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OPTIMIZATION OF SHIPBOARD MANNING LEVELS USING

IMPRINT PRO FORCES MODULE

by

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14. ABSTRACT
The Improved Performance Research Integration Tool (IMPRINT) is a dynamic, stochastic, discrete-event modeling tool used to develop a model of the system of interest. In this project, we used the IMPRINT Pro Forces Module to build models of the crew of the Littoral Combat Ship (LCS). The basic concept underlying the development of a model using the Forces module is that crewmembers spend all of their time in some sort of "planned" activities/events. In the context of the model, this term refers to activities typically occurring in the ship's daily schedule (e.g., specified times for meals, personal time, watch standing [for crewmembers who stand watch], training, preventive maintenance, sleep, etc.). These planned activities, however, are interrupted or "augmented" by unforeseen emergencies and events (i.e., unplanned activities to which the crew must respond and resolve) such as flooding, collision, equipment casualties, etc. Phase 1 of this effort was focused on model development for naval applications—specifically, to validate the use of IMPRINT Pro Forces model simulations for the LCS manpower requirements (Hollins & Leszczynski, 2014). This phase included two tasks. First, to develop the design concept of a model describing the manpower requirements of LCS-1 Freedom. Second, to develop the appropriate manning models in IMPRINT. Phase 1 successfully showed that IMPRINT Pro Forces could be used to estimate manning levels with regard to the distribution of crew rates and required qualifications (Navy Enlisted Classifications [NECs]) for the LCS 1 mission requirements through simulations of planned and unplanned events, based on actual data collected from the LCS crew. Building upon that work, Phase 2 further investigated the usefulness of Forces model simulations by focusing on determining which individual crewmembers should maintain particular qualifications (Albrecht, Fitzsimmons, Chambers, & Schultz, 2014). This study looked at one set of crewmembers, based on the current Preliminary Ship Manning Document (PSMD) with regard to crew rates, as well as required qualifications (or NECs), to determine the effects of normal underway operations—as well as unplanned events—on the fatigue levels of a typical LCS crew. The model predicts that, at current manning levels, certain critical rates (particularly engineers and combat systems sailors) consistently get the least amount of sleep, accomplish the most amount of work, and respond to more unplanned events. Phase 3 recommendations for future work are described for the upcoming fiscal year.

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ABSTRACT

The Improved Performance Research Integration Tool (IMPRINT) is a dynamic, stochastic, discrete-event modeling tool used to develop a model of the system of interest. In this project, we used the IMPRINT Pro Forces Module to build models of the crew of the Littoral Combat Ship (LCS). The basic concept underlying the development of a model using the Forces module is that crewmembers spend all of their time in some sort of "planned" activities/events. In the context of the model, this term refers to activities typically occurring in the ship's daily schedule (e.g., specified times for meals, personal time, watch standing [for crewmembers who stand watch], training, preventive maintenance, sleep, etc.). These planned activities, however, are interrupted or "augmented" by unforeseen emergencies and events (i.e., unplanned activities to which the crew must respond and resolve) such as flooding, collision, equipment casualties, etc. Phase 1 of this effort was focused on model development for naval applications—specifically, to validate the use of IMPRINT Pro Forces model simulations for the LCS manpower requirements (Hollins & Leszczynski, 2014). This phase included two tasks. First, to develop the design concept of a model describing the manpower requirements of LCS-1 Freedom. Second, to develop the appropriate manning models in IMPRINT. Phase 1 successfully showed that IMPRINT Pro Forces could be used to estimate manning levels with regard to the distribution of crew rates and required qualifications (Navy Enlisted Classifications [NECs]) for the LCS 1 mission requirements through simulations of planned and unplanned events, based on actual data collected from the LCS crew. Building upon that work, Phase 2 further investigated the usefulness of Forces model simulations by focusing on determining which individual crewmembers should maintain particular qualifications (Albrecht et al., 2014). This study looked at one set of crewmembers, based on the current Preliminary Ship Manning Document (PSMD) with regard to crew rates, as well as required qualifications (or NECs), to determine the effects of normal underway operations—as well as unplanned events—on the fatigue levels of a typical LCS crew. The model predicts that, at current manning levels, certain critical rates (particularly engineers and combat systems sailors) consistently get the least amount of

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I. INTRODUCTION

In the presence of changing geo-political climates, rapidly evolving technologies, and operational uncertainty, designing future naval ships presents a major challenge to the United States Navy. In addition, there is mounting pressure to reduce manning, accompanied by demands for increased range of missions. According to the General Accounting Office, a ship's crew is considered the single largest cost that is incurred over the ship's life cycle (United States General Accounting Office, 2003). Approximately 30% of the total ownership cost of a ship can be attributed to personnel (Spindel et al., 2000). Given the weight of manning levels on total ownership cost, it is no surprise that "optimization" of manning levels is a method of choice for reducing crew size. The latter method is clearly emphasized in the General Accounting Office (2003) report, noting that "one way to lower personnel costs, and thus the cost of ownership, is to use people only when it is cost-effective" (United States General Accounting Office, 2003, p. 1). The Naval Research Advisory Committee (NRAC), an independent civilian scientific advisory group dedicated to providing objective analyses to the Navy management, recommended that optimal human/system performance should be achieved using as few sailors as possible (Spindel et al., 2000). The challenge, however, is to optimize manning levels without degrading operational effectiveness below the minimum acceptable level.

Over the last two decades, the United States Navy has launched multiple surface combatant acquisition programs including the Arleigh Burke destroyer (DDG-51), the DD(X) destroyer, the Littoral Combat Ship (LCS), and the CG(X) cruiser. Projected manning of most of these platforms was based on crew sizes significantly reduced when compared to legacy and current ship designs. Under the optimal manning initiative, the Navy reduced the enlisted requirements and size of crews for some types of ships. The goals of optimal manning were to be achieved by implementing advanced technology, automation, and training. For example, from fiscal years 2001 through 2009, enlisted requirements declined by about 20% and crew sizes declined by about 16% on cruisers and destroyers (United States Government Accountability Office, 2010). As innovative as it seemed, the optimal manning concept reduced the size of crews too much, leading to unforeseen issues such as increased workload, failed periodic readiness inspections, and decreased maintenance capability; consequently, Navy leadership reevaluated optimal manning as a policy. As noted by Undersecretary of the Navy Robert Work, "We have concluded [optimal manning] went too far . . . . The material condition of the fleet we believe suffered because of it" (Fuentes, 2011).

In the case of the LCS, the initial aim was to achieve a core crew of only 40 sailors. Following initial underway tests and evaluations, this number appears inadequate. Consequently, the Navy decided to increase the core crew size (i.e., the sea frame crew) on the LCS to around 50 personnel. This results in a total crew (core crew and sailors to operate the ship's embarked aircraft) of about 88 sailors for a baseline LCS equipped with an Mine Countermeasures (MCM) mission package, compared to more than 200 Sailors for the Navy's frigates and about 300 (or more) for the Navy's current cruisers and destroyers (O'Rourke, 2015). But the question still remains: what is the correct crew size for future ships and how can that number be determined before a ship design is too far along in the acquisition process?

A. BACKGROUND

Naval Operations (OPNAV) Instruction 1000.16K (Department of the Navy, 2007) describes the processes for ship manpower determination and specifies that personnel levels must be adequate to perform the Navy's work and to carry out specific missions. To determine the manpower requirements, the Naval Manpower Analysis Center (NAVMAC) uses a multiphase process (United States Government Accountability Office, 2010), based on the Navy Standard Workweek (NSWW) model, to calculate the minimum number of personnel required to man a ship. The NSWW represents a standardized version of one week of work performed by a single enlisted Sailor while at sea and is used to calculate manning levels, which are a theoretical reflection of the minimum manpower resources necessary to accomplish the ship's mission. The workweek for sea duty is a guideline for sustained personnel utilization, based on the operational requirements under projected wartime conditions, with units in Condition III steaming, as described in OPNAV Instruction 1000.16K, page C-1 (Department of the Navy, 2007).

The NSWW provides guidelines for the time available per person to accomplish the required workload, including watches expressed in average hours per week. The week is divided into two categories: On Duty (or Available) time (81 hours) and Nonavailable time (87 hours). On Duty time refers to the time periods where personnel are occupied by their required duties: notionally, that amounts to watchstanding (56 hours), work (14 hours), training (7 hours), and service diversion (4 hours). Training contributes to combat readiness and includes activities such as general drills and engineering casualty damage control. Service diversion includes quarters, inspections, sick call, and administrative requirements. Productive Work time (70 hours) includes watchstanding and work. Nonavailable time is comprised of all personal time that is allotted to sleep (56 hours), messing (14 hours), personal needs (14 hours), and free time (3 hours).

Useful as it may be, the NSWW method for establishing manning has its limitations. As previously described, some of these limitations are associated with the assumptions of the model about the activities/duties of the crewmembers (United States Government Accountability Office, 2010). The results from multiple studies conducted at the Naval Postgraduate School have shown that crewmembers work longer hours and sleep less than what is allocated in the NSWW model, suffering from significant sleep deprivation (Green, 2009; Haynes, 2007; Mason, 2009; Shattuck & Matsangas, 2014; Shattuck, Matsangas, & Brown, 2015; Shattuck, Matsangas, & Powley, 2015). Specifically, Haynes (2007) found that crewmembers worked, on average, 14 hours per day, with 85% of them exceeding the 81 hours allotted by the NSWW; whereas Green (2009) found that sailors worked 12.5 hours per day, with 61% of her participants exceeding the work hours specified in the NSWW model. Both Haynes and Green suggested that the NSWW model should be revised to include adequate time for rest, part of which is the actual time set aside for sleep (Shattuck & Matsangas, 2014). Rest involves more than just the time dedicated for sleep, since it takes some time to decompress, fall asleep, and awaken. The International Maritime Organization (IMO) has proposed a minimum of 10 hours of rest during any 24-hour period and 77 hours of rest for any 7-day period (International Maritime Organization, 2010).

The NSWW model, however, has other basic constraints. First, the model assumes a fixed weekly amount of time for each of the activities in which a crewmember is involved. Second, the model is "amnesic" because it does not incorporate the dimension of time as a critical component of the daily activities. For example, when an activity is interrupted by a critical event (e.g., scheduled maintenance interrupted by general quarters), the time lost from the interrupted activity is not carried over to the next day as a need for spending more time in that activity. Hence, it cannot address the "avalanche" effect characterizing everyday activities. Even if interrupted, maintenance tasks will need to be completed at a later time. Interrupted sleep will take its toll as an increase in sleep need or cumulative sleep debt. Meals can be missed, but not forever. These examples show that the priority and time allocated to daily activities is dynamic and far from being fixed: the current state depends on prior state. Furthermore, the NSWW model can address activities only as scheduled events; over the course of a week, there are specific activities, each one allocated for a fixed duration of time. Hence, the NSWW cannot address the impact of unscheduled events like sick or injured crewmembers, catastrophic events, etc. In essence, the NSWW is a static and deterministic model.

B. PROBLEM STATEMENT

This effort explored the current manning levels onboard the LCS. The LCS platform was designed with smart ship systems, improved technology, and an innovative look at workload distribution across the naval workforce. The ship design applied reduced manning models, relying heavily on contracted and shipyard labor for both extensive planned and corrective maintenance. Unfortunately, inadequacies in the manning models may compromise the operational envelope of ship systems, exacerbate existing operational problems, and degrade the ability to react to unexpected events. This may result in reduced mission capability and degraded combat effectiveness.

