVSEA	Naval Sea Systems Command
NNPI	Naval Nuclear Propulsion Information
NPS	Naval Postgraduate School
NWCF	Navy Working Capital Fund
OFRP	Optimized Fleet Response Plan
O-level	Operational Level
OPCYCLE	Operational Cycle
OPINTERVAL	Operational Interval

PACFLT	Pacific Fleet
PHNSY	Pearl Harbor Naval Shipyard
QAC	Quantity at Completion
SSN	Submarine Nuclear (Attack)
SRA	Selected Restricted Availability
SUBFOR	Commander, Submarine Forces
SUBMEPP	Submarine Maintenance Engineering, Planning and Procurement
SWAB	Ship Work Authorization Boundary
SWLIN	Ship Work List Item Number
TFP	Technical Foundation Paper
U-NNPI	Unclassified-Naval Nuclear Propulsion Information
URO	Unrestricted Operation
VLS	Vertical Launch System

EXECUTIVE SUMMARY

The purpose of this thesis is to provide information, analysis, and direction for the Commander, Submarine Force, U.S. Pacific Fleet (COMSUBPAC) with respect to the increasing costs and duration of submarine maintenance availabilities. More specifically, this thesis identifies and explores trends between labor man-days charged for the 100 Series of maintenance and duration of availability. Additionally, a model was developed in an attempt to better describe Corporate Cost Assessment (CA) variability.

Progressive increases in cost and duration in submarine maintenance at Pearl Harbor Naval Shipyard is affecting the submarine force's ability to plan and execute the Navy's missions. With recent DON budget trends remaining relatively flat when adjusted for inflation and as a percentage of GDP, reducing inefficiency is key to restoring the submarine force readiness. From our data, between FY2010 to FY2016 only 38 percent of DSRAs completed at PHNSY were completed on time. These delays result in lost operational time, lack of assets available to Geographical Combatant Commanders for operations, and increasing cost for submarine repairs and upgrades.

The relevant research previously completed with respect to submarine maintenance at PHNSY show how the understanding of the issues has evolved and what questions have been answered. In general, the research has gone from a top-level review to a more specific view at the SWLIN level.

The research already completed has provided the following results in reference to the anecdotal claims for the relevant submarines:

- OPINTERVALs have not actually exceeded 48 months (Whitney, 2018).
- Hull age is not correlated with DSRA duration (Whitney, 2018).
- The 500 SWLIN Series and the 100 SWLIN Series are the largest increases in man-days for selected availabilities (Isley, Seagrave, & Shiver, 2018).

- Cost Variance and BQWS do not trend as expected for the selected availabilities analyzed (Wheeler, 2019).

In order to conduct further analysis on the 100 SWLIN Series, we used data provided by SUBPAC, SUBMEPP, and PHNSY on nine specific 688-class submarine DSRA availabilities conducted at PHNSY from 2010 to 2016. The 100 SWLIN series of work focuses on the submarine hull and internal tanks. The data used comes from autopsy reports, key events data, PMC data, and other schedule data. This data was used to determine the specific work within the 100 Series that by percentage was causing the largest increase in man-days expended. This will help SUBPAC and PHNSY conduct further investigation into this problem area to develop a comprehensive solution.

After analysis of the data we made the following conclusions:

- Applying a hull-age correction factor to the DSRA availabilities and within the 100 Series reduces the magnitude of the growth increase, but does not remove the trend. Hull age does not drive the expended labor increase.
- SWABs 131, 132 show significant, consistent growth.
- SWAB 131, group 27, 44, 82 contribute the majority of growth within the SWAB.
- SWAB 132, group 27, 74, 82 contribute the majority of growth within the SWAB.
- SWAB 131, group 27, component 0165 demonstrated consistent growth.
- SWAB 132, group 27, component 0200 demonstrated consistent growth.
- New Work does not account for a significant increase in expended man-days.
- Cost Variance in the 100 Series trends negative which is unexpected for a learning organization that incorporates historical work into future availabilities.

- CA2 to CA3 and FRE to Actual man-days expended models produced estimates to better inform planners of expected maximum CA3 man-days and Actual man-days expended.

In response to these conclusions, we recommend the following topics for future studies:

- Compare and analyze the trends in the 500 and 100 Series at other shipyards during a similar period of time.

- Identify and analyze maintenance items experiencing highest increases in 500 and 100 Series to ship schedules and determine if they became, or were, critical path items.

In addition, we recommend the following actions be taken by relevant responsible organizations:

- Evaluate planning and labor estimation processes at PHNSY

- Utilize probabilistic modeling for cost estimation and schedule risk

- Report on the continuous Availability Work Package (AWP) feedback loop

References

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I. INTRODUCTION

A. PURPOSE

This thesis continues the research in an ongoing study to help determine the cause of increasing costs and duration of submarine maintenance availabilities at Pearl Harbor Naval Shipyard (PHNSY). With the direction and assistance of Commander, Submarine Force, U.S. Pacific Fleet (COMSUBPAC) and by Submarine Maintenance Engineering, Planning and Procurement (SUBMEPP), we obtained a wide range of data for selected 688-class submarine availabilities at PHNSY. Prior theses indicated the 500 Series SLWINs, which included auxiliary systems, were a primary contributor to the increase in duration and final cost for the selected availabilities. Whitney in 2018 recommended that the 100 Series SWLINs required additional research to determine its impact on schedule and cost (Whitney, 2018). Analysis conducted in this thesis provides an indication that submarine overall processes improvements and data collection improvements are necessary to reduce overall cost and increase submarine availability.

1. Problem Statement

The cost and duration of U.S. Navy 688-class submarine DSRAs at PHNSY are increasing (Whitney, 2018). This increase in duration and cost results in lost operational availability and reduces the total number of ships available to execute critical missions and meet force requirements. In December 2016, the U.S. Navy announced it required 66 attack submarines in order to meet its regional obligations throughout the geographic Combatant Commands (COCOMs) (O'Rourke, 2019). According to O'Rourke, as of early 2019, the fleet consisted of only 51 attack submarines and is to continue declining until FY2028. Due to the inactivation rate of the 688-class and the construction rate of new Virginia-class attack submarines, by FY2028 it is expected that there will only be 42 attack submarines available (O'Rourke, 2019). O'Rourke goes on to say that there has been discussion regarding a few options to boost the minimum number of attack submarines in FY2028, to include nuclear refueling of certain 688s, this is not certain or guaranteed. In order to maintain maximum readiness and operational availability, reducing the duration of shipyard availabilities for the shrinking force is critical.

As the United States Department of Defense (DoD) continues to operate in a resource constrained environment, being good stewards of taxpayer dollars is critical. Defense discretionary spending has been and will likely always be constrained by increases in mandatory entitlements such as health care, social security, and debt servicing, to name a few (Candreva, 2017). Therefore, efficient resource allocation is important. Cost of submarine maintenance availabilities has increased over time as a result of increased man-days spent repairing the submarine. Over-budget projects continue to burden the Navy and result in lost operational time for some units, and leave less funding available for other units desperately in need of repair. Within the House DoD Appropriations Act for FY2020, three submarines, USS *Boise*, USS *Hartford* and USS *Columbus* appeared on the unfunded priorities list due to shortages in funding and shipyard capacity (Department of Defense Appropriations Act, 2019). With fewer submarines available and with a constrained budget, maximizing efficiency is key for the DoD and the Department of the Navy (DON). Submarine maintenance may be one area where costs can be reduced, and efficiency increased, to improve submarine readiness.

2. Research Questions

1. Does controlling for hull age help explain the identified increase in expended man-days over the studied DSRAs?

2. Within the identified increase of expended man-days across the DSRAs, what is the contribution of the maintenance included in the 100 Series?

3. Which Ship Work Authorization Boundary's (SWABs) within the 100 Series show the largest growth over time?

4. Within the growing SWABs, which Ship Work List Item Numbers (SWLINs) and subset maintenance groups and components are contributing most to the growth of the 100 Series?

5. Does categorized “New Work” demonstrate a relationship with DSRA duration and is it significant to expended labor?

6. Can a model be developed to better estimate the maximum expended man-days for CA3, and a completed DSRA?

B. SCOPE OF THESIS

In order to draw comparisons between availabilities, research was limited to the following:

- Docking Selected Restricted Availability (DSRA): Though no single DSRA is the same as another, for this comparison to help control for time spent at sea, hull age, and general work performed DSRAs at PHNSY were selected. If the analysis included all submarine work conducted at PHNSY, it would increase variability as a result of shorter and longer duration availabilities with different repair goals and at different hull age.

- Los Angeles Class (688-class) Submarines: The configuration of different class submarines currently serving in the Navy’s submarine fleet varies greatly. By controlling for class of ship going through DSRA we remove variability of individual maintenance items skewing the data and affecting the conclusion of the thesis. Although maintenance across all hulls in the DSRA are not the same, trends can still be identified.

- Pearl Harbor Naval Shipyard (PHNSY): For this thesis, work performed at only the PHNSY will be considered. This limited the variation between shipyards and how maintenance is conducted. Including other shipyards DSRA work may skew data and hide problems or trends that may be beneficial to the results of the analysis. A thesis that can obtain DSRA data from all public shipyards may be able to draw different conclusion in the comparison of the performance of different shipyards for the same work.

- 100 Series (Hull Structure and Appurtenances) SWLINs: The focus of this thesis will be on the SWLINs included in the 100 Series of work that is focused on the various hulls and tanks of the submarine. This limitation in scope allows this thesis to identify trends within the 100 Series and provide that feedback to availability planners at PHNSY and COMSUBPAC. This focus is based on the recommendation of Whitney’s previous research (2018).

II. BACKGROUND

A. LOS ANGELES–CLASS (688-CLASS) SUBMARINES

The writers of this thesis are qualified U.S. Submariners with a significant amount of time spent in Pearl Harbor. Both writers spent time on Los Angeles Class Submarines and spent time in maintenance overhauls at PHNSY.

1. 688 Class Overview

Submarines in the 688 class are fast-attack, nuclear-powered, submersible ships. They are owned and operated by the U.S. Navy and employed on Anti-Surface Warfare, Anti-Submarine Warfare, Anti-Mine Warfare, and Strike missions. O'Rourke documented that succeeding the Sturgeon Class and preceding the Seawolf class, 62 Los Angeles class were produced between 1972 and 1996 (O'Rourke, 2019). They have a nominal service life of 30 years which is limited by their nuclear reactor refueling requirements as well as hull life. There are some 688-class submarines that are being extended past 30 years based on remaining nuclear fuel life and good hull performance over time. There are different configurations and upgrades that were conducted over the life of the ship class that will be discussed below.

2. Differences within the 688 Class

There are three main versions of the 688-class submarine, the 688 (better known as "first flight"), the VLS flight, and the 688I (or "second flight"). The main differences are that first flight 688s have no Vertical Launch System (VLS) and have fairwater planes on the sail. The VLS flight has fairwater planes and four VLS tubes for launching Tomahawk missiles. 688I, or second flight 688s, have 12 VLS tubes and bow planes instead of fairwater planes.

Through the years numerous modifications were made to the 688-class submarine including changes to Forward Compartment Upper Level layout with significant changes to the radio room, engine room changes including changes to the main engines, and changes to the SONAR and Fire Control systems. Though there have been improvements and modifications over the construction time frame, major system components such as Ship's Service Hydraulics, Steering and Diving Hydraulics, and major cooling systems remained mostly similar. Modifications to these systems are generally minor, including changing to piping layout, pump sizes, loads off systems. Based on this it is assumed that the modifications made to major hydraulic, electrical, and cooling systems would not greatly affect the cost of the maintenance over time.

3. General Layout

Los Angeles–class submarines are divided into two watertight compartments. The forward compartment which houses berthing, galley, the crews mess, the officers wardroom, weapons systems, control, and required control systems. The aft watertight compartment is the Engine Room which contains the nuclear reactor and associated machinery to assist in propulsion of the ship and well as the electrical generation equipment required for the ship.

B. DOCKING SELECTED RESTRICTED AVAILABILITIES (DSRA)

According to the 2019 issue of the OPNAVNOTE 4700.7, the definition of an "availability" is the temporary period of time during a submarine's Operational Interval (OPINTERVAL) when it is removed from the operational status and designated to be available for maintenance and alterations (Chief of Naval Operations, 2019). Docking Selected Restricted Availabilities are an availability that requires the ship to enter a dry dock to complete certain repairs or complete required inspections. Typically, DRSA's include more intrusive and complex repairs since some or all of the availability is completed in a dry dock.

C. LEVELS OF MAINTENANCE

Submarine maintenance is conducted at three separate levels based on resources required and complexity required to complete the repair. The three levels are Organizational, Intermediate, and Depot Level.

1. Organizational-Level Maintenance

This is the lowest level of maintenance and is generally within the capability of ships force. This maintenance is completed during in-port periods or while out to sea and does not impede mission tasking.

2. Intermediate-Level Maintenance

Intermediate Level (I-Level) maintenance exceeds the resources or capability of ships force but does not requires Depot Level resources. The Fleet Maintenance Activity (FMA) is responsible for providing the required resources and expertise to complete this maintenance. At Pearl Harbor, I-Level maintenance is completed by the Intermediate Maintenance Facility (IMF).

3. Depot-Level Maintenance

Depot Level (D-Level) maintenance consists of major repair, fabrication, modification, refurbishment or upgrading that requires the resources and capabilities that exceed the I-Level maintenance. This work is generally conducted by a shipyard. In Pearl Harbor, this work is conducted by the PHNSY. D-Level maintenance will often require the ship to be placed in a dry dock for an extended period of time.

D. SCHEDULING AND MAINTENANCE STRATEGY

The 688-class submarine uses an Engineered Operating Cycle (EOC) to plan and conduct maintenance availabilities to ensure the submarine maximizes its operational life of 30+ years. The EOC is a maintenance strategy that keeps ships in acceptable material condition while sustaining maximum operational availability. To accomplish this period inspections of selected systems are inspected and documented for material condition trends. Periodic maintenance tasks are accomplished at specific time intervals, and the ships life cycle contains a combination of minor and major availabilities scheduled to conduct maintenance and modernization (Chief of Naval Operations, 2013).

This schedule is based on the approved OPINTERVAL. The OPINTERVAL is the max duration that a submarine may operate between accomplishing specific D-Level maintenance. This maintenance can be conducted in either a major or a minor Chief of Naval Operations availability (CNO availability). An operational cycle (OPCYCLE) is a specific operating period whose duration is defined by the requirement to accomplish D-Level maintenance that can only be accomplished during major CNO availabilities. Major CNO availability's OPCYCLE are every 10 years or 120 months, and the OPINTERVAL for 688-class submarines is 72 months (Chief of Naval Operations, 2013).

Typically, a submarine will have three I-Level availabilities between deployments, Continuing Maintenance Availability (CMAV), Pre-Overseas Movement 1 (POM1), and Pre-Overseas Movement 2 (POM2). This structure allows flexibility and continued training for the ship while preparing the ship for another deployment and additional time at sea for training and preparation. Some ships may require additional maintenance due to urgent repairs realized during training and may require a POM3 prior to deployment.

The most recent change to OPINTERVAL and OPCYCLE increased the amount of time between D-Level maintenance from 48 months to 72 months and as a result increased the amount of maintenance that much be conducted at the DSRAs and other availabilities (Chief of Naval Operations, 2013).

E. SUBMARINE INVENTORY

In December 2016, a change in the Navy force level goal required there to be 66 attack submarines included in the total force level goal of 355 ships (O'Rourke, 2019). This change was to counter the current threats faced by China, Russia, Iran, and North Korea. However, as a result of low production levels through the mid-1990s into the mid-2000s, force levels are set to decrease from their current level of 51 ships in FY2018 to a minimum of 42 ships in FY2027 with the final level of 66 ships not reached until FY2048 (O'Rourke, 2019).