The current modeling effort is based on the notion that manpower requirements are an important determinant of maintenance, crew performance, morale, readiness, and, ultimately, the ability of the ship as a system to accomplish her mission. In order to understand the impact of manning decisions, we need to develop models that are better equipped to capture the characteristics of actual shipboard operations. The goal of the current study is to provide an optimized assessment of the effect of manning on operational performance.

C. APPROACH

This project is a multiphase, multiyear effort that seeks to validate the LCS IMPRINT Pro Forces manning model, increase the utility of the model, and potentially extend its use to other maritime platforms.

Phase 1 (2013 – 2014): Phase one of this effort was focused on developing manning models for naval applications. Specifically, using IMPRINT Pro Forces software, we developed a model of planned activities and unplanned events on the LCS. These results are reported in a joint Master's thesis by Hollins and Lezczynski (2014), which can be downloaded at http://calhoun.nps.edu/handle/10945/41620.

Phase 2 (2014 – 2015): Phase two of this effort involved further development and a proof of concept of the IMPRINT Pro Forces software program.

This report includes the following Appendices, which represent the results of the two completed phases.

- Appendix A: Project presentation.
- Appendix B: Project report – Appropriate manning for the U.S. Navy Littoral Combat Ships (LCS) – A few good people
- Appendix C: Project report by Robison, Smith, Stone, and White (2015).
- Appendix C: Project report – Air warfare conducted from a Virginia-class submarine platform – A human factors analysis using IMPRINT software
- This work investigates the manning requirements necessary to add the air warfare mission area to a VIRGINIA-class submarine. Although this work is not focused on the LCS, it is based on the IMPRINT Pro Forces module and builds on the model developed for the LCS.
- Appendix D: Presentation of the study conducted by Robison et al. (2015).

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II. METHODS

A. GENERAL

For a detailed description of the methods involved in each of the study products, refer to the corresponding publications. This section will focus on the Improved Performance Research Integration Tool (IMPRINT), the NSWW model, and the general concept underlying the development of the proposed model.

B. MODELING WITH IMPRINT PRO FORCES MODULE

IMPRINT has been under development by the U.S. Army Human Research and Development Command for over a decade (United States Army Research Laboratory, 2010) and can be described as a dynamic, stochastic, discrete-event modeling tool. Hence, IMPRINT *per se* is not a model, but instead, is a tool used to develop a model of the system of interest. IMPRINT Pro integrates four software modules that can be used together or as stand-alone packages. IMPRINT Pro provides the means for estimating manpower, personnel, and training (MPT) requirements. This software tool has the capability to assist in identifying manpower constraints in a system by assessing manpower requirements or the limitations of available manpower early in the system's acquisition process (Hollins & Leszczynski, 2014).

C. NAVY STANDARD WORKWEEK (NSWW) MODEL

The NSWW model is described in Naval Operations (OPNAV) Instruction 1000.16K (Department of the Navy, 2007). The NSWW provides guidelines for the time available per person to accomplish the required workload, including watches expressed in average hours per week. Although not prescriptive, the instruction notes that extending work hours on a routine basis could adversely affect morale, retention, safety, etc., and, as a policy, habitually extending work hours should be avoided (Department of the Navy, 2007).

A number of studies conducted at the Naval Postgraduate School has shown that sailors at sea work long workdays. Mason (2009) found that Senior Chief Petty Officers and Chief Petty Officers averaged 6.26 hours of sleep, while senior officers (Lieutenant

Commanders and above) slept approximately 6.4 hours per day. Another study showed that crewmembers of the Operations Department of an Arleigh Burke class destroyer working on the 6hrs-on/6hrs-off watchstanding schedule have considerably long workdays (on average, 15 hours on duty), which corresponds to approximately 30% more time on duty than the NSWW criterion (105 hours compared to 81 on a weekly basis) (Shattuck & Matsangas, 2014). Results from a study conducted on USS Nimitz showed that 15% of the Reactor Department crewmembers working on the 5hrs-on/10hrs-off schedule worked, on average, 14 hours or more per day (Shattuck, Matsangas, & Brown, 2015; Shattuck, Matsangas, & Powley, 2015).

D. BASIC CONCEPT

Throughout this project, the IMPRINT Pro Forces Module was used to build models of the crew of the LCS. The basic concept underlying the development of the IMPRINT Pro Forces model is that crewmembers spend all of their time in some sort of "planned" activities/events. In the context of the model, this term refers to activities typically occurring in the ship's daily schedule (e.g., there are specified times for meals, personal time, watch standing [for crewmembers who stand watch], training, preventive maintenance, sleep, etc.). These activities are assumed to occur in the typical daily schedule. These planned activities, however, are interrupted or "augmented" by unforeseen emergencies and events (i.e., unplanned activities to which the crew must respond and resolve) such as flooding, collision, equipment casualties leading to the need of maintenance, etc.

III. PHASE 1 (2013 – 2014)

Phase 1 of this effort was focused on model development for naval applications, specifically to validate the use of IMPRINT Pro Forces model simulations for the LCS manpower requirements. This phase included two tasks. The first task was to develop the design concept of a model describing the manpower requirements of LCS-1 Freedom. The second task was to develop the appropriate manning models in IMPRINT. These tasks are described in the thesis by Hollins and Leszczynski (2014).

Input data were derived from data cards collected by the Center for Naval Analysis during an underway with LCS 1 Freedom in Fall 2013 and from information shared by the LCS Program Office, San Diego, California. Hollins and Leszczynski (2014) approached the problem of estimating the capability of LCS core crew sizes to respond to daily planned activities and unplanned events during a typical underway period. Using IMPRINT Pro Forces software, three different LCS core crew sizes were modeled (40, 50, 60 corresponding to enlisted crew size of 31, 40, and 48) to assess how each was able to handle day-to-day operations, maintenance, and emergencies during a (notional) operational underway. The results showed measurable and significant differences in performance among the three core crew sizes as assessed by analysis of variance (ANOVA) and Tukey tests. As crew sizes are reduced, individual performance becomes increasingly important.

Multiple watch schedules were modeled using the Fatigue Avoidance Scheduling (FAST) software tool, which uses the SAFTE model to predict individual cognitive effectiveness levels using simulated work and sleep schedules. A survey was also administered to the crewmembers of the USS Independence (LCS 2) to assess the crew's perception of the adequacy of current manning concepts and to further validate the IMPRINT model outputs. During the Phase 1 effort, researchers at the Naval Postgraduate School collaborated with Alion, the contracting agent for IMPRINT, to debug the software, which was still in the Beta Test Phase. Furthermore, the FAST predicted effectiveness suggested that individual performance is significantly affected by the watch rotation a sailor stands.

These efforts showed that IMPRINT Pro Forces module can be used to effectively model the LCS crew and to identify the extent to which the crew can effectively operate the LCS. Given the constraints of the models, the simulation results were not surprising. Comparisons between the models showed that the ability of the crew the respond to unplanned events and failures deteriorated at a statistically significant level as the crew size decreased. In other words, the IMPRINT Pro Forces models showed that as the size of the core crew increased, system performance improved (as evidenced by decreasing failure rates with increasing crew size) (Hollins & Leszczynski, 2014). The enlisted core crew of 40 consistently outperformed the enlisted core crew of 31, and the enlisted core crew of 48 significantly outperformed both 31 and 40. Table 1 shows the detailed results of the comparisons between the three different crew sizes for each of the unplanned events. For example, results showed that an increase of the crew from 31 to 40 enlisted members does not have a significant effect on the ability to respond to weapon system misfire events, main propulsion diesel engines (MPDE) casualty, and ship service diesel generators (SSDG) casualty.

Table 1. Effect of increasing the crew in their ability to respond to unplanned events; adapted from (Hollins & Leszczynski, 2014).

Event	**Does the increase in crew size make a difference in the ability of the crew to respond?**		
	31 vs. 40 enlisted crewmembers	**40 vs. 48 enlisted crewmembers**	**31 vs. 48 enlisted crewmembers**
LINK-16/NAVY RED issues	Yes	No	Yes
Weapon system misfire	No	Yes	Yes
Network issues	Yes	No	Yes
RO issues	Yes	No	Yes
MPDE casualty	No	Yes	Yes
SSDG casualty	No	Yes	Yes
VCHT issues	Yes	No	Yes
WSN-7 failure	Yes	No	Yes

The IMPRINT model predictions were further supported by the survey administered to the LCS-2 crew. The survey responses clearly emphasized the need for additional crewmembers in the Engineering Department. Aligned with these responses, the IMPRINT results for the enlisted core crew of 31 (40 core crew) showed that the Engineering Department had the highest equipment failures due to a manning deficiency

(Hollins & Leszczynski, 2014). Notably, the comparisons between the three manning models showed significant performance improvement when changing from a core crew of 31 to a core crew of 40, and a profound improvement with a core crew of 48. These results are congruent with the U.S. Navy's decision to increase the number of crewmembers on the LCS to about 50 (O'Rourke, 2015). As important as they may be, however, the results of this effort are not conclusive and cannot be used for manning decisions. These models need further work in terms of refinement of the baseline settings, validating of the underlying model assumptions, etc.

Overall, the results of this phase showed that, even though focused on the crew of the LCS, the modeling approach and analytical process can be expanded and applied to a wide range of ships and departments. More importantly, though, this phase showed that using a model developed using the IMPRINT Pro Forces module can help inform leaders of appropriate crew sizes by preventing crew size overestimation or underestimation. It can also shorten, or even prevent, misalignment of scarce human resources and/or crew fatigue, and improve the precision of manpower requirements determinations for new acquisitions and existing platforms (Hollins & Leszczynski, 2014). For detailed information regarding the work done in Phase 1 refer to the thesis by Hollins and Leszczynski (2014).

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IV. PHASE 2 (2014 – 2015)

Phase 1 successfully showed that IMPRINT Pro Forces could be used to estimate manning levels with regard to the distribution of crew rates and required qualifications (Navy Enlisted Classifications – NECs) for the LCS-1 mission requirements through simulations of planned and unplanned events, based on actual data collected from the LCS crew (Hollins & Leszczynski, 2014).

Building on that work, Phase 2 involved further development and a proof of concept of the IMPRINT Pro Forces software program. Specifically, the second phase continued the investigation into the usefulness of IMPRINT Pro Forces model simulations, focusing on determining which individual crewmembers should maintain particular qualifications (Albrecht et al., 2014). As a manning constraint, the revised model assumed that the total number of enlisted crewmembers onboard was approximately 45; officers were not modeled. This study looked at one set of crewmembers, based on the current Preliminary Ship Manning Document (PSMD) with regard to crew rates, as well as required qualifications (or NECs) to determine the effects of normal underway operations—as well as unplanned events—on the fatigue levels of a typical LCS crew.

Results showed that at current manning levels, the model predicts that certain critical rates (particularly engineers and combat systems sailors) consistently get the least amount of sleep, accomplish the most amount of work, and respond to more casualties (Albrecht et al., 2014). Specifically, simulation results showed that the crew works, on average, 11.9 hours ± 1.18 hours, ranging from 10.7 to 13.5 hours, whereas in the model with casualties, the crew spends, on average, 12.0 hours ± 1.22 hours, ranging from 10.5 to 13.8 hours, working and responding to unplanned events. These results are aligned with actual data collected in various studies on U.S. Navy ships (Shattuck & Matsangas, 2014; Shattuck, Matsangas, & Brown, 2015; Shattuck, Matsangas, & Powley, 2015).

The following diagram shows the daily requirements in man-hours for specific rates (see Figure 1). The SSDG casualty had the highest demand in terms of time; approximately three hours a day.