In the early 1990s, the end of the Cold War brought a dramatic reduction in defense expenditures (O'Rourke, 2019). The reduction in defense spending directly influenced the shipbuilding plan, and the completion of the Seawolf submarine program. The Seawolf submarine was designed to directly combat the most advanced new Russian submarine threats and included new firepower, advanced quieting techniques, new SONAR systems, and advanced propulsion techniques (O'Rourke, 2019). However, the cost of the Seawolf and the end of the Cold War would quickly signal the end for the Seawolf program after only three ships being built. Though the last Seawolf submarine became operational in 2005, and the commissioning of the USS Virginia occurred in 2004, from 1997 until 2004 only four submarines were built (O'Rourke, 2019). From FY2005 to FY2010 only one VA Class submarine was acquired per year. From FY2011 until FY2019 two Virginia Class submarines have been procured per year (O'Rourke, 2019). As a result of this large reduction in ship building between 1997 and 2005, and the continued high rate of decommissioning of 688-class submarines, force levels continue to decrease.

The Reagan administration shipbuilding plan called for a 600 ship Navy including maintaining 100 SSNs (O'Rourke, 2019). O'Rourke goes on to describe the history of the SSN requirement. In the George H.W. Bush administration, a proposed force level goal in 1991 of 400 ships included 80 SSNs. However, due to the end of the Cold War and no foreseeable great power to go against, this number was later reduced to 51–67 SSNs including 10–12 Seawolf Class Submarines (O'Rourke, 2019). In 1993, the Clinton Administration furthered lowered that number establishing a plan of 45 to 55 SSNs. In 1997, the Clinton administration's Quadrennial Defense Review (QDR) established a goal of 55 SSNs based on the reduced global tensions and the needs of a peacetime navy. The SSN force level remained fairly constant from the 1997 QDR through George W. Bush's administration, being adjusted down to requiring 48 ships in 2006 (O'Rourke, 2019). This figure remained unchanged until 2016 when it was updated to 66 submarines as part of a 355 ship force Navy (O'Rourke, 2019).

The cause of the severe shortage in SSNs dates back to the financial decisions of the U.S. Congress and the DoD between FY1997 and FY2013 (O'Rourke, 2019). When the Virginia Class Submarine procurement began in the 1990s, the DoD projected the procurement would increase to two ships per year in FY2002. However, in subsequent budgets, the date for initiating two per-year procurements was gradually pushed back until FY2010 (O'Rourke, 2019). This resulted in only four submarines being acquired from FY1997 to FY2013, greatly affecting the current force levels. With VA-Class production limited to two submarines per-year with no increase in sight, force levels will continue to decrease until FY2028 (O'Rourke, 2019).

F. PLANNING FALLACY AND PARKINSON'S LAW

Planning Fallacy is the behavior associated with underestimation of time necessary to complete a task, and regardless of the time given to complete the project people struggle to meet the deadlines. This is an elemental human tendency. Described as a form of procrastination, a overly-optimistic individual will overestimate their ability and performance and underestimate the time required to complete the task (Buehler, Griffin, & Ross, 1994). As a result, according to Buehler et al. (1994), when faced with few or no intermediate timelines that are enforced, individuals or teams will typically increase work output towards the end of the project rather than expend a consistent output to reach the desired end state. Experts are often used to provide their best assessment when estimating or predicting something that contains uncertainty (Buehler et al., 1994) . People often rely on singular information or information that consists of evidence about the particular decision, but rarely include distributional information. Buehler et al., describe Kahneman and Tversky's distributional information, base-rate data, or consisting of information about the distribution of outcomes that are possible. This states that duration estimates (estimates for the time required to complete a single job, or to complete an entire task) should be based on a probabilistic model. This helps account for randomness of schedule (Buehler et al., 1994).

Parkinson's Law, on the other hand, indicates that without sufficient or adequate incentives, and proper management, projects that are given longer to complete will always grow to fill the allotted time (Gutierrez & Kouvelis, 1991). Take for example a maintenance worker, he or she is given a task that is expected to take eight hours, if they finish the task early they can expect to be assigned more work without further reward. It is less stressful for the individual to work on the same job for eight hours versus finishing it in five and changing jobs. Though the job has the potential to be completed early and properly, allowing more to be completed on the aggregate, the worker has no incentive to do that (Gutierrez & Kouvelis, 1991). According to Gutierrez & Kouvelis, under

Parkinson's Law, additional worker time available may signal less workers are needed. In order to reduce tasking, workers aim to hit or exceed allotted time for a job in order to signal to managers more personnel are needed on these jobs. This reduces the work load for the individual, but increases overall time spent on a job needlessly (Gutierrez & Kouvelis, 1991).

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III. PLANNING

Jobs are initially scheduled to be completed within a DSRA are considered notional. These notional jobs are determined by SUBMEPP and Naval Sea Systems Command (NAVSEA). Based on historical data, jobs are determined to have an estimated time to completion. This estimate is used to determine notional man-days for a generic DSRA. The Technical Foundation Paper (TFP) is a primary maintenance strategy document produced by SUBMEPP for a class of ship with expected maintenance durations and number of man-days expected to complete availabilities (SUBMEPP, 2018). SUBMEPP periodically reviews the TFP and updates expected number of man-days to complete a series of work and the overall project. These changes are driven by historical averages as well as periodic requirement changes.

Additional maintenance is scheduled as a result of the ship's needs. Maintenance items are added prior to the start of the availability through analysis of ship systems during tours, inspections and review of ship generated issues or outstanding maintenance issues from previous availabilities. These ship specific maintenance items are added to the standard list of repairs and inspections to generate the Corporate Cost Assessments (CA1, CA2, CA3). As the ship gets closer to the start of the availability, the accuracy of what must be completed increases. Thus, CA3 is a better representation of what will be completed during the availability compared to CA1. The final planning meeting (FPM) occurs approximately four months from the start of the availability in which the baseline work is set. The work established at the FPM goes into CA3 and should be representative of maintenance performed during the DSRA. The Navy sends its CA3 to the performing shipyard (PHNSY), after which they review the estimate and send back their estimate of number of man-days to complete the maintenance.

Once the ship arrives in the shipyard, a more thorough investigation is completed of ship systems and additional work is often identified. In many cases, some spaces can only be inspected once the ship is in Dry Dock such as the floodable spaces in the ballast tanks. The TFP maintains a percentage of new work for the availability as part of the overall man-days for the availability. Rev B of the TFP maintained approximately 16% new work for the 100–700 series. Rev C increased new work to approximately 21% of total man-days expended for the 100–700 series (baseline, non-nuclear ship alts, unique work, new work included in total) (SUBMEPP, 2018).

IV. DETERMINATION OF THE MAN-DAY ESTIMATE

A. NOTIONAL MAN-DAYS

For the initial planning of the DSRA, the availability planners use the TFP to determine the notional man-days and thus cost to repair the submarine. Notional man-days estimated by the TFP are based on the Ship Availability and Planning Engineering Center (SHAPEC) Job Summary 3. The SHAPEC estimates are maintained current with NAVSEA and naval shipyard corporate production standards and practices. The estimates are validated through trend analysis for necessary component repairs, estimate feedback reviews, and by incorporating improvements through a lessons learned program. Sources of improvements include Deficiency Logs (DL), process review comments for naval shipyards who use the estimates, Critique and Trouble Reports, and reviews of new technical requirements and reductions in work scope.

B. CA1, CA2, CA3 ESTIMATES

Beginning with the notional man-day estimates in the TFP, these values will be refined for each unique DSRA at Corporate Cost Assessment (CA) events and reported in documents referred to as CA1, CA2 and CA3. Based on conditions-based maintenance and corrective action-based estimates conducted through investigations and reports during previous availabilities and inspection, additional work is added to the baseline man-day estimate. CA1 to CA2 to CA3 does not always result in additional man-days added to the estimate. Ship repairs may occur prior to the DSRA which may affect scope of work or the need to complete specific work, which may result in a reduction of man-days required.

C. FINAL REVIEW ESTIMATE

One month prior to the ship entering the shipyard to commence the DSRA, the shipyard commander sends a certified estimate for the completion of the DSRA to COMSUBPAC outlining the expected duration of the availability, number of man-days to complete the work, and an explanation of large difference in man-days between CA3 and the FRE. This difference is often based on labor required to complete specified jobs or additional labor required to support completion of the availability.

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V. LITERATURE REVIEW

A. CURRENT ISSUES AND RELATED STUDIES

With many ship projects across the DON frequently late and over budget, attempting to understand the cause and methods to reduce these issues have been studied. We first describe Baumgartner due to her significance to our thesis. In her 2018 work, "Analysis of Capacity and Schedule Risk in SSN-688 Class Submarine Dry-Dock Maintenance Operations," Baumgartner compares data from 688 DSRAs conducted before and after implementation of the 72-month Optimized Fleet Readiness Plan (OFRP) maintenance cycle and searched for maintenance which led to schedule delays and increased schedule risk. Her results showed that 688-class DSRAs have taken longer to complete since the OFRP shift and that there is a significant correlation between the DSRA duration and the amount of new work added to that DSRA, specifically within the 500 Series SWLINs. She shows that while overall work performed in the 500 Series is increasing over time from DSRA to DSRA, the Series also shows greater variability across those DSRA datasets, which indicated that the work scheduled and completed was inconsistent. This likely causes inherent difficulties in the planning process.

The next investigation into submarine maintenance at PHNSY was by Whitney in 2018. In his work, "The Impact of Direct Man-Days Executed on Submarine Maintenance Availability Delays," Whitney analyzed direct man-days charged to 688-class DSRAs at PHNSY across direct labor SWLINs to identify statistical relationships between direct labor costs and DSRA start date, hull age, duration, and OPINTERVAL. There are two results from his work which are relevant to our thesis. First, shifting from a 48-month to 72-month OPINTERVAL is not the cause of maintenance delays. This is important for our thesis since our data spans the change between the 48-month OPINTERVAL and the 72-month OPINTERVAL. Second, when the duration of the DSRA increases, the amount of man-days charged per day and the amount of jobs completed per day decreases. Thus, he concluded that longer availabilities complete less work per day. Whitney suggests this could stem from the second and third order effects of delaying work jobs that lie on the critical path.

A study conducted by Isely, Seagrave and Shiver in 2018 titled, “Analysis of Trends in Expended Man-Days for Selected SSN-688 Class Submarine Docking Selected Restricted Availabilities at Pearl Harbor Naval Shipyard,” focused on the relationship between hull age and duration of the DSRA. The group confirmed, from previous studies, that neither age nor OPINTERVAL equated to longer availabilities. Important for our thesis was the identification of the 500 Series and 100 Series SWLINs which accounted for significant growth in the overall man-days, and thus cost. This thesis provided the recommendation to analyze the 100 Series SWABs to attempt to identify trends or relationships within the increasing expended labor of the 100 Series (Isley et al., 2018).

The last study conducted on DSRAs at PHNSY was by Wheeler in 2019. In his thesis titled, “An Analysis of The Increase in Duration and Cost for Selected Ship Work Line Item Numbers (SWLINs) at Pearl Harbor Naval Shipyard,” Wheeler focused on selected SWLINs within the 500 Series that directly contributed to the increase in man-days during the selected DSRAs. These SWLINS contined work that was common across DSRAs. This finding indicated that cost variance (CV) is not trending as expected. The relationship between BQWS and CV is inversely related and opposite of expected. This indicated that inefficiency during planning and execution of the availability is contributing to schedule and cost issues. Additionally, Wheeler indicated a potential weakness in the feedback loop from one project to next. Evidence of human inefficiency related to Learning Curve Theory was noted during his thesis due to this unexpected BQWS and CV relationship (Wheeler, 2019).

B. SUMMARY

In the background, we provided the reader with sufficient information of the 688-class submarine to understand the basic layout and class history that we deemed necessary to understand the scope of this thesis. Additionally, we discussed the historical decisions that have resulted in the submarine ships levels declining in a period of time when more are needed not fewer. The dramatic post war reduction in spending and acquisition of submarines has led the United States to its current situation it finds itself, a submarine inventory shortage. This shortage has already been felt by geographical leaders specifically in the Pacific against a rising China and resurgent Russia and in the Atlantic with the increased tensions in the Middle East and increasing Russian influence.

The maintenance and repair delays and cost overruns exacerbate the shortages of hulls by more submarines sitting idle waiting for repairs, or the repairs keeping them in the shipyard longer than expected. Though recent increases in funding for the Department of the Navy has been a significant help, more needs to be done to ensure maximum readiness.

Next we introduced the main concepts and issues being discussed in the research below and provided some important details to understand the uniqueness and complexity of the maintenance being done on 688-class submarines in DSRAs at PHNSY. We defined key terms that will be discussed during this thesis which ensures concepts are not misunderstood.

Finally, we covered the relevant research previously completed on this topic and discussed key findings that help explain our thesis basis and methodology. In general, reports from major government agencies (CBO and GAO) provide top-level analysis indicating there is a problem. Past research from students at NPS attempt to narrow the focus for shipyard leaders by analyzing data from past projects at PHNSY and finding SWLINs and SWABs that greatly increase the duration of the availability. Additionally, this research indicates that hull age at time of availability is not significant to the duration of the availability and that the 500 and 100 Series most significantly affect the duration of the DSRA.

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VI. DATA AND ASSUMPTIONS

This chapter discusses where the data used in this thesis came from, what it does and does not include, the details focused on within the larger data set, and the significance of its security classification. Furthermore, this section discusses the assumptions made about this data in order to organize, analyze, and draw conclusions from it.

A. DATA SOURCES USED

To obtain the data used for this research, SUBMEPP, SUBPAC, and PHNSY provided autopsy reports from the nine DSRAs, Performance Metric Cost (PMC) spreadsheet developed from the nine DSRAs, associated training documents used by PHNSY and SUBMEPP, FRE and CA3 documents to track estimates of man-days in the planning stages, and the TFP rev B and C. We chose to use both the autopsy reports and PMS data to validate both sources and provide the most accurate information. The PMC data is more detailed as compared to the autopsy reports. The PMC data further reduces SWABs into their Job Order (JO) and Key Op (KO) codes. This distinction allowed us to provide additional information and specificity.

These reports were generated after the completion of nine DSRAs competed at PHNSY from 2010 to 2015. Both the autopsy and the PMC data provide the user with information of planned work in man-days, actual work completed in man-days, new work, and total number of man-days for series of work. The work is broken down into series as shown in Table 1.

Table 1. Maintenance Series Breakdown

SWLIN Series	**Series Major Ship System**
000	Support Services
100	Hull Structure and Appurtenances
200	Propulsion

SWLIN Series	Series Major Ship System
300	Electric Plant
400	Communication and Control
500	Auxiliary Systems
600	Outfitting and Furnishings
700	Armament
800	Nuclear
900	Project Management/Admin

Within the 100 Series, the majority of baseline work in this series is associated with inspection, repairs, and preservation of built-in tanks, sail, hull welds, pressure and non-pressure hull inspections and repairs, restoration of cathode protection anodes, corrosion associated with dampening and acoustic tiles, and restoration of the watertight access hatches, and escape trunks.

B. ASSUMPTIONS

a. All DSRAs Analyzed Have Similar Scope of Work

This thesis assumes that work completed across all DSRAs in the data provided are similar enough to compare. Based on DSRAs being classified a minor CNO Availability, there is a notional amount of work that is consistently conducted from one ship to next. For the 100 Series, while notional work remains about the same (as prescribed by the TFP Rev. B), ship specific work accounts for an average 16% difference between the notional and CA3 man-day estimates with a standard deviation of 8%.

b. Man-Day Increase May Not Result in Delay of Availability

As a result of data limitations, this thesis assumes that an expended man-day could result in a risk to schedule. This is because, without a full understanding of critical path items for each availability, an increase in man-days expended for any job not on the critical path does not necessarily result in an increase in overall availability duration..

c. Component Maintenance Remains Relatively Constant

As a result of changing requirements by NAVSEA and other organizations, the length of time and amount of work required to complete maintenance may change over time. To investigate and track requirement changes to maintenance items would require significant additional resources which would not contribute substantionally towards the research questions posed by this thesis. Thus, all work requirements as dictated by NAVSEA are assumed to be similar, or produce limited effects on total man-days expended.

C. SUMMARY

This section discussed the nature of the information found in the reports provided by SUBMEPP, COMSUBPAC and PHNSY, how that information is organized for analysis, and the significance of its NNPI classification. In addition, in order to organize, analyze, and make conclusions from this data, several assumptions are made.

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VII. METHOD AND ANALYSIS

Our analysis of the 100 Series SWLINs focused on breakout trends between SWABs, maintenance groups, and their underlying components. We analyzed these trends to determine which maintenance was likely substantively affecting DSRA availabilities at PHNSY.

The 100 Series of maintenance involves primarily the hull and non-pressure hull along with hatches and bulkheads, all of these items are summarily more related to the age of the submarine than most systems since they are physically born at the time of construction. Thus, prior to investigating the 100 Series, we wanted to examine the effect of hull age on the expended labor. Following this examination, we focused on the bulk of our analysis that investigated major trends in man-days executed at the SWAB, group, and component levels of maintenance within the 100 Series.

To help develop a estimation model for CA3 as well as actual expended man-days for a DSRA, we used Monte Carlo simulation to develop a proababistic model for all nine projects. The model determines percent difference between the desired attribute (CA3 or Actual man-days expended) and uses a distribution to help model randomness within maintenance activities. The goal of this is to better understand risk associated with random events that occur during major projects and to provide a method to better estimate man-days expended and thus cost and duration of an availability.

A. HULL-AGE CORRECTION FACTOR

We wanted to revisit the analysis of the effect of hull age on the trend of increasing man-days. Previous research by Whitney in 2018 indicated that hull age did not explain the increase in man-days (Whitney, 2018). To do this, hull age was determined as the difference of start date of the DSRA and the submarine's commissioning date. Hull age was calculated in days. We analyzed both total man-days and each Series, 100-700, to identify trends. The goal of this correction factor was to adjust expended man-days for each availability to a theoretical condition of the youngest hull in our data set.

In order to correct for hull age, all hulls were "corrected" to the youngest hull via a correction factor. The correction factor was unique to each hull and determined so that when multiplied by the hull age, the resultant age (in days) was that of the youngest hull. This correction factor was then used to adjust all man-days to the theoretical youngest hull by multiplying the correction factor times the given man-days value. With the data provided, the youngest hull modeled was USS *Columbia* (SSN-771) with a hull age of 6,119 days. Table 2 contains the correction factors used in our analysis.

Table 2. Hull-Age Correction Factor by Hull Youngest to Oldest

Ship	**Hull Age at Start of DSRA (days)**	**Correction Factor**
USS *Columbia* (SSN-771)	6,119	1.000
USS *Cheyenne* (SSN-773)	6,184	0.989
USS *Charlotte* (SSN-766)	6,199	0.987
USS *Columbus* (SSN-762)	6,237	0.981
USS *Santa Fe* (SSN-763)	6,604	0.926
USS *Greenville* (SSN-772)	6,822	0.896
USS *Louisville* (SSN-724)	9,495	0.644
USS *Jacksonville* (SSN-699)	10,880	0.562
USS *Olympia* (SSN-717)	11,119	0.550

Our first correction was conducted on the total man-days expended to observe the trend in expended labor. Figure 1 is a graph of corrected man-days expended by availability oldest (left), newest (right).

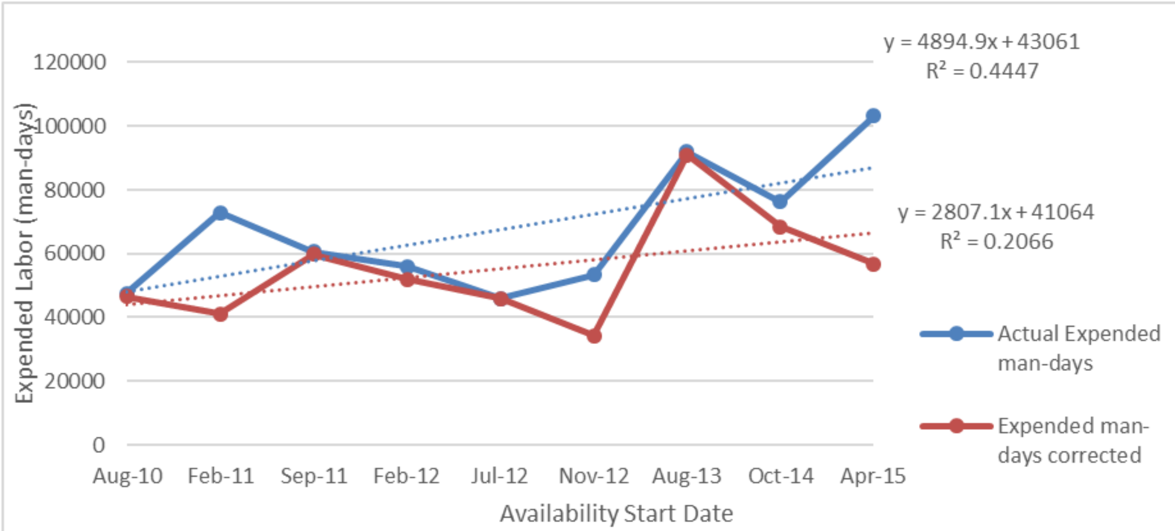

Figure 1. Total Expended Man-Days Hull-Age Corrected by Availability Start Date

Figure 1 illustrates that with hull-age corrections, the trend of expended man-days for an availability still increases. This demonstrates that regardless of hull age, total work conducted in man-days still increases.

Once we determined that the overall man-days expended increased for the nine DSRAs, we evaluated all non-nuclear work completed across the 100–700 Series to verify which Series demonstrated the largest increases with the hull-age corrections. This is illustrated by Figure 2 and Figure 3.

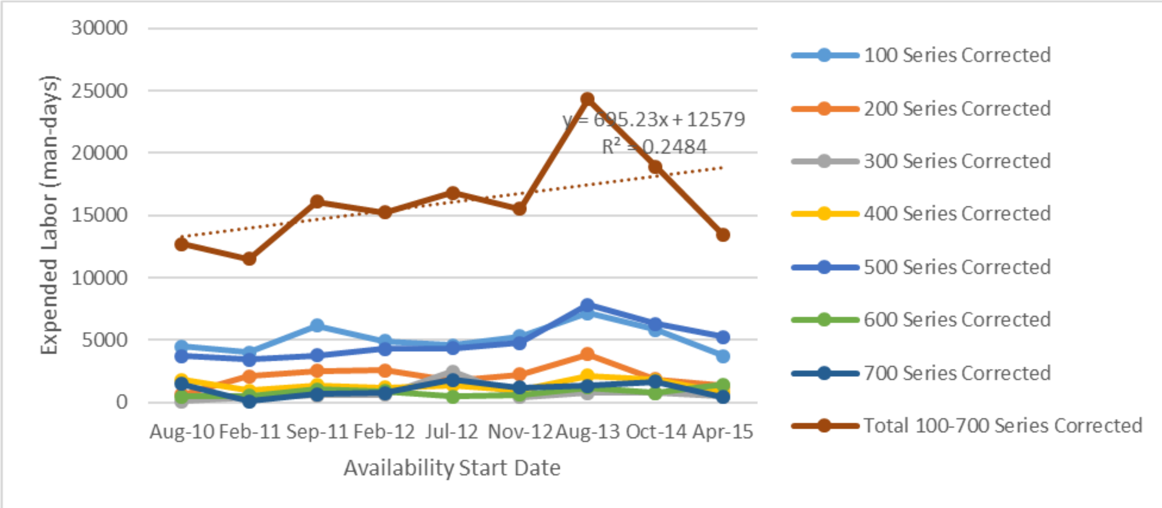

Figure 2. Expended Labor in Man-Days by Availability Start Date with Hull-Age Correction

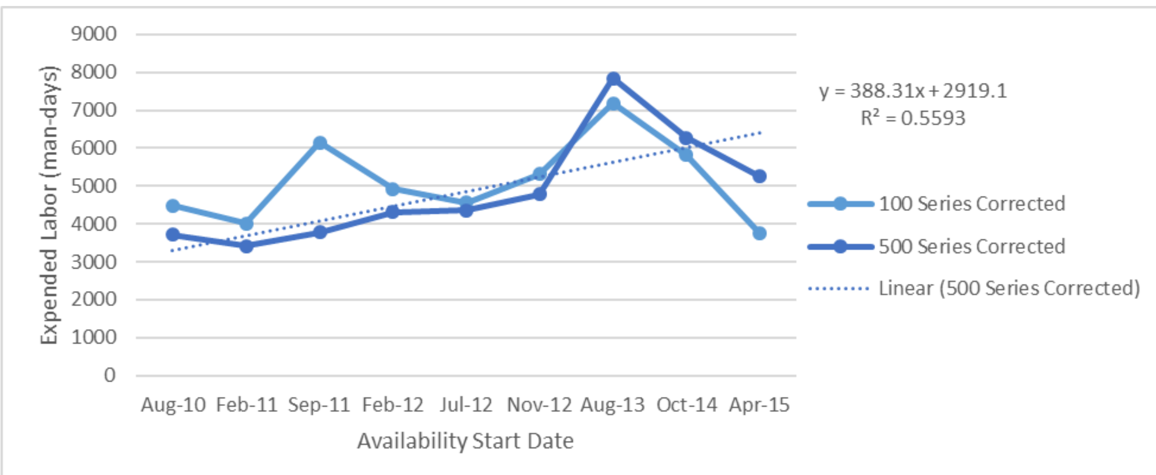

Figure 3. Expended Labor in Man-Days by Availability Start Date with Hull-Age Correction Breakout of 100 and 500 Series

The 100 Series and 500 Series experienced the highest growth followed by the 200 Series of work. The 500 Series was previously evaluated by Isley, Seagrave, and Shiver in 2018 and Wheeler in 2019. The 200 Series will not be evaluated due to its lower magnitude of increase over time and proportion of the total increase in man-days.

B. TRENDS IN SHIPYARD LABOR (MAN-DAYS) EXECUTED

1. Analysis of 100 Series SWLINs

As observed by Whitney in 2018, the trend in overall labor expended to complete these DSRAs has increased over time. Isley et al. (2018) identified the specific 500 Series SWABs, SWLINs, Groups, and Components that contributed to the largest increase in expended labor over time. Our analysis is similar in scope and depth, but conducted on the 100 Series of maintenance. As shown in Figure 4, there is a clear positive trend in 100 Series expended labor (man-days) across the DSRAs, this addressed Research Question 2. Thus, our first task for Research Question 3 was to examine the SWABs within the 100 Series to determine which of them consistently contained the most labor, and additionally showed growth across the DSRAs. To accomplish this, we used the Job Order / Key Op (JOKO) data to determine the expended labor and plotted across the DSRAs, arranged by availability start date as seen in Figure 5. Of note, one SWAB, 156 (Ballast), is excluded from our analysis because it doesn’t have any repair component and serves to track the performance of ballasting services during the DSRA. Within Figure 5, it is obvious that three SWABs, namely 131, 132, and 176, make up the large majority of the expended labor. These three SWABs comprise 85% of the expended labor within the 100 Series. We decided to focus our analysis on these three SWABs primarily due to the magnitude difference in labor, but did an analysis on the other four smaller contributors and found that they did not meaningfully affect the total Series. While the 176 SWAB accounts for the greatest man-days expended at 34% of the total 100 Series, it possesses a negative trend over the DSRAs. Therefore, we chose to further analyze SWABs 131 (Pressure Hull) and 132 (Non-Pressure Hull), which demonstrated positive trends over time (Figure 6), to search for the likely cause(s) of 100 Series overall increase in expended labor.

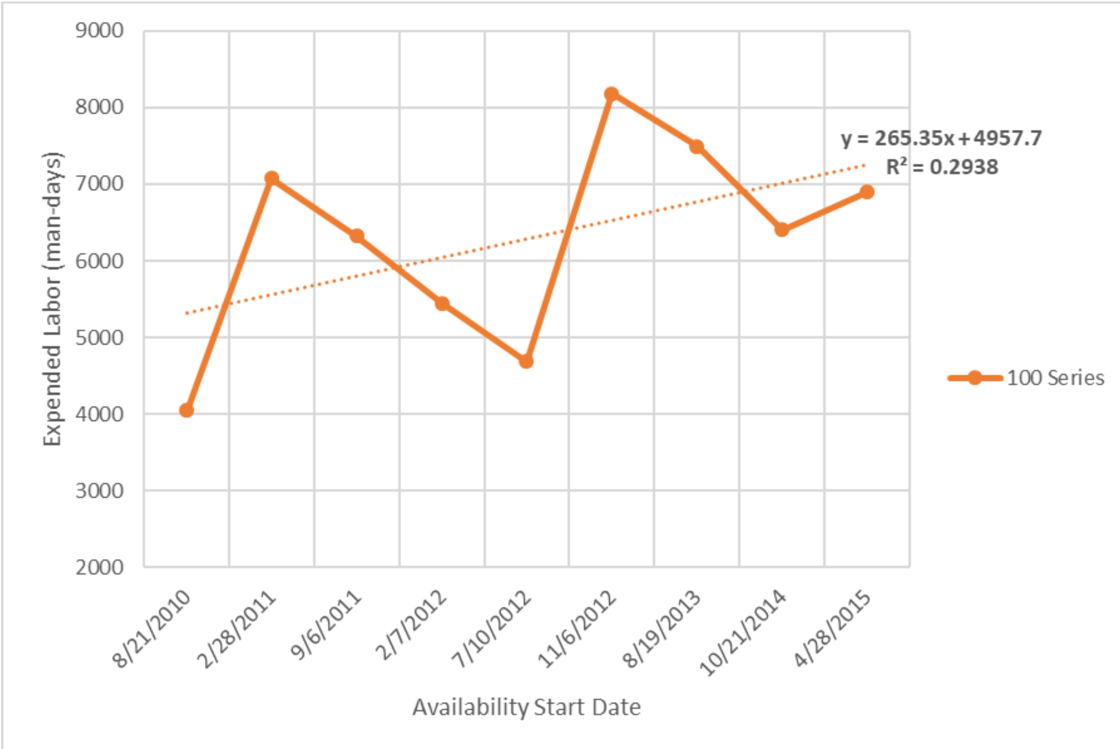

Figure 4. Labor Expended within the 100 Series Arranged by Availability Start Date