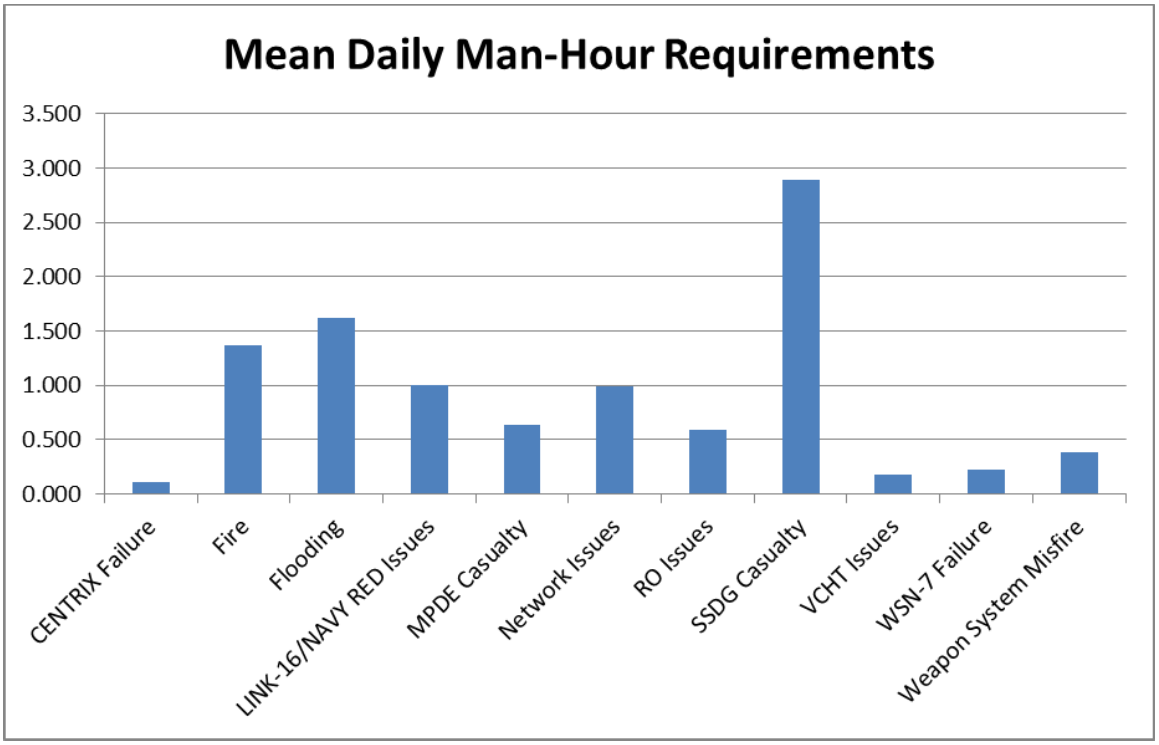

Figure 1. Mean daily demand for unplanned events (in man-hours).

Redundant qualifications or increased manning for engineers and combat systems sailors are predicted to improve combat effectiveness and reduce the potential for mishaps. Having overly-fatigued individuals working on high-demand, critically important tasks can negatively impact overall crew readiness.

Furthermore, this project identified a number of issues regarding the external validity of the model assumptions on its output predictions. First, there was insufficient data available to accurately model the distributions of the unplanned events; consequently, the model was unable to accurately model unplanned events (Albrecht et al., 2014). To the extent possible, future efforts should include a more thorough and exhaustive approach to model unplanned events. This goal will further strengthen the external validity of the model and will provide better insight about the constraints of manning solutions. Second, the model output is affected by the order of events in the trump matrix (i.e., the priorities among activities). Unrealistic priorities (e.g., sleep may be assigned a higher priority than “quarters”) will bias the external validity of the model predictions. The trump matrix must be vetted carefully through the LCS Squadron

(LCSRON) staff and experienced LCS sailors. Overall, the second phase of this project provided interesting insights into the utility of the model; however, it clearly emphasized the sensitivity of the predictions to the assumptions about the characteristics of the activities modeled.

This second phase included one more modeling effort. Although not focused on LCS manning *per se*, it used the IMPRINT Pro Forces module to address manning requirements in naval systems. Specifically, this study investigated the manning requirements necessary to add the air warfare mission area to a VIRGINIA-class submarine (Robison et al., 2015). The study was constrained to investigate only two enlisted submarine rates in normal, underway-manning conditions. The initial hypothesis was that the current manning does not permit the reserve capacity to accept the additional workload. Therefore, there would be a need to add additional personnel to the submarine to manage the increased workload.

This hypothesis was proven correct. Simulation results showed that four additional personnel, two from each enlisted rate studied, would be needed when a High Energy Laser weapon system suite is integrated into a VIRGINIA-class submarine platform. The additional personnel that were determined to be necessary would cost the VIRGINIA-class submarine program approximately $500 million in pay alone.

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V. RECOMMENDATIONS AND FUTURE DEVELOPMENTS

The first two phases provided valuable results that can be used for Phase 3 of this project in the 2015-2016 time frame. Phase 3 of this effort will focus on further model development and a systematic reevaluation of the LCS model, its characteristics, and the external validity of the underlying assumption. NPS will continue debugging the software, with the assistance of Alion, in order to increase IMPRINT Pro utility for conducting Monte-Carlo simulations. We will also explore the impact of unscheduled events on specific shipboard departments and rates. The goal of Phase 3 is the verification and validation of the IMPRINT Pro Forces LCS Model (i.e., to further develop the model, to increase the accuracy of the model parameters, and to increase its external validity).

Once these are accomplished, we will be able to extend the model to other ship platforms. In order to extend these efforts, we will need to compare IMPRINT predictions with actual workload data collected from existing platforms. For these tasks, Phase 3 will require additional data collection to measure the workload of an actual LCS crew during various underway evolutions, to include unplanned events. Adjustments will need to be made to the existing models and comparisons made between model predictions and actual crew performance during specified conditions.

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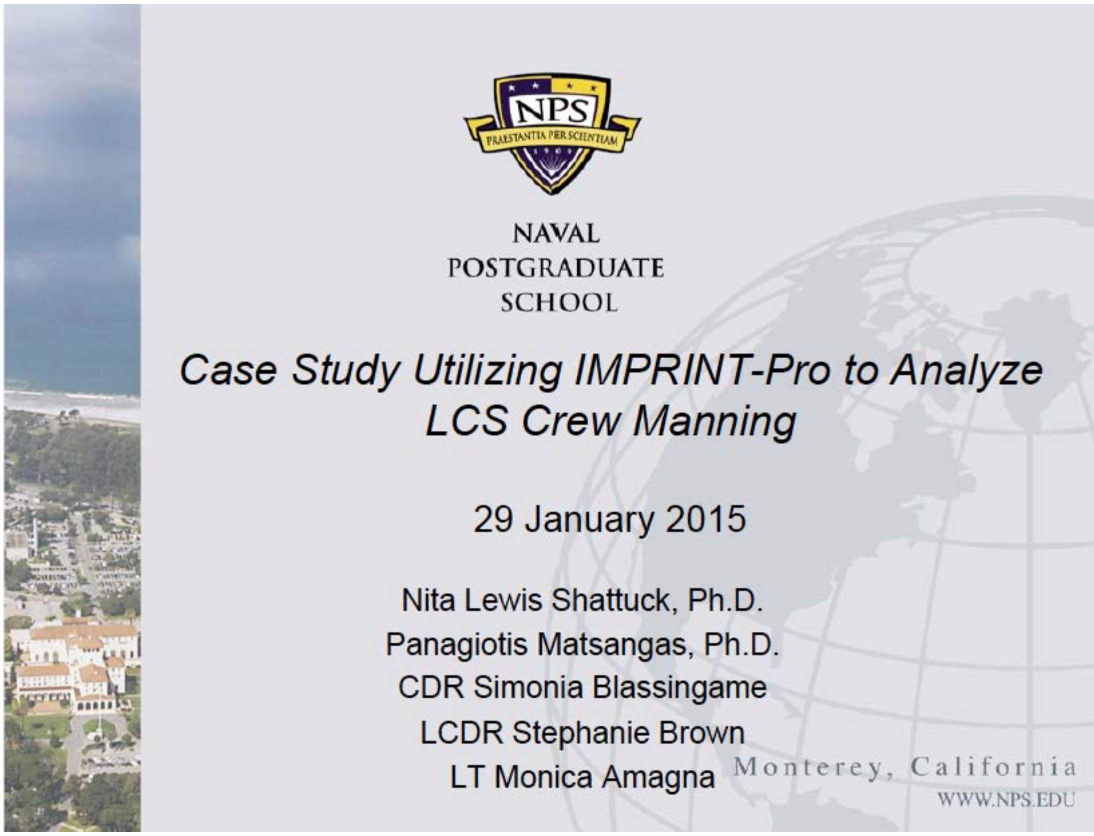
APPENDIX A: PROJECT PRESENTATION



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Overview

Objective
Conduct a case study to validate the use of IMPRINT-Pro Forces model to simulate different crew sizes on LCS and address the question of appropriate crew size.

Overview

- IMPRINT-Pro Background
- NPS Thesis by Hollins/Leszczynski
  - IMPRINT-Pro application to the case study of analyzing LCS Crew Manning
  - IMPRINT-Pro Model approach and input
- Follow-on OR Course Project utilizing IMPRINT-Pro
- IMPRINT-Pro Results of OR Course Project
- Recommendations

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IMPRINT-Pro Background

- IMPRINT-Pro
  - Provides the means for estimating manpower, personnel, and training (MPT) requirements and constraints for new weapon systems very early in the acquisition process.
  - It is a stochastic, discrete event network modeling program used in this case study to assess the current LCS manning doctrine levels using planned and unplanned evolutions.

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IMPRINT-Pro Application to LCS Manning
NPS Thesis

Data Resources

Used "Afloat Workweek" data collected by the Center for Naval Analyses (CNA) during an underway with LCS 1 Freedom and information shared by the LCS Program Office in San Diego.

IMPRINT-Pro Model Approach

– 21 day simulation that captures the "Afloat Workweek"

– Using the "Afloat Workweek" data cards, 3 models were created in IMPRINT-Pro to depict varying LCS crew sizes

- Crew size of 31 (enlisted)
- Crew size of 40 (enlisted)
- Crew size of 48 (enlisted) * larger size done for notional purposes

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IMPRINT-Pro Application to LCS Manning
NPS Thesis Cont'd

IMPRINT-Pro Simulation Inputs*

Planned and Unplanned Activities

- Planned
  - Eat
  - Hygiene
  - Meeting
  - Personal Time
  - Preventative Maintenance
  - Quarters
  - Sleep
  - Sweepers
  - Training
  - Watch
  - Work
- Unplanned
  - CENTRIX Failure
  - Fire
  - Flight Quarters
  - Flooding
  - LINK-16/NAVY RED Issues
  - MOB/SAR Drills
  - MPDE Casualty
  - Network Issues
  - RO Issues
  - SSDG Casualty
  - VCHT Issues
  - Weapon System Misfire
  - WSN-7 Failure

Trump Matrix

Activities

Priority	Name	Type
0	Watch	Planned
1	MOB/SAR Drills	Unplanned
5	Fire	Unplanned
10	Flooding	Unplanned
20	SSDG Casualty	Unplanned
30	MPDE Casualty	Unplanned
60	Flight Quarters	Unplanned
70	RO Issues	Unplanned
80	VCHT Issues	Unplanned
90	WSN-7 Failure	Unplanned
100	LINK-16/NAVY RED Issues	Unplanned
110	Network Issues	Unplanned
120	CENTRIX Failure	Unplanned
130	Weapon System Misfire	Unplanned
190	Preventative Maintenance	Planned
195	Sleep	Planned
200	Eat	Planned
210	Work	Planned
260	Training	Planned
270	Meeting	Planned
275	Sweepers	Planned
281	Personal Time	Planned
300	Quarters	Planned
320	Hygiene	Planned

*This information was vetted with LCS 2 crew JAN 2014

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IMPRINT-Pro Application to LCS Manning NPS Thesis Cont'd

Initial IMPRINT-Pro Results from NPS Thesis

- Initial results obtained using Beta Version of IMPRINT-Pro Forces software
- Concern with the preliminary results due to IMPRINT-Pro software glitches
- Programmers from Alion Science addressed software issues
- Modified the existing IMPRINT-Pro models and ran the model simulations again

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One Step Further

NPS Follow-on Project

- Continued the investigation of the usefulness of IMPRINT Pro Forces model simulations while focusing on answering the question:

  "Which individuals of the crew should maintain particular qualifications given the current manning constraints of approximately 45 total crew onboard?"