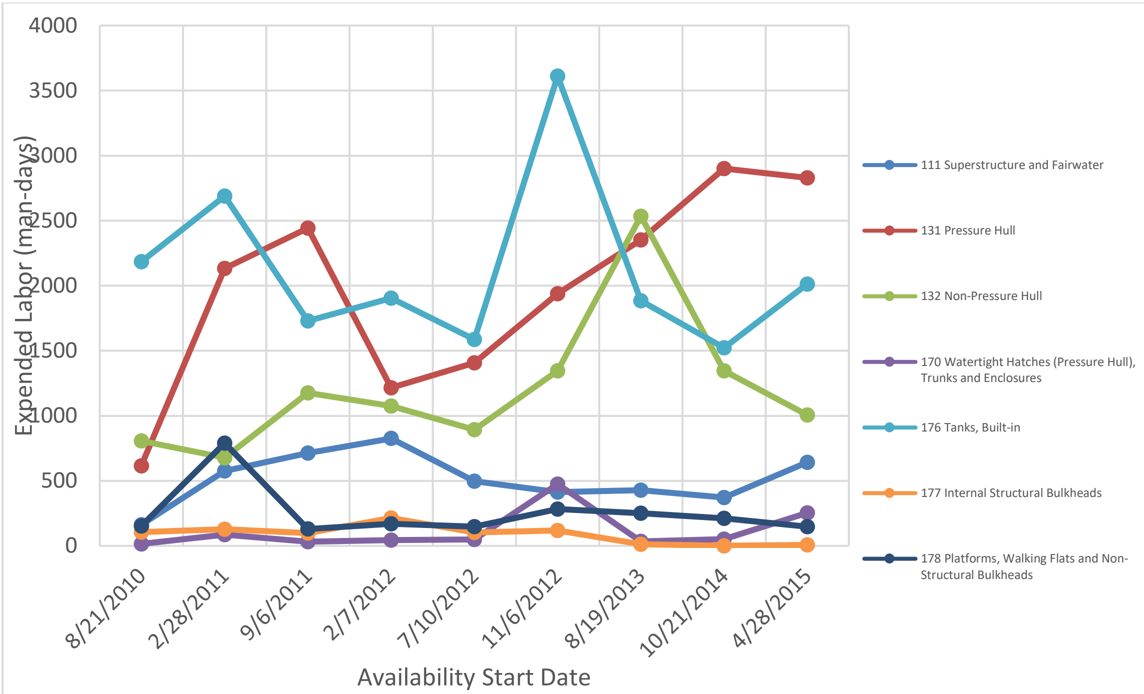

Figure 5. Labor Expended for all SWABS within the 100 Series Arranged by Availability Start Date

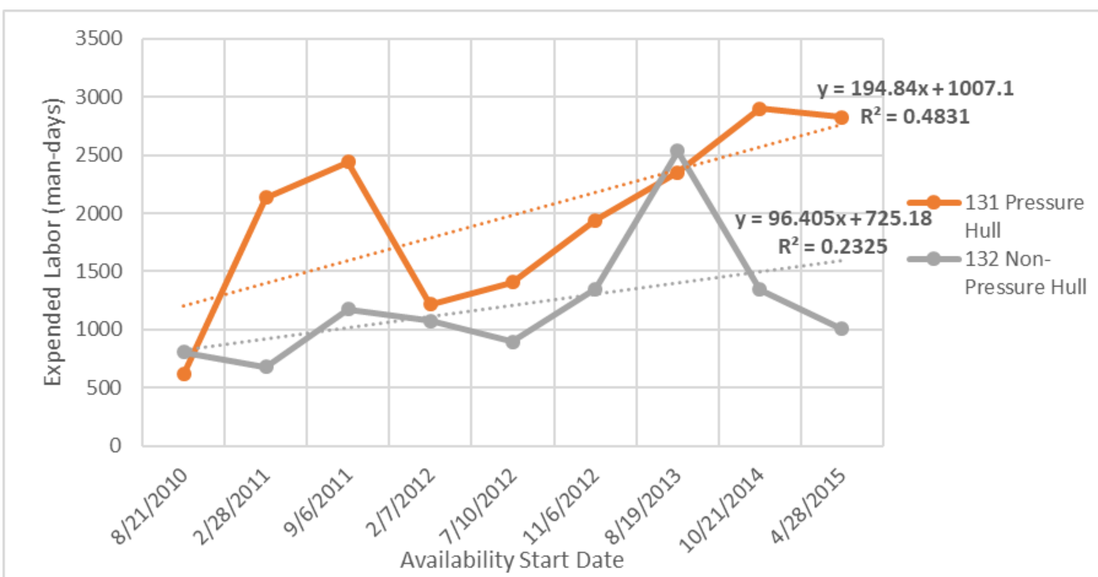

Figure 6. Labor Expended for SWABs 131 and 132 Arranged by Availability Start Date

Next, we wanted to observe any correlation of availability duration with the expended labor of the complete 100 Series and our identified largest growth contributors, SWABS 131 and 132. Shown in Figure 7, there tends to be more 100 Series expended labor as the duration of the availability increases, this is expected and similar to the observed 500 Series maintenance identified by Isley, Seagrave, and Shiver (Isley et. al, 2018). In Figure 8 we arranged the 131 and 132 SWABs by the duration of the availabilities. While the trend is positive, indicating duration may be affected by the increase in expended labor for these two SWABs, the best-fit trend lines do not account for much of the variation in the data. This is expected with our small dataset, and we continued to dig deeper into the group and component levels within both SWABs to find the cause for the observed increases.

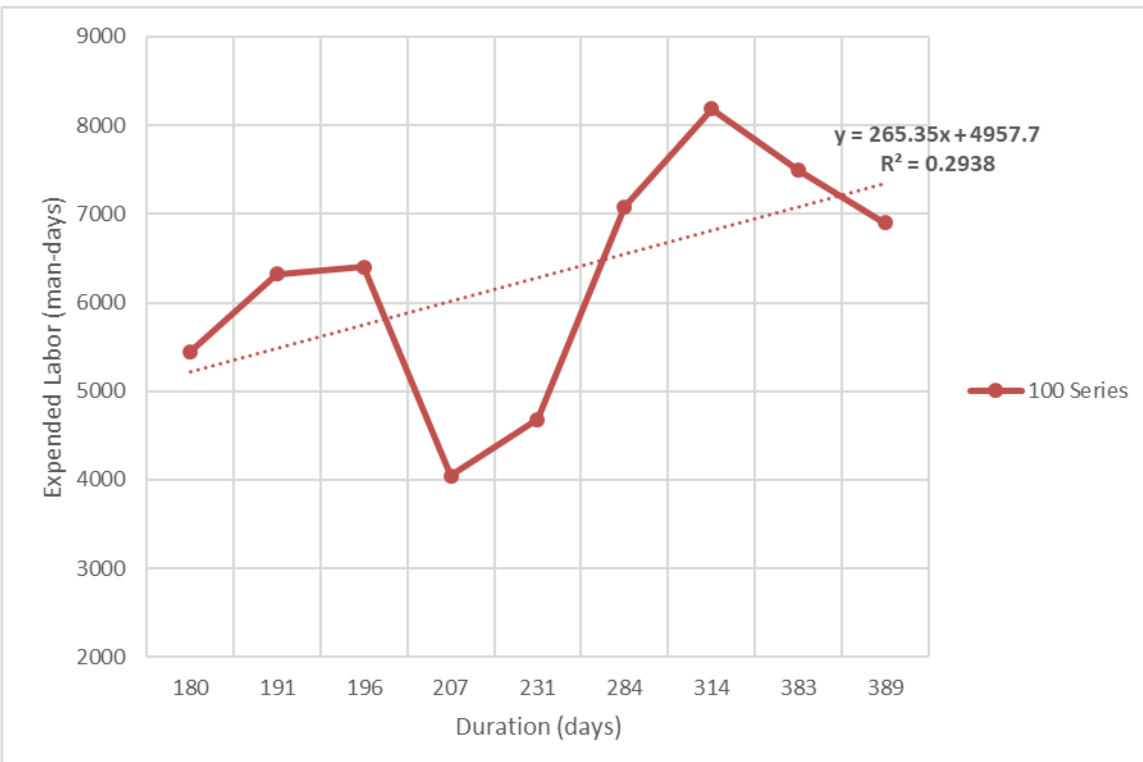

Figure 7. Labor Expended within the 100 Series Arranged by Availability Duration

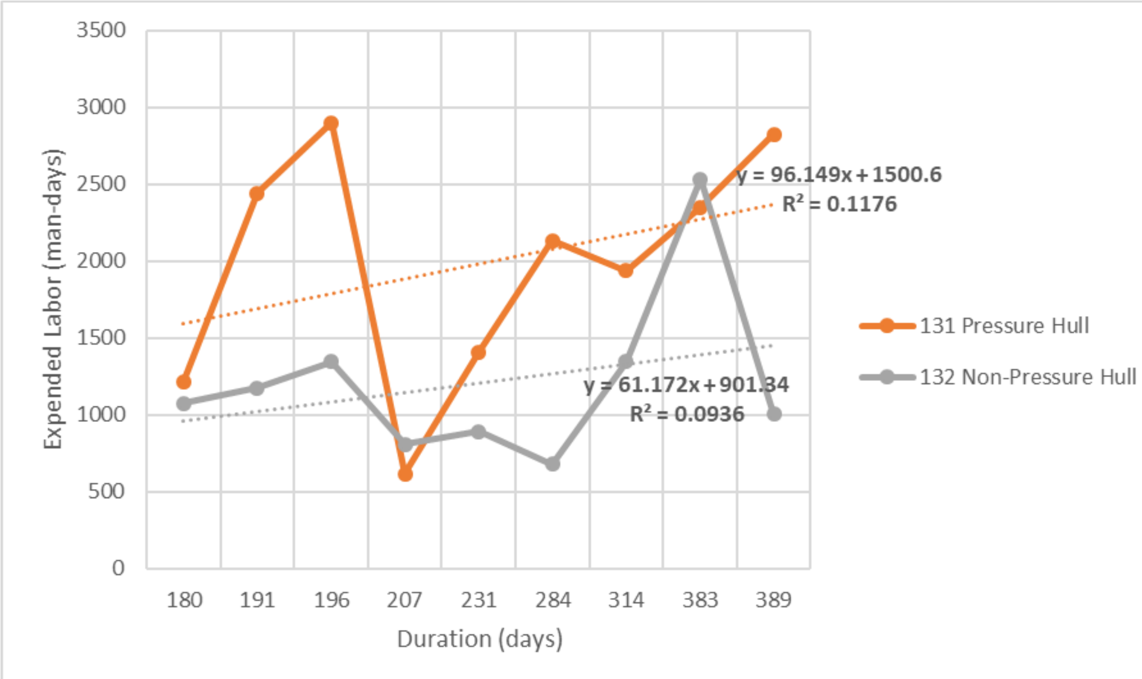

Figure 8. Labor Expended for SWABs 131 and 132 Arranged by Availability Duration

2. Analysis of Groups within the 131 SWAB

Following the identification of the 131 SWAB (Pressure Hull) Series as a potential driver for the increase in man-days expended, further analysis was conducted to isolate maintenance items driving the increase. To conduct this analysis, maintenance groups were selected from each DSRA and analyzed by availability start date (Figure 9).

To better answer Research Questions 3 and 4, two groups illustrated the largest growth within the 27 (Inspection and Surveys), 44 (Valves), 82 (Preservation) group. The 27 group showed the most significant growth compared to the other groups within the 131 SWAB. The 82 group showed the next largest growth, followed by the 44 group. The total man-days for the 131 SWAB averaged 1981 man-days. Figure 10 shows the trend in major common maintenance groups of the 131 SWAB. The total man-days shows a strong increase over time, followed by the main driver the 27 Series. Figure 9 also includes work classified as New Work.

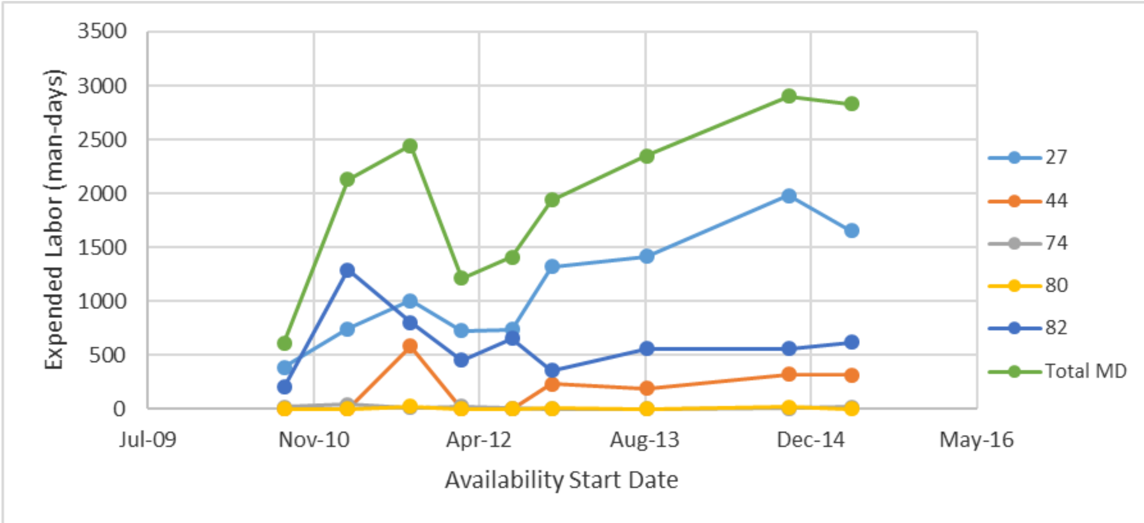

Figure 9. Labor Expended for all Groups within SWAB 131 Arranged by Availability Start Date

Without New Work included, Figure 10 demonstrates a consistent increase in the total man-days expended by availability with similar increases to 27. This indicates that New Work makes up about 13.4% of total work conducted in the 131 SWAB.

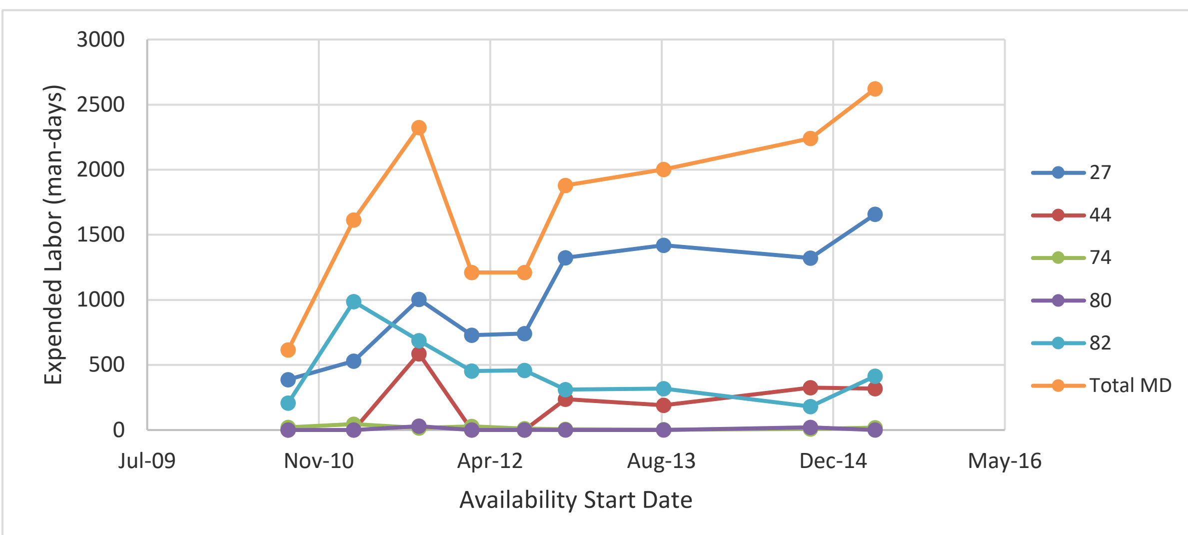

Figure 10. Labor Expended for all Groups within SWAB 131 without New Work Arranged by Availability Start Date

3. Analysis of Groups within the 132 SWAB

Following the identification of the 132 SWAB as a possible significant growth driver in expended labor, three primary groups were identified to be consistent with all of the DSRAs. These were the groups of 27 (Inspection and Surveys), 74 (Cathodic Protection Anodes), and 82 (Preservation). There were an additional four groups, which were included in a select few of the different DSRAs, but not consistently enough to be significant. In Figure 11, Group 27, Inspections and Surveys, showed a clear and positive growth trend over the DSRAs. This assisted in answering Research Questions 3 and 4.