- This follow-on study looked at one set of crew members, based on the current PSMD with regards to crew rates as well as required qualifications (NECs), to determine the effects of normal underway operations as well as unplanned events on a standard LCS crew.

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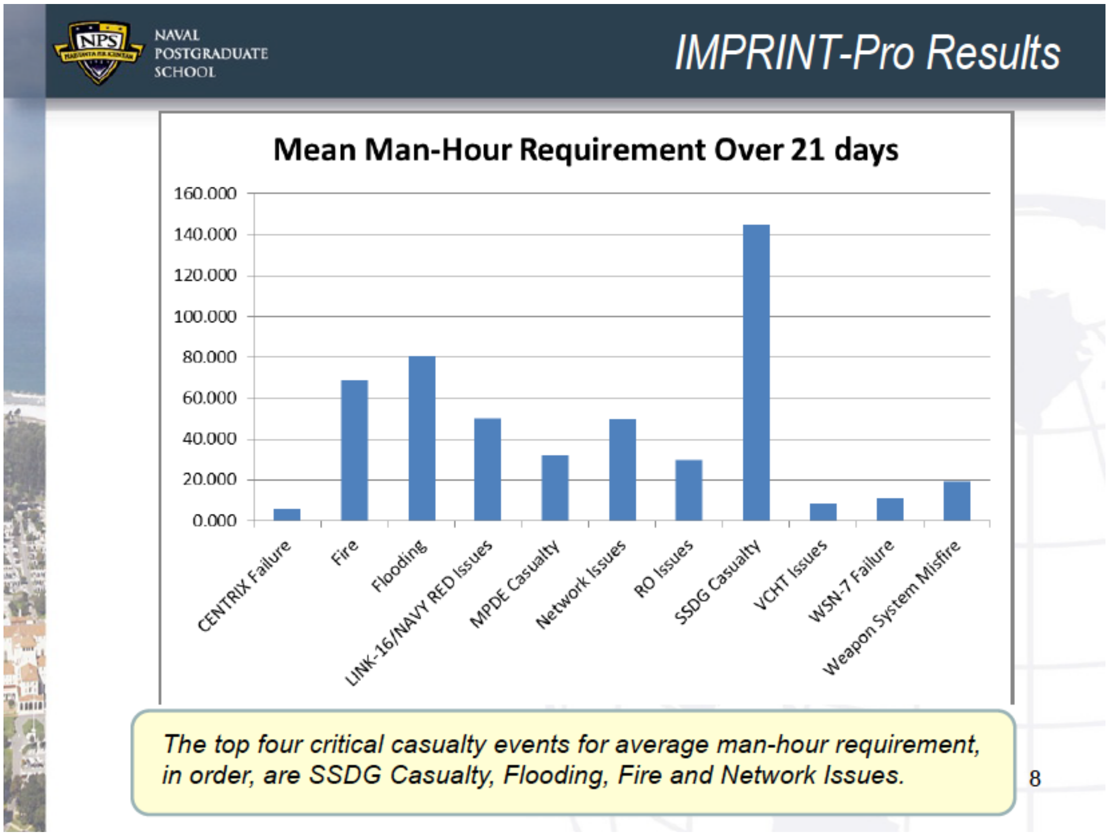
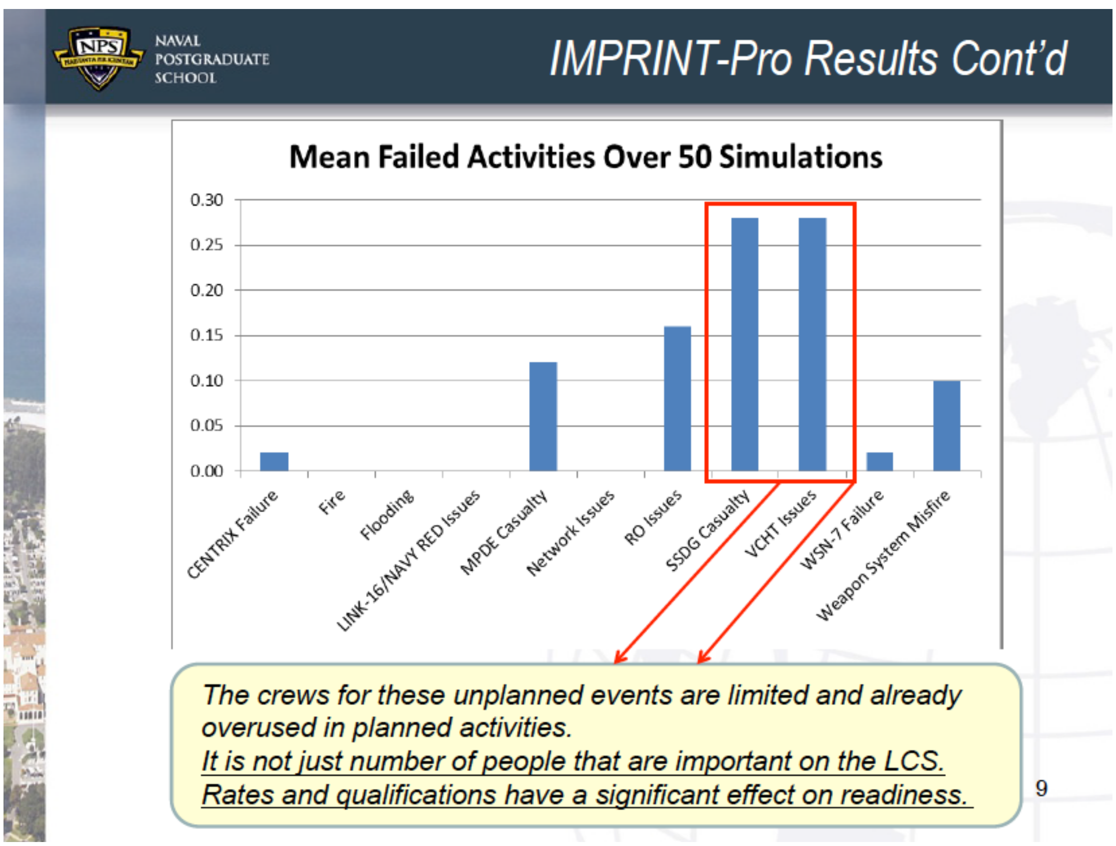

NAVAL
POSTGRADUATE
SCHOOL
IMPRINT-Pro Results
Mean Man-Hour Requirement Over 21 days
160.000
140.000
120.000
100.000
80.000
60.000
40.000
20.000
0.000
CENTRIX Failure
Fire
Flooding
LINK-16/NAVY RED Issues
MPDE Casualty
Network Issues
RO Issues
SSDG Casualty
VCHT Issues
WSN-7 Failure
Weapon System Misfire
The top four critical casualty events for average man-hour requirement, in order, are SSDG Casualty, Flooding, Fire and Network Issues.
8


NAVAL
POSTGRADUATE
SCHOOL
IMPRINT-Pro Results Cont'd
Mean Failed Activities Over 50 Simulations
0.30
0.25
0.20
0.15
0.10
0.05
0.00
CENTRIX Failure
Fire
Flooding
LINK-16/NAVY RED Issues
MPDE Casualty
Network Issues
RO Issues
SSDG Casualty
VCHT Issues
WSN-7 Failure
Weapon System Misfire
The crews for these unplanned events are limited and already overused in planned activities.
It is not just number of people that are important on the LCS.
Rates and qualifications have a significant effect on readiness.
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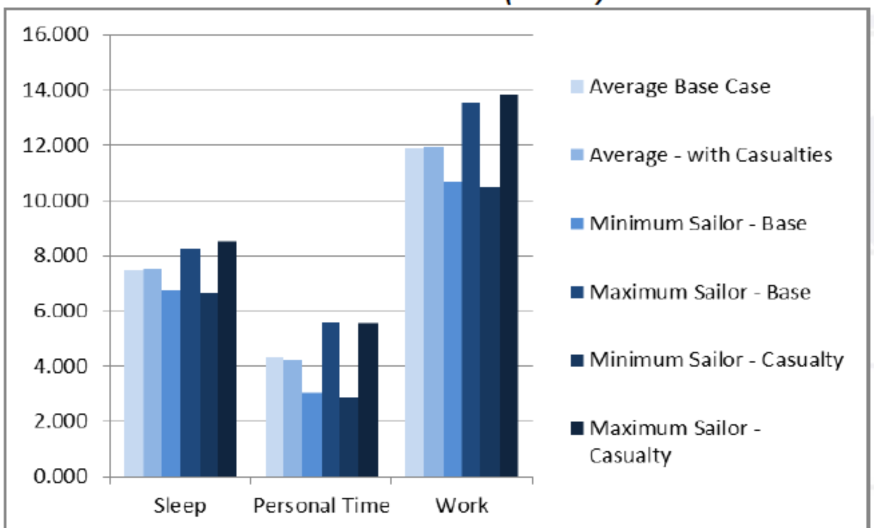
IMPRINT-Pro Results Cont'd

Average Crew Member's Time Spent Sleeping, Working or Personal Time *(in hrs)*



The average crew member spends practically 50% of every given day working, on watch or responding to casualties. These results indicate over-work and eventual crew member fatigue.

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Results Cont'd

IMPRINT-Pro Simulation Results
5 Lowest Sleepers and 5 Highest Workers

	Baseline		Unplanned Events	
	Critical Rate	Avg Time (hrs/day)	Critical Rates	Avg Time (hrs/day)
Least Sleep	EN2 *DCC* IT3 GM1 GM2	6.8	IT3 GM2 GM1 EN1 EN2	6.7
Most Work	*EN1 EN2* IT3 *FC1* DCC	13.5	QMC EM1 OS1 IT3 DCC	13.5
Casualties	N/A	N/A	ET2 EN3 ENCS EN2 EN2	1.0

The primary factor resulting in low sleep and high workload in the unplanned event model is the lack of enough qualified individuals for casualty response.

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Results Summary

- Current manning levels show that critical rates (particularly Engineers and Combat Systems sailors) consistently get the least amount of sleep, accomplish the most amount of work and respond to more casualties.
- Redundant qualifications or increased manning in these rates will improve combat effectiveness and reduce the potential for mishaps.
- Fatigue in high demand, high importance tasks can negatively impact overall crew readiness.