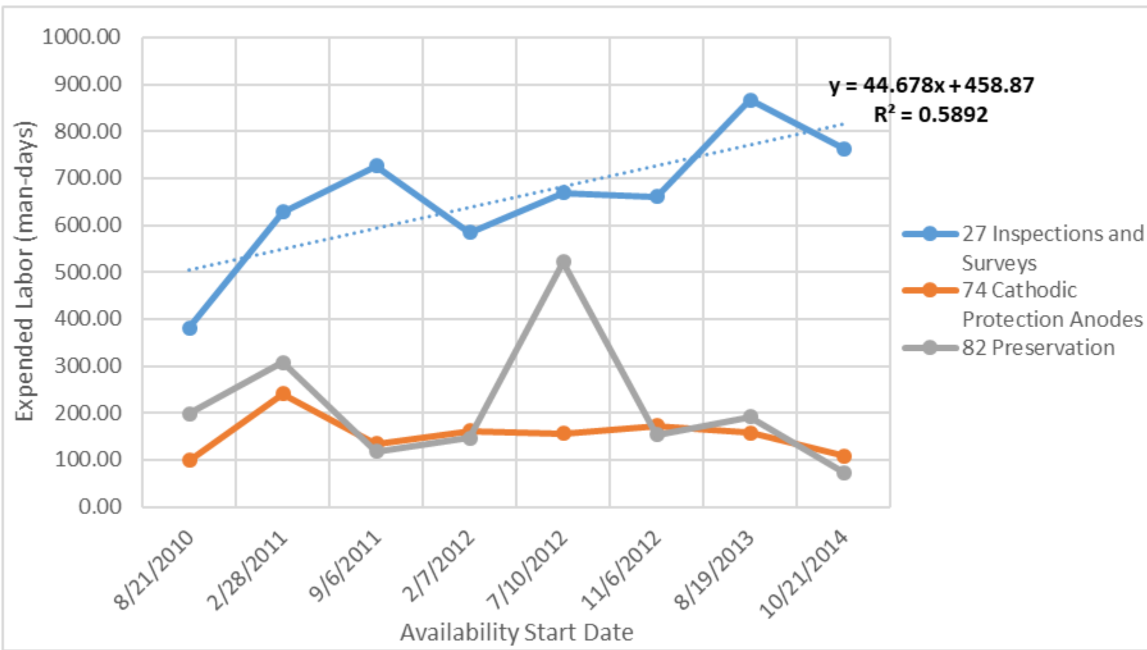

Figure 11. Labor Expended for All Groups within the 132 SWAB Arranged by Availability Start Date

4. Analysis of Components within Group 131.27

To answer Research Question 4 fully, our analysis continued one level further down from the Group and into the Components of the expended labor. For the 131.27, the nine DSRAs often contained components that were only worked within a couple of the DSRAs, though some of that work was significant in terms of man-days expended, the trend could not be established. To conduct the trend analysis, only work conducted on a minimum of eight hulls were considered. The four common components were 0136, 0150, 0165, and 0142. Figure 12 shows the trend of these components by availability start date. There is a strong upward trend for 27.0165 (Pressure Hull [VISIBLE FROM DRY DOCK]). This indicates there is significant growth in the labor required to complete maintenance related to this component.

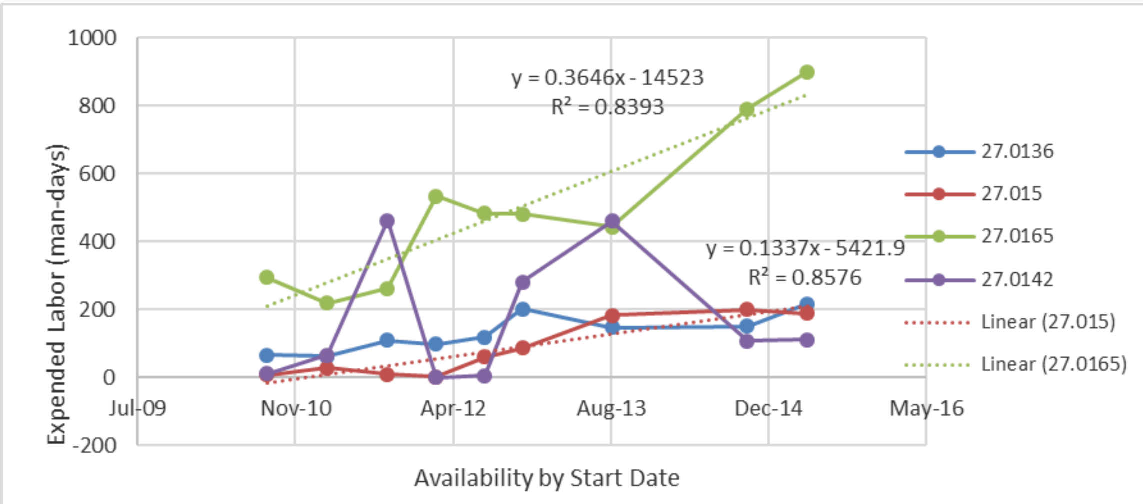

Figure 12. Labor Expended within SWAB 131 Group 27 Arranged by Availability Start Date

5. Analysis of Components within Group 132.27

To answer Research Question 4 fully, our analysis continued one level further down from the Group and into the Components of the expended labor. While some DSRAs included up to nine components within the 27 (Inspection and Surveys) Group, five of the components were used across all nine DSRAs, and none of the remaining four appeared in more than three DSRAs. Therefore, we analyzed the five consistent components to determine significant growth drivers among them. Shown in Figure 13, three of the five groups stood out both in magnitude and growth, they were 27.0200 (Exterior of Non-Pressure Hull), 27.1480 (Fairing Covers Over Retractable Towed Array Stowage Tubes), and 27.0320 (Non-Watertight Access Hatches, Cover Plates, & Access Manhole Covers). However, to answer Research Question 4 and shown in Figure 14, one component, the

27.0200 (Exterior of the Non-Pressure Hull) was identified as the significant contributor to the total growth exhibited in SWAB 132.

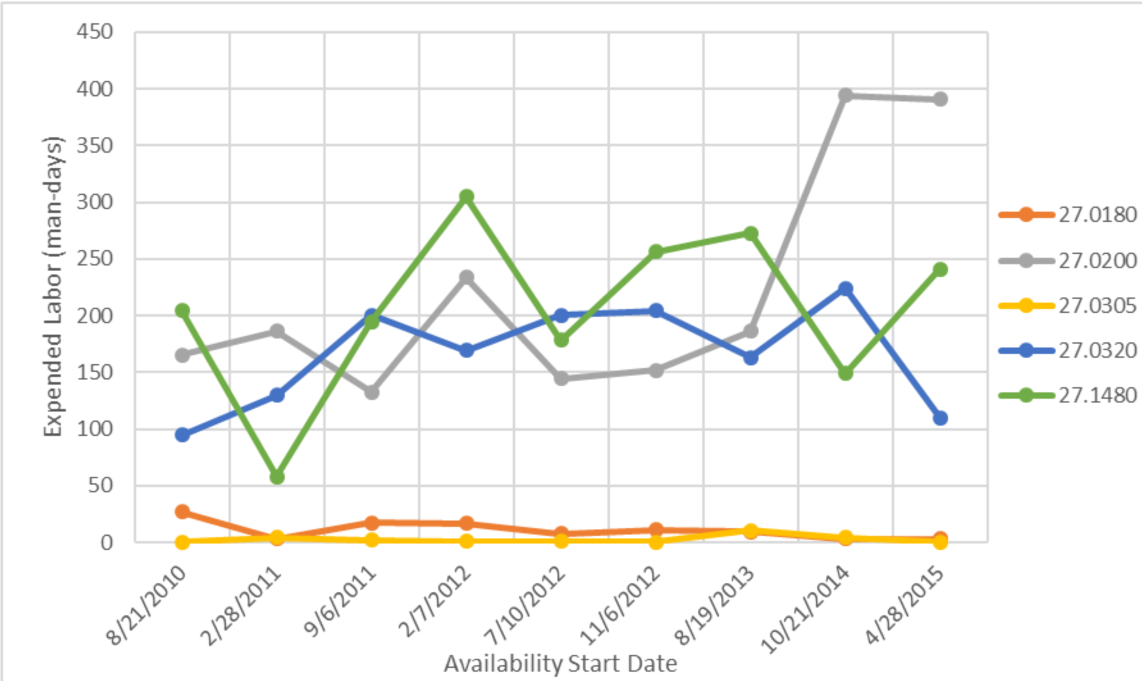

Figure 13. Labor Expended within SWAB 132 Group 27 Arranged by Availability Start Date

Figure 14. Group 27 Labor Expended by Components 0200, 1480, and 0320 Arranged by Availability Start Date

C. NEW WORK ANALYSIS

1. 100 Series New Work

"New Work" as per discussion with SUBMEPP refers to work completed during the availability that is added after the generation of Corporate Cost Assessment 3 (CA3). All work included in the Availability Work Package (AWP) prior to the generation of CA3 is considered "Baseline" work. An important distinction exists between New Work and "Growth Work." Growth work refers to work found during the course of the availability that is added once found. Therefore, all Growth Work is New Work, but not all New Work is Growth Work. Our data does not distinguish between the two; therefore, New Work is only defined as work added after CA3 in our thesis. New Work is denoted by "ANW" within our dataset.

As shown in the Figure 15, when expended labor is broken out into both Baseline Work and New Work, both increase over time. New Work accounted for an average of 8.7% of total man-days across within each of the nine DSRAs, while accounting for 9.1% of the total labor expended within the 100 Series for all nine DSRAs. These numbers are consistent, indicating that within the 100 Series, a point estimate of 9% of total 100 Series labor will be from ANW. Figure 16 shows more clearly the minor growth of New Work. However, as stated above, the 100 Series New Work is relatively consistent as a percentage of total work, therefore New Work does not account for significant increases in total expended labor.

When arranged by DSRA duration (Figure 17), as asked in Research Question 5, the relationship between Duration and increasing New Work is apparent. This supports the logical conclusion that if you have more New Work, you tend to have a longer DSRA duration. This could be due to any number of reasons, but the relationship does seem sound, if you desire a shorter DSRA, seek to add less New Work.

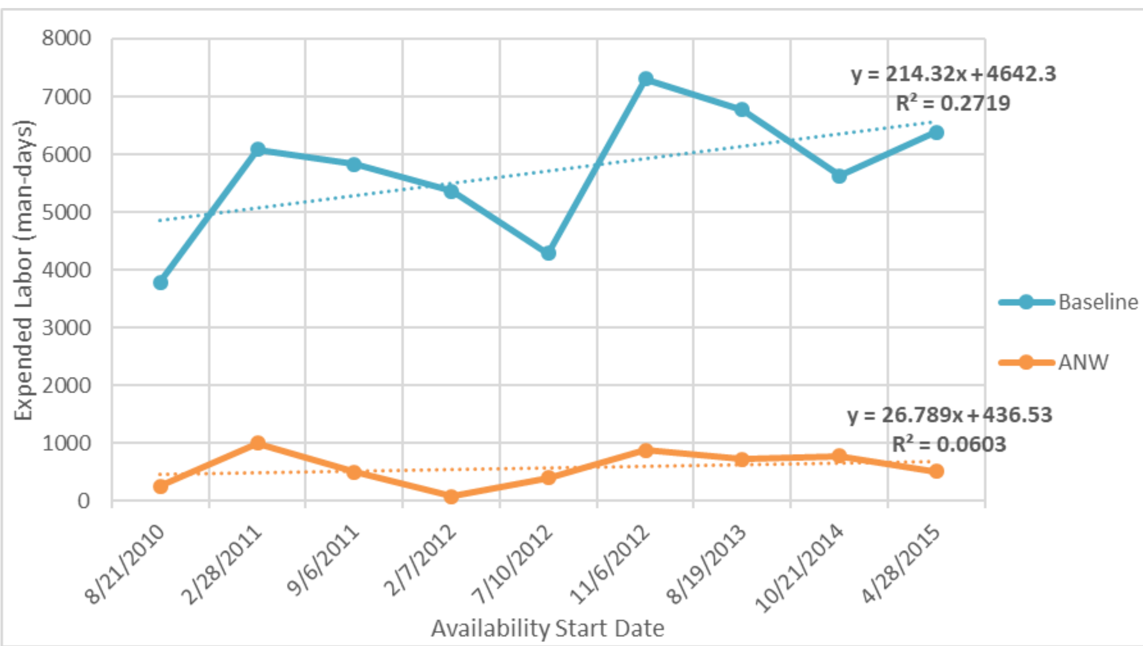

Figure 15. 100 Series Baseline and New Work Expended Labor Arranged by Availability Start Date

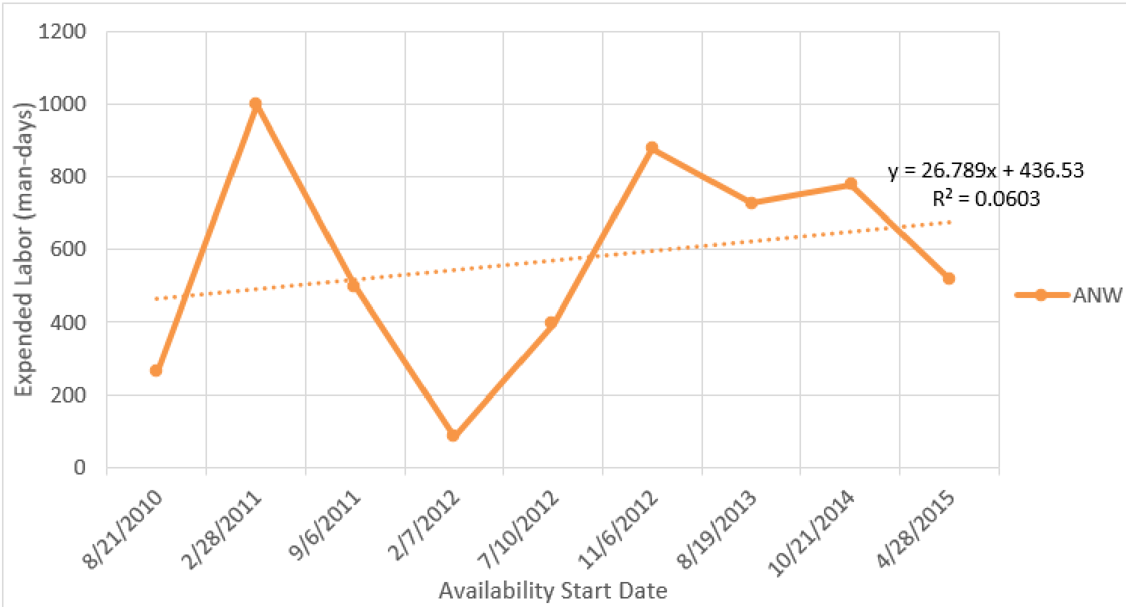

Figure 16. 100 Series New Work Expended Labor Arranged by Availability Start Date