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Proposed Way Ahead

- Continued work to validate this approach
- Tweak existing models in IMPRINT to reflect makeup of an actual LCS crew
- Measure the workload of this crew during various underway evolutions
- Compare predictions from IMPRINT with actual crew performance
- Extend model to other ship platforms

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NPS Support

- Students supporting this effort:
  - LT Renaldo Hollins, GSBPP MSA Thesis Student
  - LT Kelly Leszczinski, GSBPP MSA Thesis Student
  - LT Kevin Kerno, OR Dept. Thesis Student
  - LCDR Michael Albrecht, OR Student
  - LCDR Van Fitzsimmons, OR Student
  - LT Travis Chambers, OR Student
  - LT Dustin Schultz, OR Student
  - Anant Kumar, SEAP Summer Intern

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APPENDIX B: PROJECT REPORT – APPROPRIATE MANNING FOR THE U.S. NAVY LITTORAL COMBAT SHIPS (LCS) – A FEW GOOD PEOPLE

Project Report

by

LCDR Michael Albrecht, USN

LCDR Van Fitzsimmons, USN

LT Travis Chambers, USN

LT Dustin Schultz, USN

December 2014

ABSTRACT

The Littoral Combat Ship (LCS) was designed to be a small, reconfigurable surface combatant capable of countering mines, submarines, and swarm boat attacks with significantly smaller crew sizes than traditional combatants. A previous NPS thesis conducted a case study which sought to validate the use of IMPRINT Pro Forces model simulations in the comparison of different crew sizes and answer the question of what the minimum crew size should be. This study continued the investigation of the usefulness of IMPRINT Pro Forces model simulations while focusing on answering the question of which individuals of the crew should maintain particular qualifications given the current manning constraints of approximately 45 total crew onboard (officer numbers are not certain, and were not modeled in this study). This study looked at one set of crewmembers, based on the current Preliminary Ships Manning Document (PSMD) with regards to crew rates as well as required qualifications, or Navy Enlisted Classifications to determine the fatigue effects of normal underway operations as well as unplanned events on a standard LCS crew.

I. INTRODUCTION

The Littoral Combat Ship (LCS) was designed to meet the present needs of the navy as well as those in the future. The navy must maintain its missions of power projection in the form of carrier strike groups and nuclear deterrence in the form of ballistic missile submarines. With the pivot to the East, the new navy must adapt its platforms to fit the challenges of that environment. The need for a multi-mission craft to project power on the littorals cannot be undervalued. While the navy has overcome many obstacles in development of the LCS platform, initial trails have revealed another major issue: crew manning. Many ways exist to look at the manning of ships in the Navy, but one must account for the dynamic interactions of the diverse rates and qualifications as a ship undergoes daily operations as well as contingency ones.

A. STUDY OBJECTIVE

The objective of this paper is to asses the current LCS manning with regards to the capacity to accomplish scheduled and unscheduled events during underway periods as well as its impact on the fatigue and readiness of the crewmembers. This information should empower decision makers to make appropriate choices in which members of the crew are most vital and if possible where adding members would have the largest effect to the warfighting capability of the ship-crew combination.

B. PREVIOUS WORK

Several previous works have results that pertain directly to the development of a detailed crew-manning model. IMPRINT is the software used to create a manning simulation. It has many upsides but, as with any software, has downsides as well. The army has used the software extensively for analysis of manning.

1. Joint Base Station Variant 1 MOS-Workload Skill Requirements Analysis

This analysis, conducted by the army, looks at a very specific manning problem: the composition of a Joint Base Station team. The army developed the joint base station to communicate in a small team for a forward stationed unit. The problem examined was to determine if a crew of three could successfully operate the proposed base station during a 12-hour shift.

The study used several independent factors to analyze the base station. The independent variables were the configurations of the manning, the average time to complete a task and its standard deviation, the average complexity or difficulty of completing a teak along with that standard deviation. The accuracy was also looked at. The workload estimates were controlled as well. Dependent variables included the setup, programming, operation, and tear down of the base station.

This was a very appropriate model because other experimental procedures would have taken much longer and not been near as accurate. The IMPRINT model used 500 executions of the mission segment model to be accurate on the estimates of task time, accuracy, and workload. The process for the station was fairly simple and therefore the model seemed to represent the work processes very well.

The results of the data were broken down in averages and reported in times for each mission. The times are then divided even further into average workload and times for each task for each mission. Also, average error rate was examined as well. The results supported the conclusion that the three person team could support the operation of the JBS without dipping below accuracy levels or going above workload levels.

2. Littoral Combat Ship: How We Got Here and Why

The next article examines the current state of the LCS program and how the navy has arrived at the current challenges in manning, capabilities, and the perceived capabilities gap. The article was very informal, including no citation for much of the information about how the navy developed the LCS.

The author brings up a valid critique of how the LCS does not fit the mission set the navy currently but rather the future mission sets. While not addressing the manning issue directly, the article goes into depth about many of the recent gripes surrounding manning. The paper is very biased and analytical but lays the groundwork for further research on manning. It established a very real need for the manning to be examined.

II. METHODOLOGY

A. METHODOLOGY OVERVIEW

This study used a model created in a previous thesis as the basic input model. The model used a program called IMPRINT PRO, which is predominantly a deterministic model, with the exception of unplanned events, which are generated based on a set of stochastic distributions. Individual agents, or crewmembers in the model respond to simultaneous events based on a priority or “trump” matrix. This allows the crewmembers to respond to an emergency event instead of attending sweepers. The output of the model is highly dependent on the distributions defined for the unplanned events and the order in which events are listed in the trump matrix.

B. IMPRINT PRO FORCES MODULE METHODS

The model used for this study simulated a 21 day underway period. Only a single simulation was needed for analysis when unplanned activities were not allowed, due to the purely deterministic nature of the model in the absence of unplanned events. When allowing for unplanned events, the study conducted 100 replications of the simulation with different random seeds. From these 100 replications, 50 were selected for analysis due to the extensive time required to convert the data from the IMPRINT PRO model to usable data for analysis. From the single run with no unplanned events and the means of the 50 runs analyzed with unplanned events, the top 5 crewmembers who received the most sleep, least sleep, conducted the most work, and the least work were analyzed. From these lists, the study was able to determine which positions are over utilized and under staffed based on the crewmember’s qualifications.

1. Inputs to the Model

Agents in the model, in this case, members of the crew of the LCS 1 variant were derived from the Preliminary Ships Manning Document (PSMD). The PSMD provided current specific information about crew rates and training requirements, or Navy Enlisted Classifications (NECs) for the LCS1 variant. This manning plan is used currently by all LCS 1 variant crews. Scheduled events in the model were provided based on the previous IMPRINT PRO model, which closely imitates the standard daily routine of the LCS crew in an underway environment, where certain rates are in a port and starboard, or two section rotation, while other watch standers are in a three section rotation. The remaining crewmembers are not watch standers, but do have work hours, and are able to respond to unplanned events, provided they possess the qualifications to respond. Unplanned events were created using generic categories of events, such as Fire, Flooding, WSN-7 failure, etc. and were taken from the previous model. Corrections were made to the stochastic distribution sets used in the model due to concerns about the validity of using a normal distribution to produce times between events as used in the previous model. To rectify this a Poisson distribution was adapted in all applicable areas. The final input into the model was the event trump matrix, which dictates the priority that all crewmembers place on each event type in the list of events (planned and unplanned,) in the model.

2. Model Design

Once the inputs were created in the model, along with modifications of existing inputs from the previous model, the model was set to simulate a 21 day underway period. 21 days was used due to the fact that LCS is not intended to complete longer periods underway. There are several reasons for this, all of which extend beyond the scope of this study.

III. RESULTS AND ANALYSIS

A. IMPRINT PRO FORCES RESULTS

The initial phase of the model analyzed the impact of a standard ship underway schedule with no unplanned events on an LCS variant 1 crew. Following this analysis, the study assessed similar metric effects on the crew under the same initial schedule, with the addition of unplanned events, such as fires, flooding, and system casualties. From these runs, the study viewed quality of life metrics for each crewmember. These metrics included hours of sleep, hours of work and watch, and hours of free time. From the study, it became apparent that certain rates are overstressed in a base case with no unplanned events, however it became even more evident that there is a very limited set of individuals available to respond to a large portion of unplanned events, which resulted in a dramatic decrease in the quality of life of those crewmembers who possessed those qualifications and identified them as critical points of failure if those individuals were not available for the underway period. The model does not accurately model unplanned events, as there was not enough data available to accurately model the distributions of the unplanned events. In addition to this, there are still inaccuracies in the model that the study did not have time to address. Chief among these concerns is the order of events in the trump matrix. According to the model, as currently designed, a crewmember will select sleep before quarters and sweepers. This does not reflect reality, and constitutes a major flaw in the model. Given more time, the trump matrix could be re-analyzed and corrected such that it more accurately models the decision priorities for a typical crewmember of LCS.

B. READINESS

An investigation into the Qualifications-Rates matrix (Table B-1) yields a greater understanding of what qualifications are connected to which rates. On one side of the spectrum, nearly the entire crew is qualified as damage control response personnel. Other qualifications are much more sparsely distributed. The Navigation system technician qualification is held by the ET2 and ET1 rates. These same rates also are two of the three personnel qualified in communications technician. Only three Information technicians are manned to respond to associated unplanned events. The limited number of individuals with specific qualifications who can respond to casualty events becomes problematic when viewed against the requirements for each unplanned casualty events.

Table B-1. IMPRINT Pro Forces Model Qualifications for LCS Manning

Name	Rank	Specialty	Job Roles							
			ASTAC	Auxiliary System Techs	COMMS Tech	Computer Software Techs	Damage Control Response Teams	Nav System Tech	VCHT Team	Weapon System Tech
BM2	E5	BM – Boatswain's Mate					TRUE			
BM3	E4	BM – Boatswain's Mate					TRUE			
BMC	E7	BM – Boatswain's Mate					TRUE			
CS1	E6	CS – Culinary Specialist					TRUE			
CS2	E6	CS – Culinary Specialist					TRUE			
CS3	E4	CS – Culinary Specialist					TRUE			
DC3	E4	DC – Damage Controlman					TRUE		TRUE	
DCC	E7	DC – Damage Controlman					TRUE		TRUE	
EM1	E6	EM – Electricians Mate					TRUE			
EM2	E5	EM – Electricians Mate					TRUE			
EN1	E6	EN – Engineman		TRUE			TRUE			
EN2 #1	E5	EN – Engineman		TRUE			TRUE			
EN2 #2	E5	EN – Engineman		TRUE			TRUE			
EN3	E4	EN – Engineman		TRUE			TRUE			
ENCS	E8to9	EN – Engineman		TRUE			TRUE			
ET1	E6	ET – Electronics Technician			TRUE		TRUE			
ET2 #1	E5	ET – Electronics Technician			TRUE		TRUE	TRUE		
ET2 #2	E5	00A – Placeholder			TRUE		TRUE	TRUE		
FC1	E6	FC – Fire Controlman					TRUE			TRUE
FC2 #1	E5	FC – Fire Controlman					TRUE			TRUE
FC2 #2	E5	FC – Fire Controlman					TRUE			TRUE
FCC	E7	FC – Fire Controlman					TRUE			TRUE
GM1	E6	GM – Gunner's Mate					TRUE			

			Job Roles							
Name	**Rank**	**Specialty**	**ASTAC**	**Auxiliary System Techs**	**COMMS Tech**	**Computer Software Techs**	**Damage Control Response Teams**	**Nav System Tech**	**VCHT Team**	**Weapon System Tech**
GM2 #1	E5	GM – Gunner's Mate					TRUE			
GM2 #2	E5	GM – Gunner's Mate					TRUE			
GSE1	E6	GSE – Gas Turbine Systems Technician – Electrical								
GSM2	E5	GSM – Gas Turbine Systems Technician – Mechanical					TRUE			
HM1	E6	HM – Hospital Corpsman								
HT2	E5	EN – Engineman					TRUE		TRUE	
IT1	E6	IT – Information System Technician				TRUE	TRUE			
IT2	E5	IT – Information System Technician				TRUE	TRUE			
IT3	E3	IT – Information System Technician				TRUE	TRUE			
LSC	E7	SK – Storekeeper					TRUE			
OS1	E6	OS – Operations Specialist	TRUE				TRUE			
OS2	E5	OS – Operations Specialist					TRUE			
OSC	E7	OS – Operations Specialist	TRUE				TRUE			
QMC	E7	QM –Quartermaster					TRUE			

The Unplanned event table yields even more information about the way that IMPRINT handles unplanned events. The table shows the list of unplanned events on the left. Each event is distributed during each simulation with a Poisson distribution, where applicable. The chart shows the number of crew that is required to respond along with what qualification these must maintain. For example, if fire occurs onboard, 8 Damage Control personnel are required to respond. If that does not occur, then the ship fails the fire response and ship readiness suffers. In comparison, if there is a WSN failure, the desired number of personnel is 2 Navigation Systems Technicians. The required number of Navigation Techs is 1. These results are shown in Table B-2.

Table B-2. Unplanned Activity required qualifications

Unplanned Event	Qualification	Required	Desired
CENTRIX	Computer Software Tech	1	1
Fire	Damage Control	8	10
Flood	Damage Control	8	10
Link 16	Communications Tech	1	2
MPDE	Aux Systems Tech	2	4
Network issues	Communications Tech	1	2
RO	Aux Systems Tech	2	4
SSDG	Aux Systems Tech	2	3
VCHT	VCHT Team	1	1
WSM misfire	Weapons Systems Tech	2	2
WSN-7	Navigation Systems Tech	1	2

After looking at the inputs and setup of IMPRINT, the simulations were conducted and their results were examined. The limitations from the above discussion are further supported by running IMPRINT. The mean daily man-hour requirements show that the SSDG casualty has the highest amount of time in response by personnel. This is one of the qualifications that is very limited on the ship. Aux systems techs are required to respond. While the engine room has five personnel with this qualification, they also have other obligations that restrict this response.

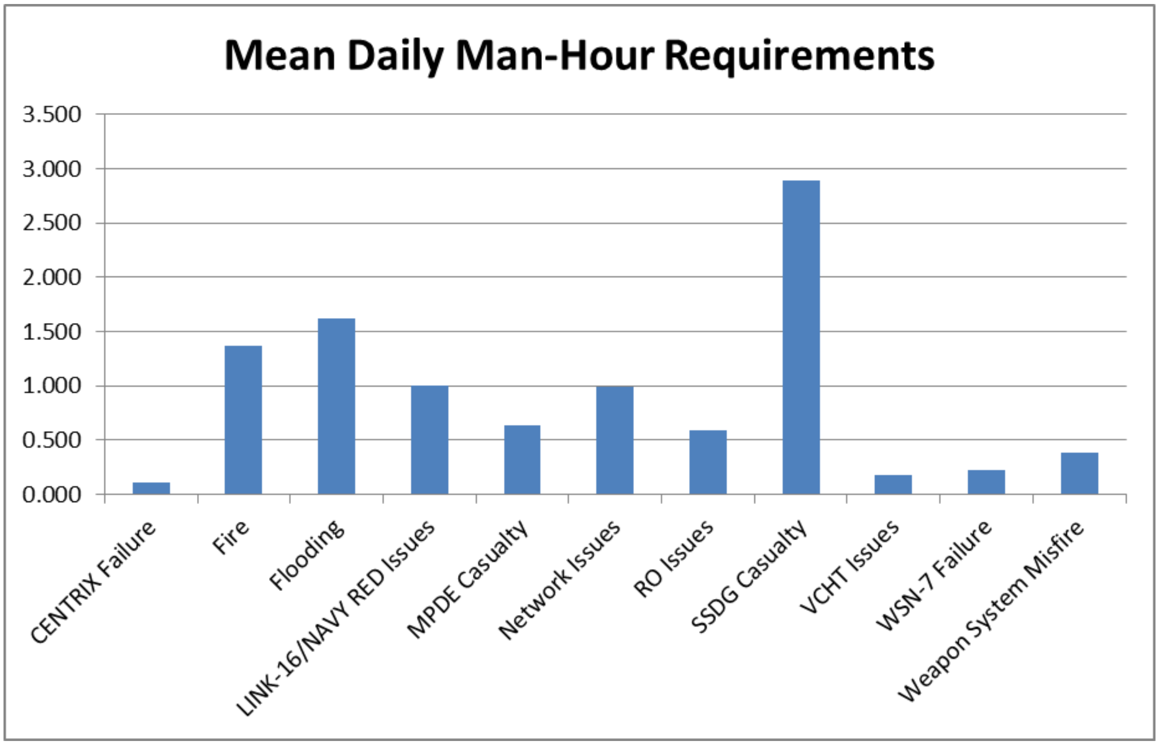

Figure B-1. Mean Daily Man-Hour Requirement for Casualties

As shown in Figure B-2, the 21-day simulation shows a similar story. The mean man-hour requirement over that time shows similar trends in time spent on responding to unplanned events. The SSDG is by far the largest requirement on a very few personnel. While flooding and fire take the second and third place for man-hour requirements, there are also the most amount of responders with qualifications to meet these events successfully. Therefore, the top three most critical casualty events for man-hour requirement, in order, are SSDG Casualty, LINK-16/NAVY RED Issues, and Network Issues.

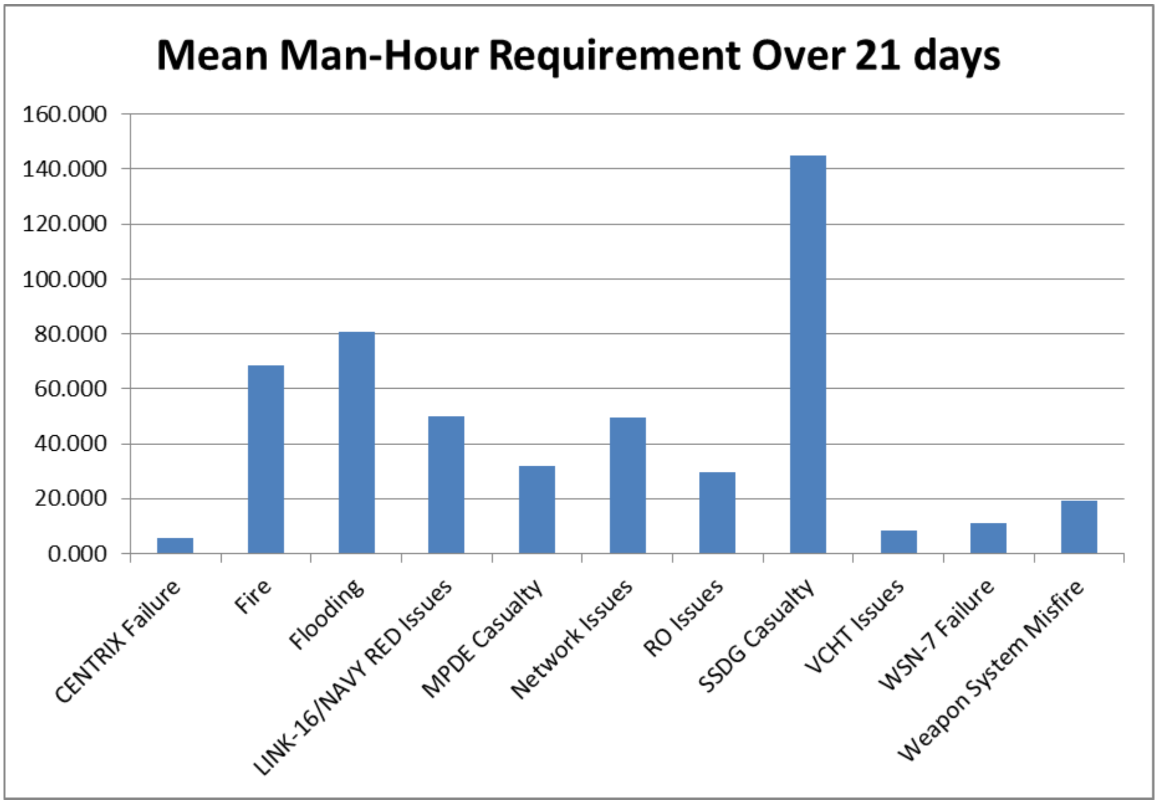

Figure B-2. Mean total man-hour requirements over 21 days

Finally, the mean failed activities over 50 simulations show that SSDG and VCHT failures were the most often failed unplanned events. The crews for these unplanned events are limited and already overused in planned activities. It is not just number of people that are important on the LCS. Rates and qualifications have a significant effect on readiness.

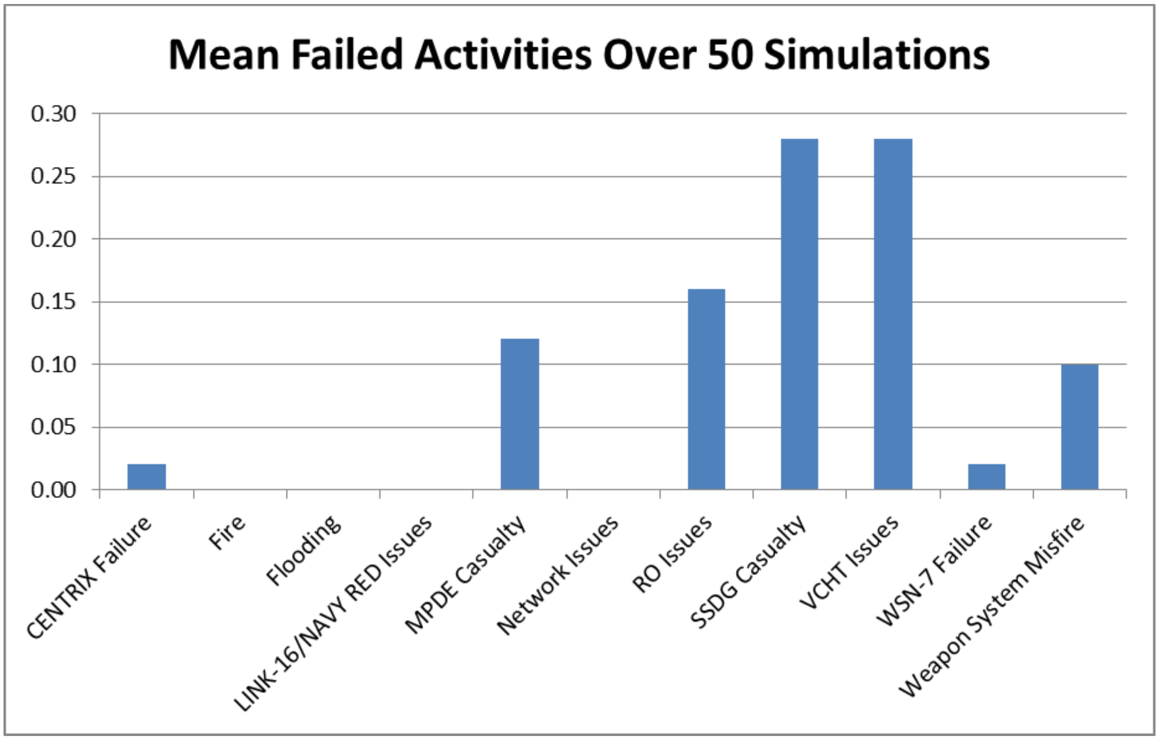

Figure B-3. Mean number of failed activities in 21 days

One point to note in this result is that watch standing had a higher priority than handling casualties. Because of this the simulation could not have someone relieve a watchstander with a pertinent qualification, like Aux Systems Tech, in order to handle an SSDG Casualty or RO Issue. Therefore, the simulation results of failed activities, while informative, lose some of their emphasis as compared to the analysis of man-hour requirements and the overall effect of casualty events upon crew time demands.