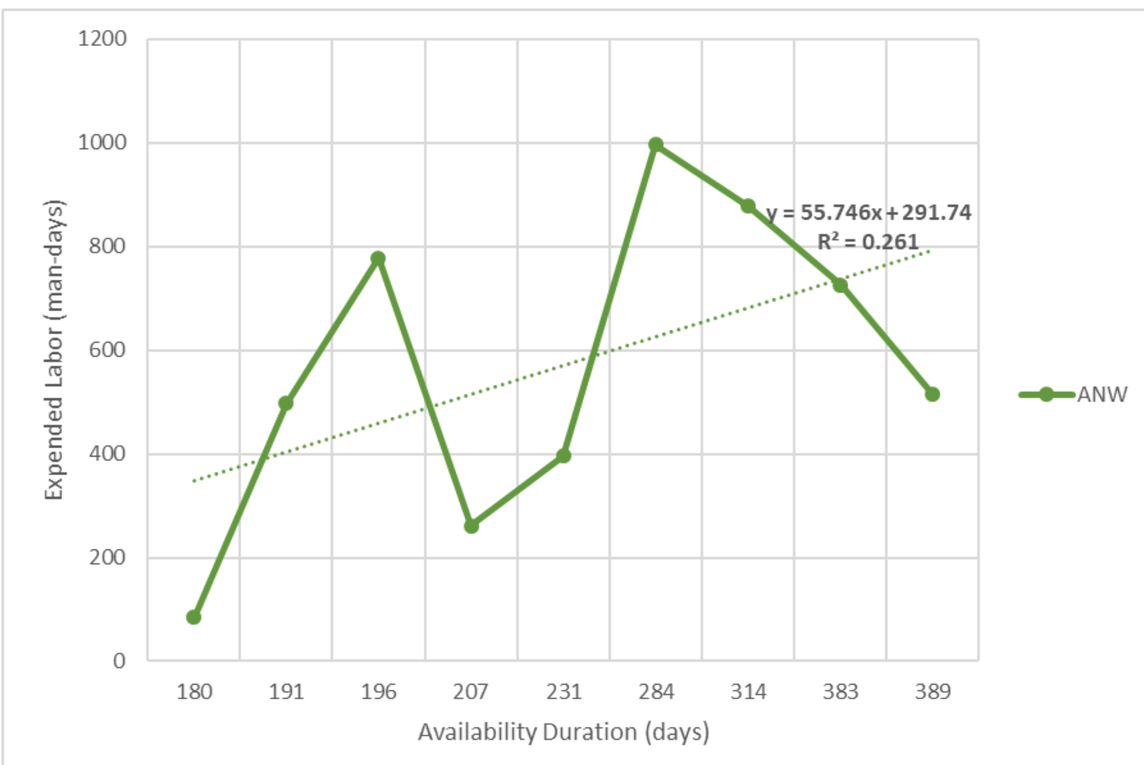

Figure 17. 100 Series New Work Expended Labor Arranged by Availability Duration

2. 100 Series Cost Variance

Wheeler in 2019 identified that within the 500 Series, Cost Variance (CV) does not trend in a way that is typical for learning organizations that should lower cost based on Learning Curve Theory (Wheeler, 2019). As defined in Earned Value Management, CV is the difference between the Budgeted Cost of Work Performed (BCWP) and the Actual Cost of Work Performed (ACWP). Within the 100 Series, as seen in Figure 18, our analysis yielded a negatively sloped CV trend line, indicated that, similar to Wheeler's conclusion for the 500 Series, the 100 Series is also not improving over time. One would expect the feedback loop over the course of the nine DSRAs to have incorporated additional work, improve labor practices and management, and yield better estimates for the BCWP, which would over time drive the CV back towards zero. Unfortunately, this is not observed, and we can therefore say that the organization has not improved either its practices or estimation capability.

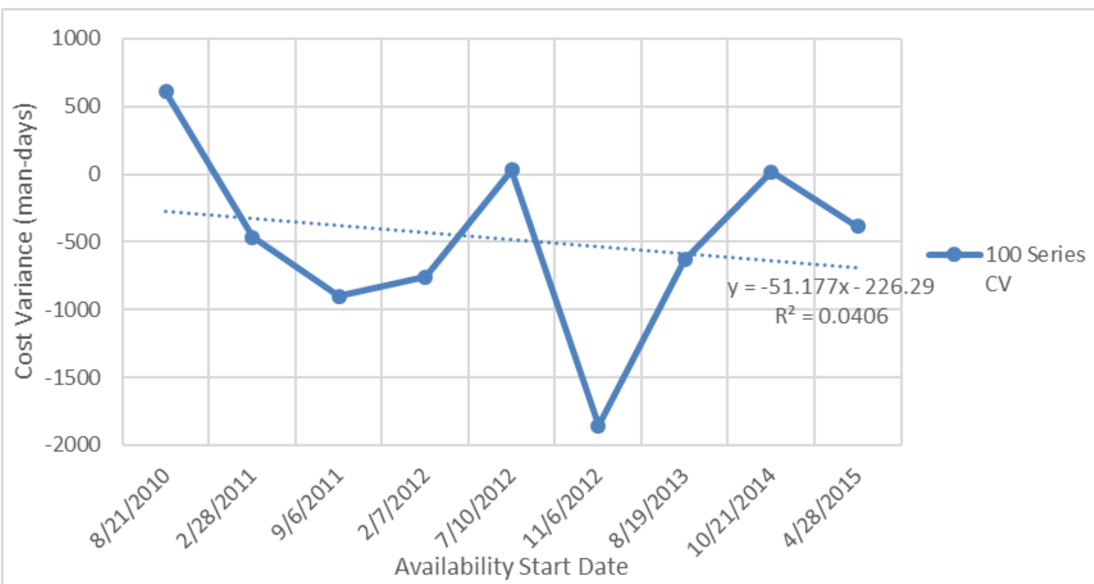

Figure 18. 100 Series Cost Variance Arranged by Availability Start Date

D. COST ESTIMATE PREDICTION MODELS

1. Monte Carlo Simulation

Monte Carlo simulation was used in this thesis to better determine the maximum value for various Corporate Cost Estimates. Monte Carlo simulations are a computerized iterative mathematical technique that is used to approximate the likelihood of outcomes by running thousands of trail scenarios. This allows the user to conduct a quantitative risk assessment and decision analysis. The simulation takes user inputs, develops a range of values based on a probability distribution, and it calculates results. The model runs for a defined amount of trials, each trial using a different set of random numbers. The Monte Carlo simulation produces a distribution of possible outcomes from which risk can be assessed and decisions can be made.

2. Why Monte Carlo Simulation Is Beneficial

This type of simulation is advantageous for this topic because hundreds of iterations of randomly created data points can be assessed and produce a higher confidence value. With few data points currently available (nine DSRAs), without Monte Carlo simulation, information would have excessive variability and would provide limited information to the end user. Additionally, just using Excel to evaluate the data limits the amount of risk information that can be analyzed.

For this application, three different distributions were modeled. With limited data points available post OPINTERVAL change, only the nine DSRA's data were available to model. With the completion of additional projects the distributions can be changed and updated as needed. The three distributions selected and analyzed were lognormal, uniform, and triangular. These distributions will be discussed below.

a. Lognormal Distribution

The Lognormal Distribution is widely used in situations where values are positively skewed with uncertainty variables that can increase without limits but cannot go below a lower bound. This distribution has larger tails than a normal distribution and may better compensate for risk in the extremems of the simulation. Due to the shape of the distribution, with the majority of the values occur near the minimum, this distribution will result in a lower estimation compared to the other distributions used. A weakness of this distribution is the values on the lower bound is confined to a finite value. With only nine observations, the lower bound was defined by the minimum percent difference observed. The model then assumes no value can be less than this which introduces potential error. This model may best fit the data because the performance of one DSRA to another may be constant within a range of performance making the percent difference between Cost Estimates similar. Outliers have a lower probability of occurance, both in more man-days expended and less man-days expended.

b. Uniform Distribution

The uniform distribution was selected as another distribution based on its over estimation of risk in the extremes of the distribution. Uniform distributions allow events to occur at the defined min and max to be equally likely to occur, thus maximizing risk and resulting in more man-days expended. Modeling with this distribution is the safest and is expected to indicate the highest percentage difference of all three distributions. However, a weakness of this distribution is the defined lower and upper bounds based on only nine observations.

c. Triangular Distribution

The Triangular distribution is commonly used in project management planning where the min, max, and mean can be established. A weakness of this distribution is the defined min and max values required. The minimum value of the distribution is possible to be less than the previous cost estimate, but not less than zero man-days. The maximum does not have a maximum value and thus is challenging to estimate. To alieviate this, when modeling the in Crystal Ball, the lower bound was 10%, the middle was defined as the mean, and the upper bound was 90%. This allows the model to select random values above and below the witnessed min and max within the nine data points, being more conservative.

3. Using CA2 to Estimate CA3

To better estimate the CA3 maximum expected expended man-days, CA2 data from the nine DSRAs was used. Using Crystal Ball, an add on for Microsoft Excel to run Monte Carlo simulations, three distributions were modeled. Since PHNSY has not conducted a statistically large amount of DSRAs, insufficient data existed to best fit a distribution (min 15 observations required). Selected for this estimation was a lognormal distribution, uniform distribution, and a triangular distribution. Within each DSRA, the percent difference was modeled between CA2 and CA3. Based on the data provided, the CA2 and CA3 data were correlated at 0.95. To ensure accuracy of the model, 40,000 simulations were conducted. This number was selected based on increasing the number of simulations run incrementally and finding negligible changes between the results.

The distribution models' results are reported in Table 3. Results and confidence interval are reported in man-days. The values reported are for a probability of 85%, meaning that there remains a 15% chance a DSRA will exceed this value on CA3. Figures 19 through 24 are the Crystal Ball outputs for the various distributions.

Table 3. CA2 to CA3 Estimation Results by Distribution

Parameter	**Result in man-days**	**95% Confidence Interval**
Lognormal Distribution	8,493	8,315-8,874
Uniform Distribution	11,159	11,055-11,239
Triangular Distribution	11,818	11,689-12,016

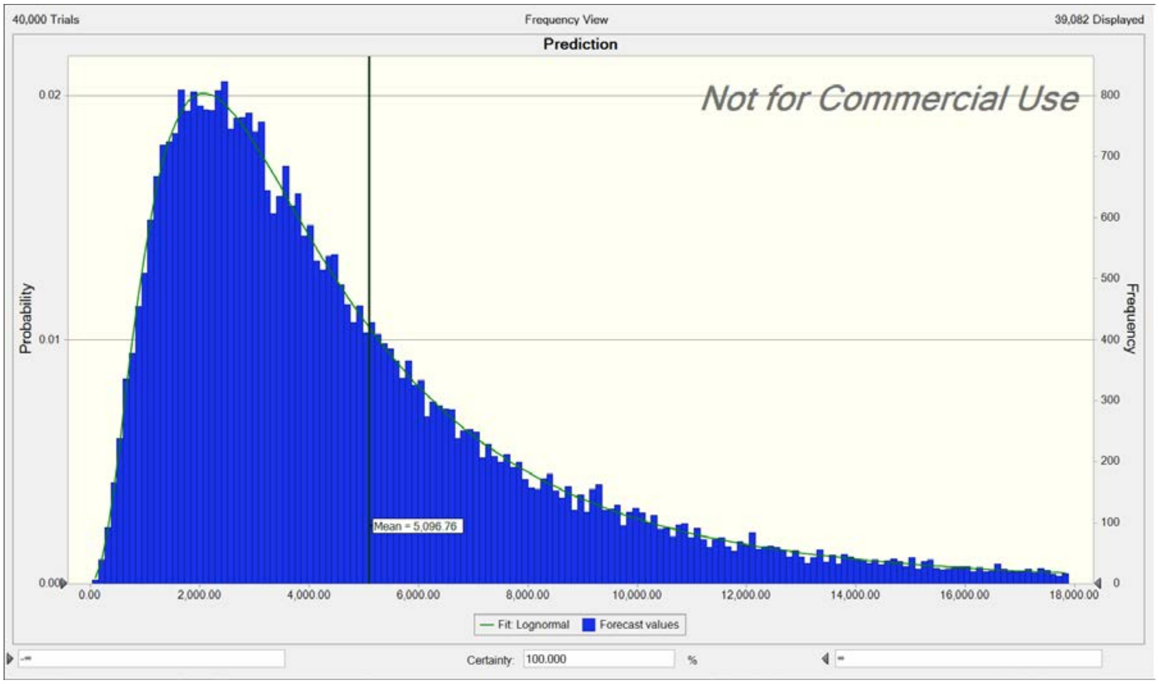

Figure 19. Lognormal Distribution for Maximum Expended Man-Days CA3 Based on CA2

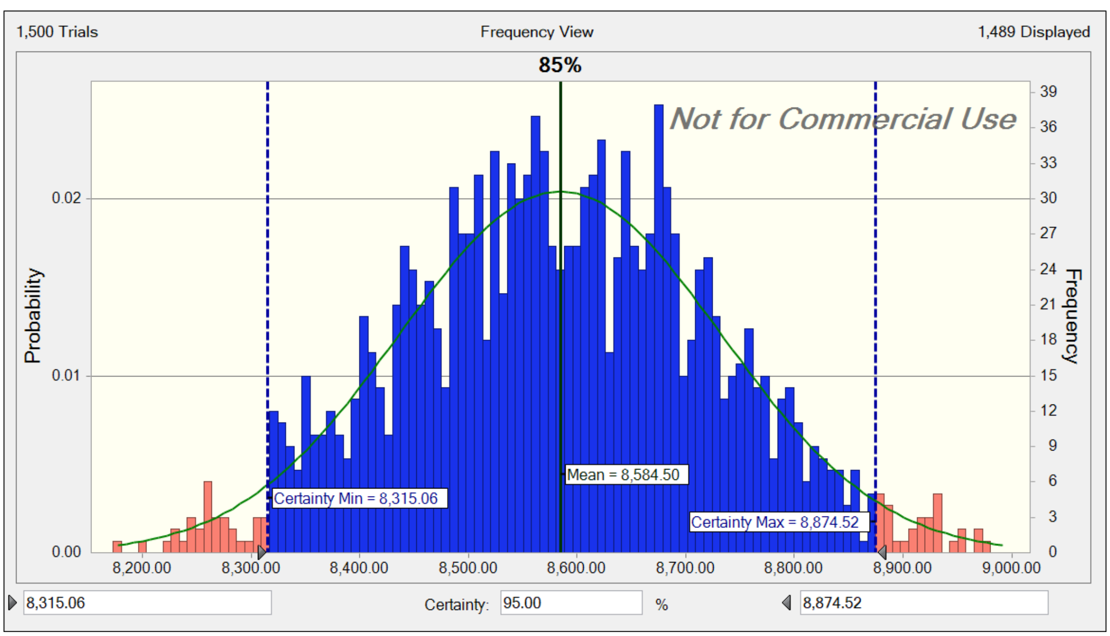

Figure 20. Lognormal Distribution for Maximum Expended Man-Days CA3 Based on CA2 Confidence Interval