C. DEMAND ON CREW

Based on average values of simulation runs made in both a base case (no casualty) mode, as well as with unplanned events included, there is an appreciable difference between the amount of time crewmembers are allowed sleep, the amount of time they are afforded free time (including time to eat, relax, and focus on hygiene), and the amount of time the crewmember spends working or on watch. On average, in the crewmembers spend 7.494 hours sleeping in the base case, and 7.544 hours sleeping in the casualty case (standard deviations of .526 and .584 respectively). This increase in sleep between a more relaxed model and the more challenging one is believed to be another artifact of the priority trump matrix, whose issues are highlighted earlier. More telling are the minimum sleep values, drop from 6.75 in the base case, to 6.68 in the casualty model. The maximum sleeper in the base case gets 8.23 hours of sleep, and 8.53 hours in the casualty included model. The increase is again due to errors in the trump matrix. The crew works 11.89 hours on average with a minimum of 10.67 and a maximum of 13.54 (standard deviation of 1.18 hours), whereas in the model with casualties, the crew spends 11.95 hours on average, with a minimum of 10.47 and a maximum of 13.83 hours (standard deviation of 1.216 hours) working and responding to unplanned events. The fact that the average crewmember spends practically 50% of every given day working, on watch or responding to casualties is a major indicator of over-work and eventual crewmember fatigue. Below is a visual representation of the time spent sleeping, working, or enjoying free time for the average sailor, the minimum sailor, and the maximum sailor for both the base case and the casualty response case. These results are shown in Figure B-4.

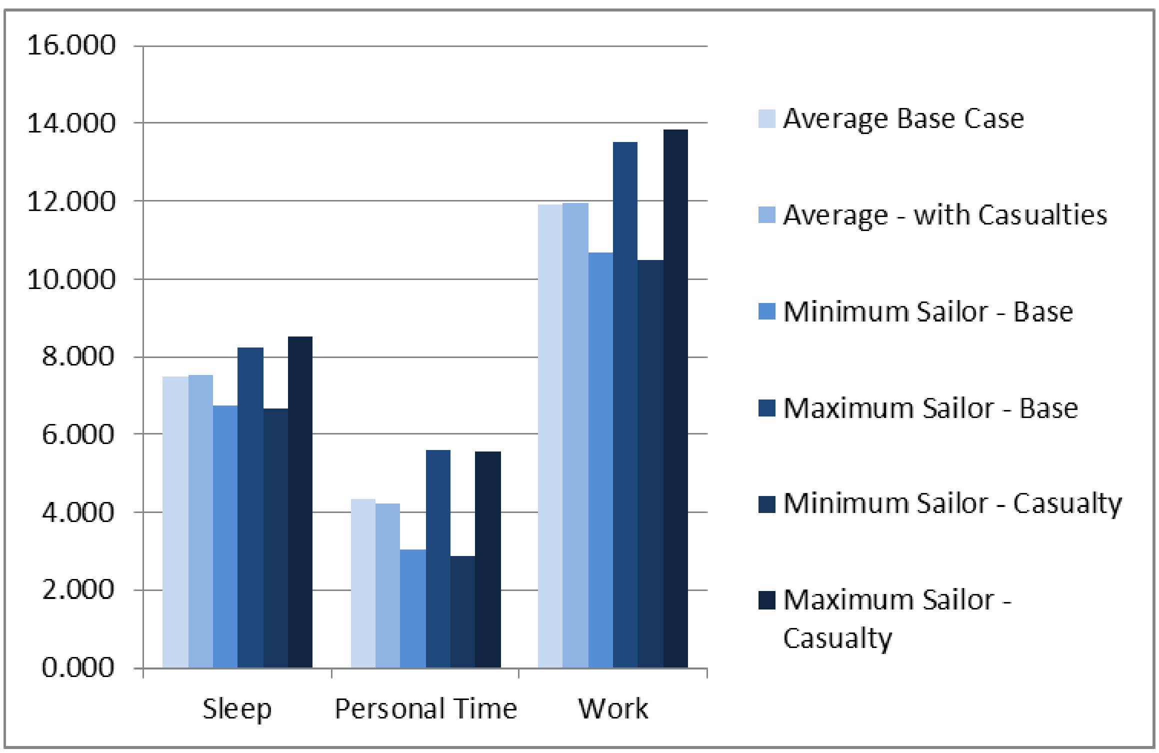

Figure B-4. Simulation study hour results

Based on the above information, the question arose during the study: which crewmembers were experiencing the least sleep and the most work. Further, in the casualty response case, was this a result of the specific crewmember possessing qualifications and training that made that crewmember a critical factor? In the below table, you will see that those members who are underlined in the unplanned events list are members who were not in the top 5 lowest sleepers, or most workers until unplanned events were added in. While the list of the top 5 lowest sleepers and hardest workers in the base case are likely a result of poor watch plan management and low crew numbers, the primary factor resulting in low sleep and high workloads in the unplanned event model is the lack of enough casualty response qualified individuals. While the crew is likely to have every member qualified in damage control, the specific casualties to engineering plant systems and combat systems, which all require extensive training and NEC qualifications do not have a deep enough bench of qualified responders on the LCS to continue operations during a 21 day underway period without adding additional strain on the crewmembers, above and beyond an already excessively fatiguing daily routine.

	Baseline		Unplanned events	
	Critical Rates	Average Time (hours/day)	Critical Rates	Average Time (hours/day)
Least Sleep	EN2, *DCC*, IT3, GM1, GM2	6.8	IT3, GM2, GM1, EN1, EN2	6.7
Most Work	*EN1*, *EN2*, IT3, *FC1*, DCC	13.5	QMC, EM1, OS1, IT3, DCC	13.5
Casualties	N/A	N/A	ET2, EN3, ENCS, EN2, EN2	1.0

IV. CONCLUSION

A. FUTURE WORK

This study considered only the current approved case of LCS variant 1 manning with current training requirements. Future studies could consider fatigue effects on increased or decreased manning levels, a more robust and accurate unplanned activity design, and a more accurate trump matrix. Future studies could also consider the possibilities of adjusting training requirements for existing crewmembers as well as adjusting actual crewmember numbers. Finally, the results should be validated against surveys provided to current crews and LCS leadership.

B. IMPRINT PRO

The following paragraphs describe further improvements specific to IMPRINT Pro implementation.

1. IMPRINT Pro Unplanned Activity Mean Time Implementation

One of the first things that the case study team attempted to resolve was to analyze an accuratestochastic distribution for unplanned events. Given the short time allowed, this study was unable to obtain any data from the Navy safety center, or other locations to verify the distributions. With more data and time, a comprehensive review of unplanned activities could be completed, lending more validity to the results of the study. Several of the distributions in the model were originally designated as normal, which could allow for negative times between events, as well as not being memoryless, and potentially having end effects in the tails that were not intended. This study made several corrections to the distributions that existed in the initial model, but due to some limitations with the IMPRINT Pro software where the simulation would fail on Poisson distributions with mean times near or greater than 21 days, not all the distributions were able to be fixed.

2. IMPRINT Pro Batch Running and Reports

IMPRINT Pro batch running capabilities are fairly limited at this time. While the company is working on correcting much of the feedback from our study, the issues the study encountered were many. The batch runner could only complete 35 runs at a time, and attempts to complete more runs in a single command would result in an error. To counter this, our team conducted batches in groups of 10-20. Each subsequent run would take the initial random seed input and simply increment by 1 providing results that were not entirely random, and potentially creating highly correlated series of results. To counter to this was that after each batch of 10-20, a new seed was used in the base file for the batch runner. Finally, the reports that were created by the batch runner were in an INPRINT Pro specific format, which required approximately 40 seconds for each simulation run in order to receive in a format which could readily be manipulated by post processors (in the case of this study, excel and python). During those 40 seconds the user was required to navigate several menu options, and this for each individual simulation run conducted, which all could easily be automated.

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APPENDIX C: PROJECT REPORT – AIR WARFARE CONDUCTED FROM A VIRGINIA-CLASS SUBMARINE PLATFORM – A HUMAN FACTORS ANALYSIS USING IMPRINT SOFTWARE

Project Report

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ABSTRACT

The research conducted in this project investigates the manning requirements necessary to add the air warfare mission area to a VIRGINIA class submarine. It was assumed that the current manning does not permit the reserve capacity to accept the additional workload. This hypothesis was proven correct and 4 additional crewmembers were needed to return the personnel utilization to that of the current submarine baseline. The additional personnel that were determined as necessary would cost the VIRGINIA class submarine program approximately $500 million dollars in simply their pay alone. Other observations from the research are also included.

The research was conducted using the Improved Performance Research Integration Tool (IMPRINT) and constrained to investigate only 2 enlisted submarine rates. The research only investigated normal underway manning conditions. Future implications of this research include the recommendations for the addition of personnel and specific rates or skills that those personnel should have.

I. INTRODUCTION

The U.S. Navy is researching and developing the use of High Energy Lasers (HEL) on many types of platforms that are currently available. The Navy is also looking at various ways to implement lasers onto many future platforms since this weapon is capable of unlimited ammunition and therefore does not require additional logistics outside of its regular operations and maintenance. OPNAV N97 has asked the Naval Postgraduate School to conduct research and analysis into the concept of integrating a HEL onto a submarine platform. This request for analysis did not include any discussion or need to research the area of the submarine's personnel involved, though it is quite obvious that this is a major human systems integration task that the Navy is indirectly asking to research.

The use of a HEL onboard a submarine proposes the question, what for? The two main threats initially considered are very small surface boats and slow moving unmanned aerial vehicles (UAV's) such as the Harpy. While there are many other threats and uses for a laser onboard a submarine, only the aerial threat will be considered for this project. The aerial threat is considered because it is the threat that will force the submarine to conduct what could be easily argued as a new warfare area – air warfare. With focused consideration to the air warfare area this will allow analysis to encompass the more extreme case that would help determine the maximum challenge presented for human system integration with a HEL and a submarine. A submarine does not currently employ technology to conduct attacks at any type of aircraft. Therefore, many new systems will need to be added to the submarine platform in order to adequately perform this type of warfare.

A. HYPOTHESIS

Current Virginia class submarine manning and watch team coordination is not suitable to conduct the additional air warfare mission area that standard surface combatants are capable of conducting. Additional personnel are going to be required onboard the submarine in order to implement the HEL and its complementary equipment into the standard submarine's combat weapon suite. Without additional personnel to augment the current watch teams and maintenance, the HEL will be required to become much more autonomous (more machine, less human interactions) than it more than likely is being designed for.

II. LITERATURE REVIEW

Research has been conducted in several areas regarding the overall crew-manning concept. The research that has been previously performed seemed to focus on the entire ship's manning and how different overall crew numbers would alter the performance of the ship as a whole entity. This particular study is focused on a submarine's control room watch-standers and the personnel assigned to perform maintenance on the expected new systems. Moreover, since there was no specific, directly related research that could be found the following documents helped to frame the overall project of implementing air warfare onto a submarine from a human systems integration perspective.