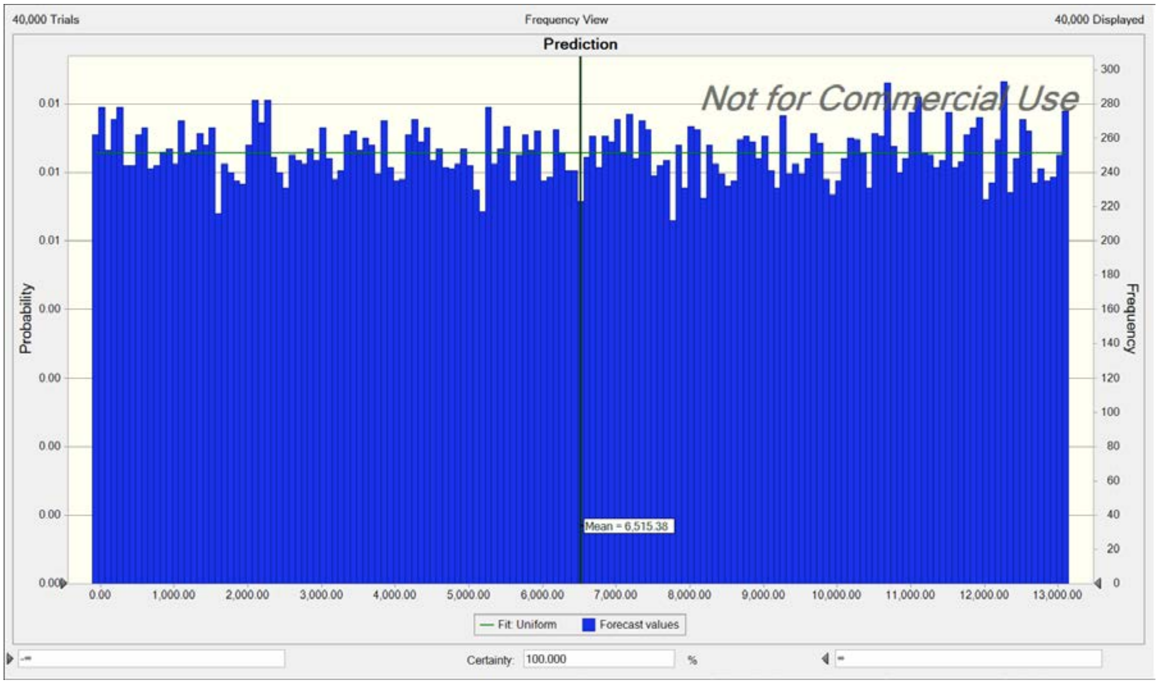

Figure 21. Uniform Distribution for Maximum Expended Man-Days CA3 Based on CA2

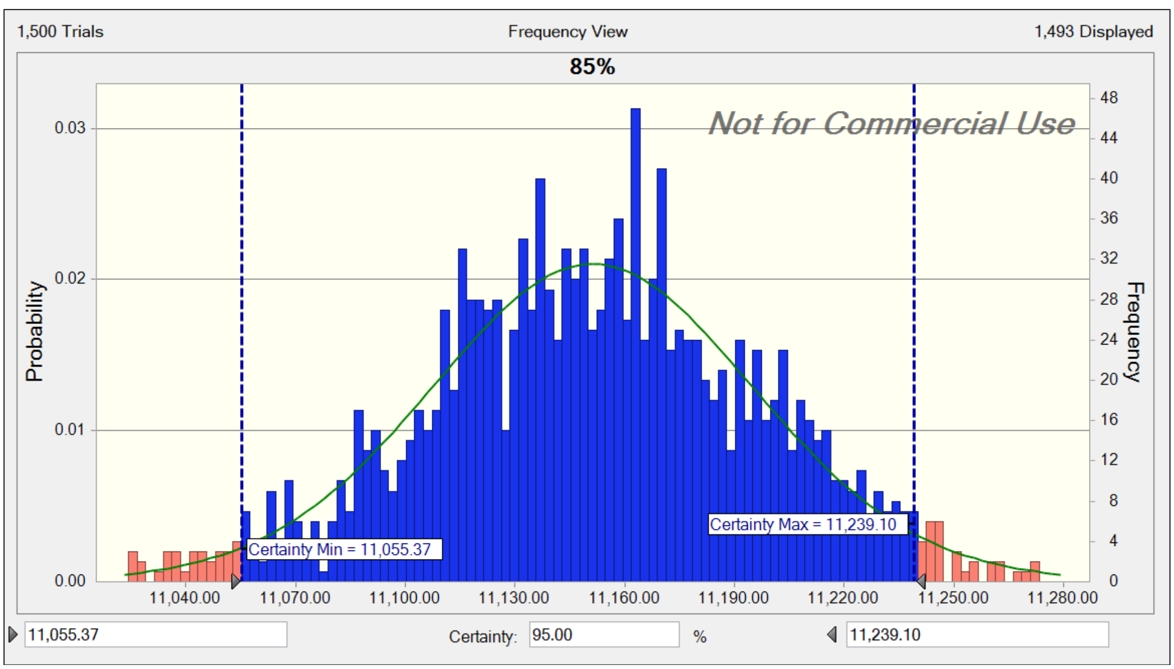

Figure 22. Uniform Distribution for Maximum Expended Man-Days CA3 Based on CA2 Confidence Interval

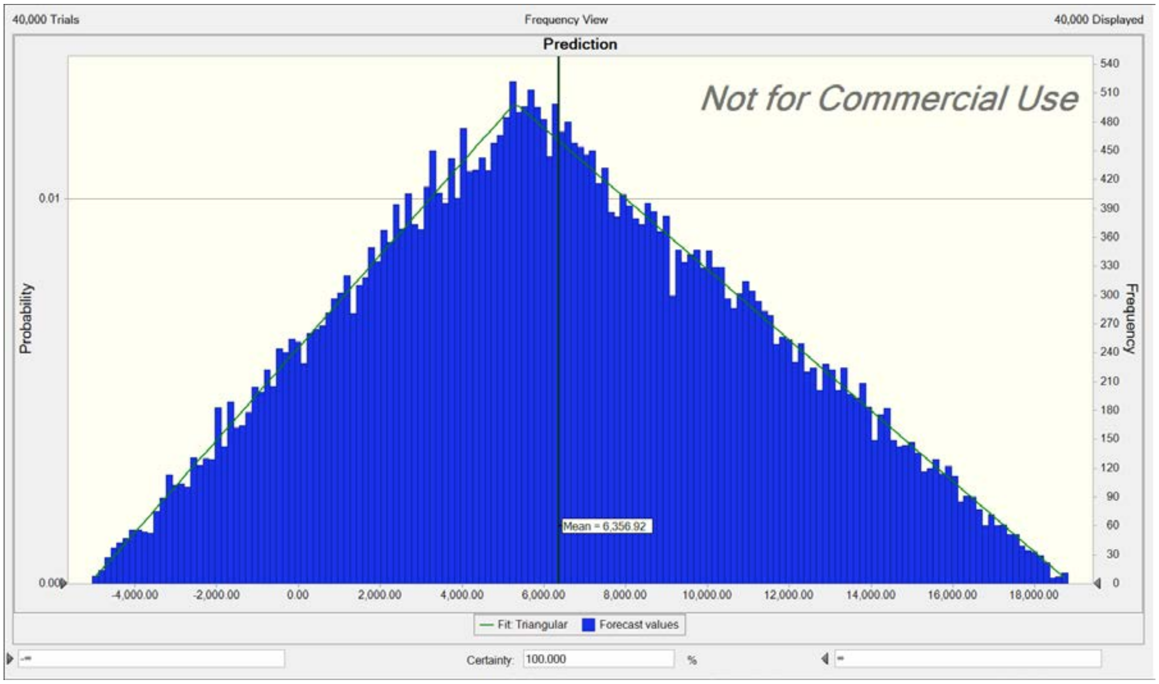

Figure 23. Triangular Distribution for Maximum Expended Man-Days CA3 Based on CA2

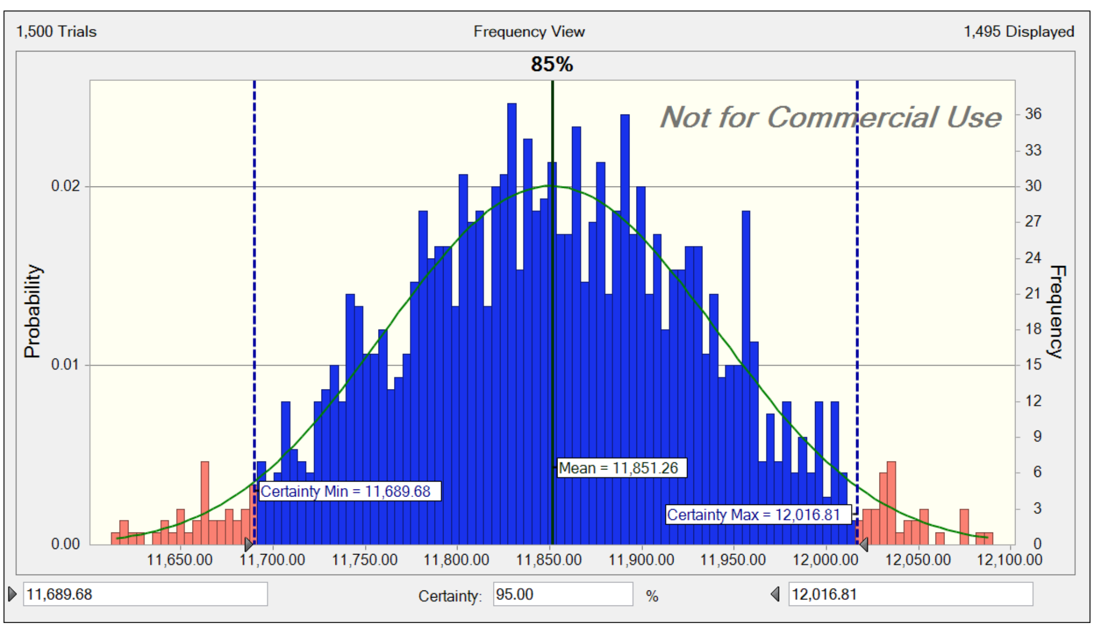

Figure 24. Triangular Distribution for Maximum Expended Man-Days CA3 Based on CA2 Confidence Interval

4. Using FRE Data to Estimate the Maximum Final Man-Days Expended

The FRE data is the most accurate estimate of how many man-days will be expended to complete the availability taking into account ship condition. To estimate the maximum numbers of final expended man-days, a similar process was used as described above. Crystal Ball was used to model three different distribution models. Since there is larger variability in the data between FRE and Final expended man-days for each of the nine DSRAs, the results indicated a larger number of man-days needed to be added to the entire project for high confidence. The results for this model are listed in Table 4. Figures 25 through 30 are the Crystal Ball outputs for the various distributions.

Table 4. FRE to Actual Final Estimation Results by Distribution

85% Parameter	**Result in man-days**	**95% Confidence Interval**
Lognormal Distribution	19,387	18,729–20,024
Uniform Distribution	33,482	33,130–33,820
Triangular Distribution	35,974	35,261–36,546

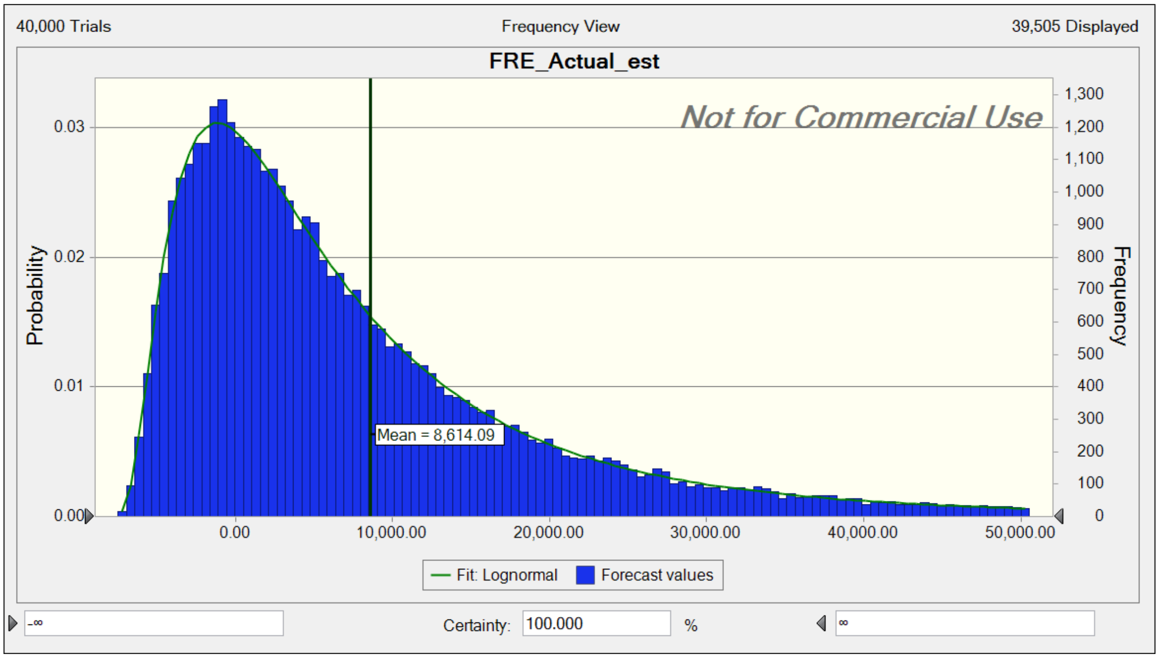

Figure 25. Lognormal Distribution for Actual Expended Man-Days Based on FRE

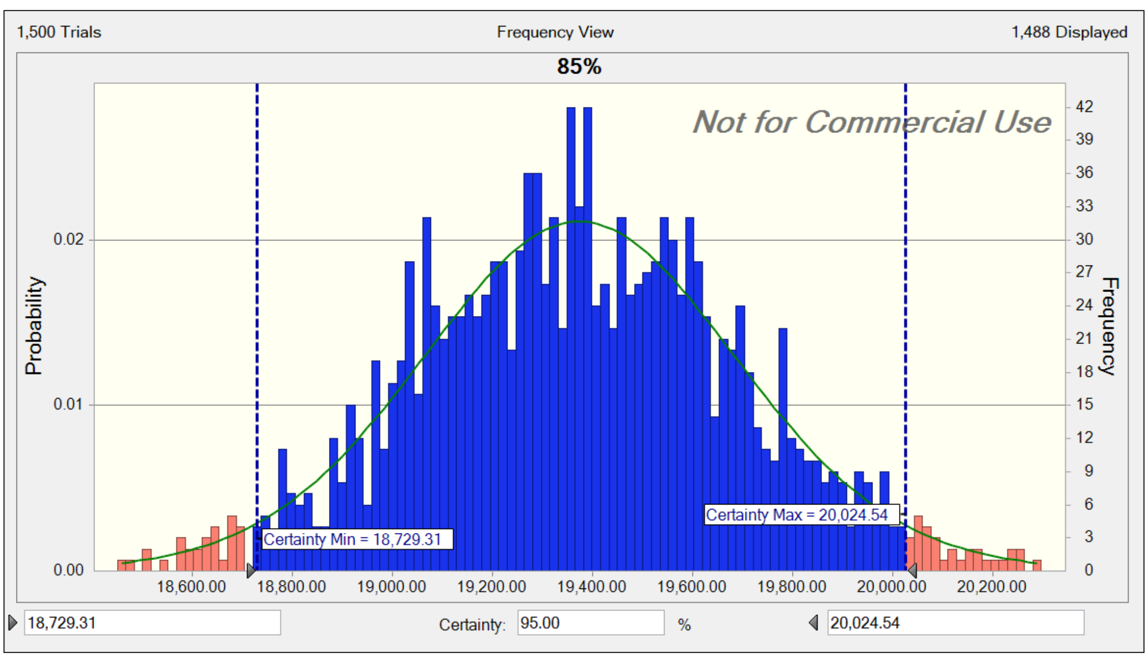

Figure 26. Lognormal Distribution for Maximum Expended Man-Days Actual Based on FRE Confidence Interval

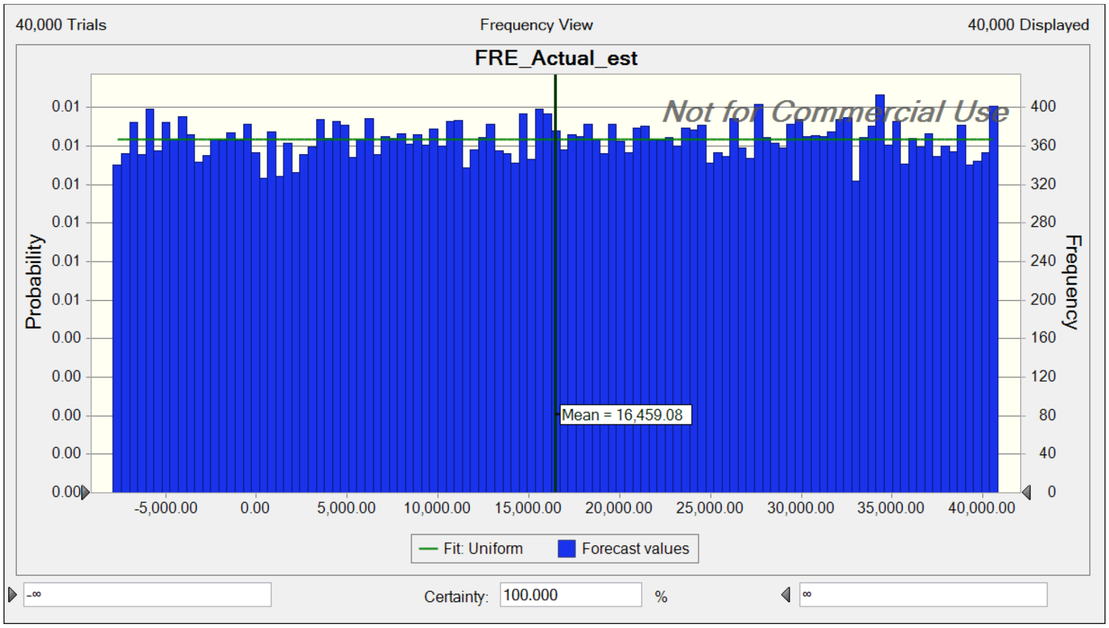

Figure 27. Uniform Distribution for Actual Expended Man-Days Based on FRE

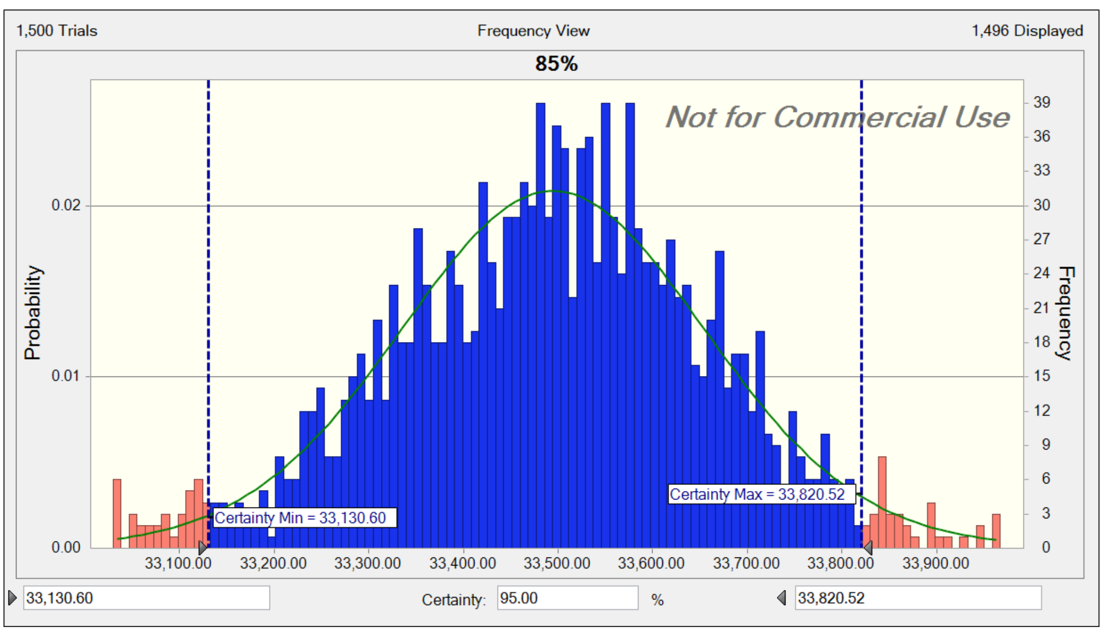

Figure 28. Uniform Distribution for Maximum Expended Man-Days Actual Based on FRE confidence interval

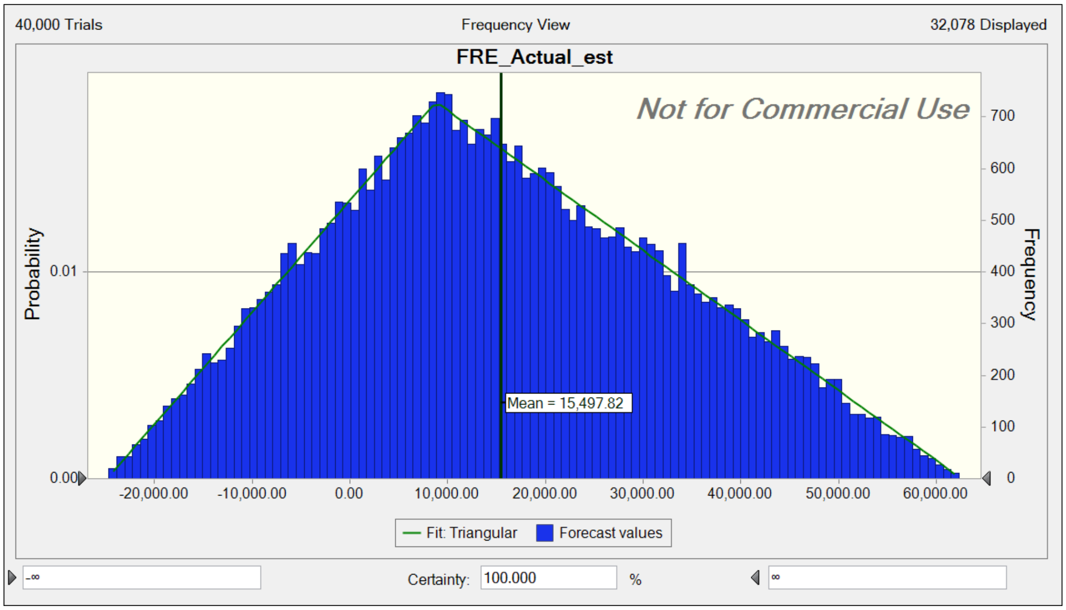

Figure 29. Triangular Distribution for Actual Expended Man-Days Based on FRE

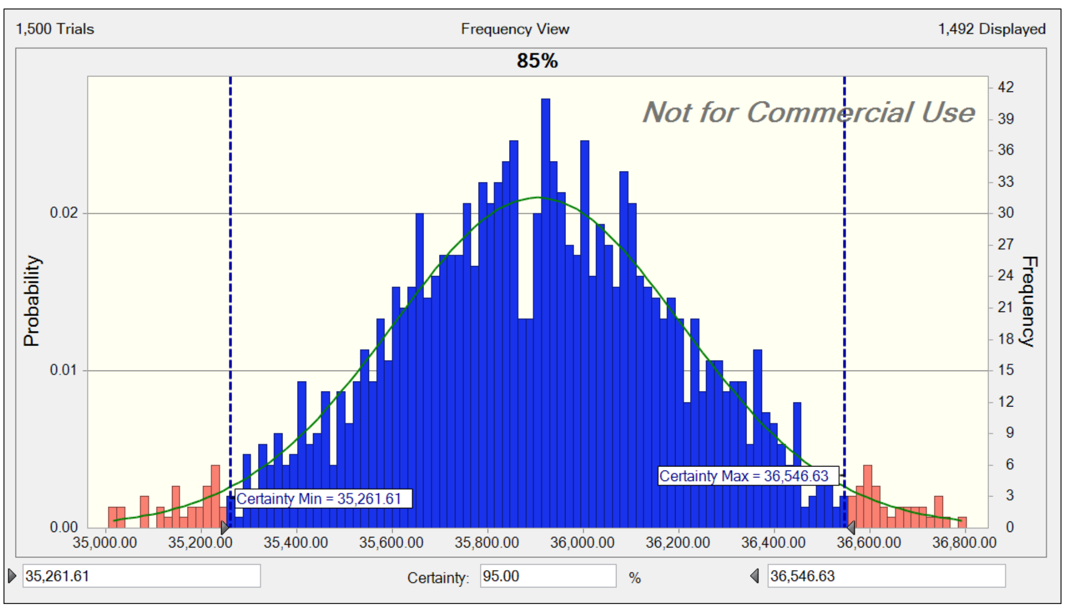

Figure 30. Triangular Distribution for Maximum Expended Man-Days Actual Based on FRE Confidence Interval

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VIII. CONCLUSION

A. FINDINGS

(1) Applying a correction factor for the age of hull at start of DSRA does not account for growth in expended labor

In reference to Research Question 1, after applying a simple correction factor to the expended labor of the nine DSRAs in our data set, we still observed a significant increase in man-days. This indicates that while it is expected for the hull age (and all components therein) to affect the amount of work necessary to maintain the condition-based maintenance standard, our correction could not account for the increase in expended labor. Thus, the increase exists within the maintenance conducted.

(2) 100 Series of maintenance demonstrates consistent growth in expended labor

In reference to Research Question 2, as Whitney (2018) identified, the 100 Series of maintenance demonstrates clear and consistent growth over the DSRAs analyzed.

(3) SWABs 131 and 132 contributed significantly to the growth of the expended labor in the 100 Series

Within the 100 Series of maintenance, the two largest and most significant contributors to the growth in expended labor were the 131 and 132 SWABs. These are the Pressure and Non-Pressure Hull groups of maintenance. Specifically, the maintenance actions within these SWABs which demonstrate the largest and most consistent growth is Inspection and Surveys of major items. These items answer Research Questions 3 and 4.

(4) New Work is relatively constant and is not a major contributor to expended labor growth

Our results indicate that the answer to Research Question 5 is not readily apparent in this data set. While a growth in New Work did occur, it was not consistent across DSRAs, and as it comprised of only 9% of the total work within the 100 Series, this relatively low amount of New Work compared to the significant growth of total work leads us to conclude that while New Work growth is occurring, it should not be a focus area for further research or examination by SUBMEPP or COMSUBPAC.

(5) New Work is related to longer duration

Per Research Question 5, we were interested in knowing if 100 Series New Work was related to the overall duration of the DSRAs. Essentially, if there was more New Work in a DSRA, was the duration of that DSRA longer? Our analysis demonstrates that there is a positive correlation between an increase in New Work and a longer duration. This could be caused by many factors, but it logically follows that if you do not desire to extend the duration of a DSRA, you should seek to add less New Work. Though New Work does contribute significantly to the overall man-days expended in a given DSRA, its effect on duration does seem to be significant. This may be related to the shortened planning timeline which exists after CA3, but before the start of the availability.

(6) Cost variance does not trend as expected

Similar to Wheeler's 2019 analysis of cost variance within the 500 Series, we observed that CV does not tend towards zero as would be expected for a learning organization such as PHNSY. In fact, it trends negatively, which is indicative of further issues in either estimation or work practices.

(7) Improved man-day estimates are required by the Shipyard as well as naval organizations

During the effort to address Research Question 6, the predictive models generated indicated that the estimates conducted at CA2, CA3 and the FRE are not representative of the final expended man-days for these DSRAs. The FRE to Actual Man-days expended model demonstrated that the estimates conducted by the shipyard require improvement to lower the variability between the estimate and actual. Conversely, this also supports the other findings in this thesis, that the shipyard is unable to meet their estimates and needs to perform maintenance more efficiently in order to meet these goals.

The FRE to Actual model supports currently adding 19,536 man-days to the FRE to achieve an 85% probability the actual will end up less than that value. Therefore, 15%

of the time, the DSRA's expended man-days may be greater than the model predicts. This could be significant for shipyard and COMSUBPAC planners in order to have a better estimation of actual man-days expended greater than 6 months in advance of completion of the project.

The CA2 to CA3 model improves upon the current model used by SUPMEPP in which only historical differences are used to calculate the expected increase to CA2. This model, though only based on nine DSRAs provides an indication that if planners add 8,517 man-days to the CA2 estimate, there is an 85% probability that the CA3 estimate will be less than that value.

B. SUMMARY

To summarize, our research set to answer six questions. Listed below are those questions and answers:

(1) Does controlling for hull age help explain the identified increase in expended man-days over the studied DSRAs?

No. There is consistent and significant growth in expended labor which is unexplained by applying a simple hull-age correction factor.

(2) Within the identified increase of expended man-days across the DSRAs, what is the contribution of the maintenance included in the 100 Series?

Maintenance within the 100 Series accounts for significant and consistent growth which, in conjunction with the 500 Series accounts for the large majority of increase in expended labor over time.

(3) Which Ship Work Authorization Boundary's (SWABs) within the 100 Series show the largest growth over time?

SWABs 131 (Pressure Hull) and 132 (Non-Pressure Hull) demonstrated the largest growth over time.

(4) Within the growing SWABs, which Ship Work List Item Numbers (SWLINs) and subset maintenance groups and components are contributing most to the growth of the 100 Series?

Within both SWABs 131 and 132, the largest contributor to growth across the DSRAs was Group 27 (Inspection and Surveys).

(5) Does categorized "New Work" demonstrate a relationship with DSRA duration and is it significant to expended labor?

Categorized "New Work" does demonstrate a relationship to duration of a DSRA. When a DSRA has more New Work, it tends to last longer in duration. New Work over time does not demonstrate a similar magnitude in growth as baseline or overall expended labor.

(6) Can a model be developed to better estimate the maximum expended man-days for CA3 and a completed DSRA?

Yes. A simple probabilistic model was developed using a Monte Carlo simulation that estimates maximum man-days expended based on the FRE as well as the number of man-days CA3 will indicate based on CA2. This technique can assist planners in defining the upper bound of a DSRA costs and thus allow better financial planning.

C. FUTURE STUDIES

(1) Identify and analyze SWABs and GCMA line items on the critical path

With the information provided in this thesis as well as previous work, analyze shipyard schedules prior to the start of the DSRA, identify critical path work or near critical path work and determine if work with significant delays identified within the 100 and 500 Series affects the critical path work and thus duration of the availability

(2) Analyze performance of DSRAs across other shipyards

Analyzing the 500 Series and 100 Series for completed DSRAs across other shipyards and comparing the performance trends between shipyards will indicate further if PHNSY has yard-specific problems it needs to address. Our current analysis gives no indication if this inflation of baseline work and new work for the 100 Series is also true in other shipyards that conduct similar maintenance. Looking at DSRAs during a similar time period may provide leaders a better indication of performance for PHNSY.

D. RECOMMENDATIONS

(1) Evaluate planning and labor estimation processes at PHNSY

Previous research (Whitney [2018], Isley et al. [2018], Wheeler [2019]) as well as our own, has determined that significant and consistent growth in expended labor occurred over the nine DSRAs analyzed. Along with the growth in expended labor, the duration, on the aggregate, also increased. While we have been able to identify specific maintenance items which have contributed, we cannot tie delays and growth in maintenance to the increase in duration, due to lack of critical path project planning data. Thus, in an attempt to improve and optimize performance of the PHNSY, we would recommend an in-depth review of maintenance planning and scheduling practices by an external organization which specializes in such activities.

(2) Utilize probabilistic modeling for cost estimation and schedule risk

Current methods employed by SUBMEPP to develop Corporate Cost Assessments rely on averages of historical differences observed between previous projects' CA2 and CA3. This results in underestimation of expended man-days and thus increases risk to the overall project. A probabilistic model using Monte Carlo simulation allows planners to better estimate CA2 as well as Actual Final expended man-days, as described in our thesis.

(3) Report on the continuous availability work package feedback loop

SUBMEPP incrementally updates the notional Availability Work Package (AWP) for specific classes of submarines based on the time-in-life maintenance overhaul which will be performed. These updates are based on observed trends and tendencies for specific maintenance actions which are becoming more (or less) frequent, or requiring more (or less) labor to perform, fleet-wide. However, as identified first by Wheeler (2019) and confirmed by our thesis, if the feedback loop were being utilized effectively, the amount of "New Work" or "Growth Work" should be decreasing as baseline is increased. This would be most clearly shown in the Cost Variance analysis, with a more accurate BQWS leading to a zero or positive Cost Variance over time. However, this has not been observed, and in fact the opposite is occurring. Therefore, the feedback loop must be analyzed for effectiveness.

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