A. USN MANPOWER DETERMINATION DECISION MAKING: A CASE STUDY USING IMPRINT PRO TO VALIDATE THE LCS CORE CREW MANNING SOLUTION.

The Littoral Combat Ship has become a case study in many areas from its designed mission use to its expected crew size. This project centered on the overall manning of the LCS platform. IMPRINT Pro Forces software was used to analyze three different crew sizes in order to assess the most optimal number of crewmembers. This project further analyzed the individual cognitive effectiveness of the members using simulated tasking schedules. This additional step helped to provide additional validation to the results of the three crew size comparison study. The main objective of this project was to assess the human performance software, its applicability, and capability to help predict optimal future ship manpower levels.

A review into the three core crew sizes was conducted because of the hypothesis that the current manning is not optimal for the LCS platform. The reduction in manning on previous ships has led to their failing inspections and not being combat ready because of the concept that less work will be needed because of the higher technological automation. Since it became a concern to both the Navy and the Congress that ships may not be able to complete their expected service life if these failures were to continue, the idea of reduced manning has become more of an “optimal manning” strategy. It was further found that the smaller a crew size was made that the less of an ability they had to absorb additional work that was not initially presumed to matter.

Finally, the previous work performed in this thesis project helped to provide a framework for the challenge of implementing air warfare onto a submarine platform. The thesis describes a detailed analysis into how to apply data inputs into the IMPRINT Pro Forces module and the types of outputs and analysis to expect to be conducted and gained through this study.

B. FEW GOOD PEOPLE FINAL REPORT

This project followed on the work of the previous thesis case study just discussed. The focus of this project was to determine the optimal spread of qualifications among the individuals of the LCS crew based upon the current core crew manning concept. The project centered on the fatigue levels of the crew to determine the adequate critical manning given the current crew constraints from the Preliminary Ship’s Manning Document. The results concluded that certain rates were very critical because of the limited quantity of qualified personnel based upon unplanned events such as casualties that arise during a deployment period. Also, the level of fatigue between various rates was significant as some rates averaged almost double the workload compared to other rates. Furthermore, this work helped to continue to validate the framework for implementation of the air warfare area onto a submarine using IMPRINT Pro Forces module as the analysis tool. Valuable lessons were taken away from this material about the use of the IMPRINT software as to what it is capable of doing and more importantly what it is not.

C. Navy Total Force Manpower Policies and Procedures, OPNAVINST 1000.16K CH-1

This document provides the overall guidance on manpower policies and procedures as the title indicates. Specifically, the take-away from this was Appendix C, the Navy Standard Workweeks section. This provides the baseline number of hours that a member of the Navy, onboard a ship, is expected to be capable of performing. The document states "they are guidelines for sustained personnel utilization…and are not intended to reflect the limits of personnel endurance." This is an important statement although for this project the NSWW will be considered the limit for personnel activity and beyond that limit additional personnel will be needed. These quantified hourly values are then applied to the required operational capabilities and projected operational environments documents in order to determine the number of required personnel a ship needs to perform its mission. This leads to the creation of a Ship's Manning Document which lists out the various ranks and rates each ship is expected to have in order to fulfill its designed mission set.

The NSWW that has been used in the analysis of this project was the Afloat (Wartime) for military personnel workweek which assumes a three-section watch rotation under Condition 3 wartime steaming. The workweek will be discussed in further detail during the analysis portion of this project but it separates an individual's time into three main categories; watch, training, and non-available (personal) time. Each of these categories will be shown to be important in the overall project's analysis of air warfare on a currently employed operational submarine.

III. METHODOLOGY

A. METHODOLOGY OVERVIEW

Research was conducted in order to obtain various Navy surface combatants' manning documents in order to determine the critical, wartime number of personnel required to conduct various air warfare mission areas. Ship's manning documents were obtained from the different types of naval platforms and thoroughly reviewed to isolate the specific personnel required to operate the functional areas of air warfare. Based upon the optimal manning strategy that the Navy currently uses to fully man each ship, the number of personnel will be based upon Condition 3 watches. Condition 3 watches are the required watches to man the ship in normal underway mission conditions. It was also important to determine the number of maintainers needed for the equipment. Additional data was obtained to determine the number of submarine control room personnel required to perform current required operations. The Virginia class submarine's Ship's manning document was obtained and narrowed down to focus on the rates or navy enlisted classifications of interest for the air warfare and laser system operations.

Assumptions were made regarding the specific mission areas that would apply to the implementation of air warfare onto a submarine from what a surface combatant can perform against air threats. This step was essential in order to narrow down the massive amount of systems that a submarine would need if it were to conduct the full complement of air warfare that for instance a destroyer is capable of performing.

The project team decided after researching different weapons systems and warfare areas that the VIRGINIA Class submarine and a new AEGIS Baseline 7.1R ARLEIGH BURKE destroyer (DDG-51) most accurately represent the submarine class that would have a laser system installed and the surface class of ship to use for an analogy to air warfare. This decision was based on multiple criteria including the COTS baseline architecture of both ships, the similarities in crew training in new computer systems technology, and that these are the premiere platforms for each warfare area respectively in terms of design, capability, and new technology.

The research conducted will be able to provide the expected number of additional personnel required to perform the smaller sub-sections of air warfare. Based upon the Navy Standard Work Week (NSWW) it will be possible to more specifically determine the required number of well-defined hours that these additional personnel will be expected to perform or present to the submarine.

Using the Improved Performance Research Integration Tool (IMPRINT) software it will be possible to determine based upon the current submarine manning the effects of adding the additional workload presented by the air warfare mission area to the current submarine's personnel. The IMPRINT software will help to determine if additional personnel are needed to perform the day-to-day operations onboard a submarine with an integrated HEL. This process will require an iterative approach using the software in order to determine the most optimal performance model between additional personnel and having current onboard personnel work more.

Finally, a detailed analysis will be conducted to determine the recommended number of additional submarine personnel that will be required in order to conduct air warfare. The requisite number of additional personnel will only be considered to reduce the increased workload due to the laser system integration not to reduce the potentially already overworked crew.

B. IMPRINT PRO FORCES MODULE METHODS: BUILDING THE MODELS

A baseline model was created using IMPRINT Pro software, specifically the Forces module, for the particular rates that will be required in the conduct of air warfare and the operations of the laser system onboard a submarine. The submarine rates were chosen based upon the current rates onboard a submarine defined by the experience of which rate should be most capable and would be considered to be expected of conducting the air warfare mission area provided the additional training to do so. This baseline model was designed around the planned and unplanned events that are of particular importance to only the rates chosen. Then the baseline model was evaluated to determine the overall outlook of the assumed current VIRGINIA class submarine operations for these rates. This baseline will be used as the objective for the additional manning impact to achieve. In other words, if the VIRGINIA class submarine has sub-optimal manning conditions in the baseline, the project's goal is not to correct existing manning concerns. The project's goal is to avoid creating additional sub-optimal manning conditions with the introduction of the Air Warfare mission area.

1. The Baseline Model Construction and Assumptions

The combat systems or control room personnel members for the VIRGINIA Class submarine were obtained from the Ships Manning Document (SMD). The analogous air warfare ratings from the DDG-51 Class were taken from the ship's Fleet Management and Planning System (FLTMPS) report for air warfare from DDG-112. The baseline does not include the inputs for the air warfare systems, but the analogous ratings that are going to be affected needed to be identified to form the baseline. It was determined that the Submarine Fire Control Technicians (FT) and Electronic Technicians (ET) were the analogous rates to the air warfare systems operators and maintainers required from the DDG-51 class Fire-controlman (FC), Electronic Technicians (ET), and Operations Specialists (OS). The FT and ET manning for the Virginia class was used as an input into the IMPRINT forces model. Deciding which ratings would be involved in the new laser system if it were installed was the first step. The next step was to develop a model of their daily activities while underway in condition 3. This model consists of maintenance, eating, sleeping, watch rotation, personal time, casualties, drills, briefs, and training. The following table, table 1, shows the baseline daily planned event schedule.

Table C-1. Submarine Daily Schedule.

Activities | Force Models | Warfighters | Unplanned | **Schedules**

Special Evolution Team | WATCH SECTION 1 OF 3 | WATCH SECTION 2 OF 3 | WATCH SECTION 3 OF 3

Activity	Start Time	End Time	Total Activity Time
Sleep	00:00	05:00	05:00
Watch Preparation	05:00	05:30	00:30
Eat	05:30	06:00	00:30
Watch	06:00	11:30	05:30
Eat	11:30	12:00	00:30
Off Watch	12:00	17:30	05:30
Eat	17:30	18:00	00:30
Sleep	18:00	23:00	05:00
Watch Preparation	23:00	23:30	00:30
Eat	23:30	1 00:00	00:30
Watch	1 00:00	1 05:30	05:30
Eat	1 05:30	1 06:00	00:30
Off Watch	1 06:00	1 11:30	05:30
Eat	1 11:30	1 12:00	00:30
Sleep	1 12:00	1 17:00	05:00
Watch Preparation	1 17:00	1 17:30	00:30
Eat	1 17:30	1 18:00	00:30
Watch	1 18:00	1 23:30	05:30
Eat	1 23:30	2 00:00	00:30
Off Watch	2 00:00	2 05:30	05:30
Eat	2 05:30	2 06:00	00:30
Sleep	2 06:00	2 11:00	05:00
Watch Preparation	2 11:00	2 11:30	00:30
Eat	2 11:30	2 12:00	00:30
Watch	2 12:00	2 17:30	05:30
Eat	2 17:30	2 18:00	00:30
Off Watch	2 18:00	2 23:30	05:30
Eat	2 23:30	3 00:00	00:30

Table C-2 below provides the assumed inputs for the baseline model to include the manning, roles, and unplanned events. The watch-standers (ET's and FT's) were assumed to be on a 3-section rotating watch with an off-watch maintenance period directly following the operator watch which is the standard submarine watch rotation schedule.

Table C-2. Submarine unplanned events baseline.

Item	Purpose	Quantity or Frequency	Duration
Electronic Technicians	Radio Operator, Radio Tech, Radio Maintenance, Electrical Tech, DCT	8	3 Section Operators, 3 Sections Maintenance
Fire Control Technicians	Fire Control Operator, FT Tech, FT Maintenance, Network Tech, DCT	6	3 Section Operators, 3 Sections Maintenance
Damage Control Team	Fire and Flooding Response	14	As needed by events
Electrical Casualty	Electrical casualties throughout the combat system	Mean: 5 Days 20 hours Std. Dev: 6 Hours (Norm Dist.)	Mean: 3 Hours Std. Dev: 2 Hours (Normal Dist.)
FT Casualty	Summary of all FT related system casualties	Mean: 14 Days (Poisson Dist.)	Mean: 1 Hour Std. Dev: 20 Minutes (Normal Dist.)
Radio Casualty	Summary of all ET related casualties	Mean: 10 Days (Poisson Dist.)	Mean: 1 Hour Std. Dev: 20 Minutes (Normal Dist.)
Network Issues	Summary of all tactical network issues	Mean: 6 Days 17 Hours Std. Dev: 6 Hours (Normal Dist.)	Mean: 30 Minutes Std. Dev: 30 Minutes (Normal Dist.)
Fire	Fire casualty	Mean: 2 Days 2 Hours Std. Dev: 6 Hours (Normal Dist.)	Mean: 3 Hours Std. Dev: 1 Hour (Normal Dist.)
Flooding	Flooding casualty	Mean: 3 Days 19 Hours Std. Dev: 6 Hours (Normal Dist.)	Mean: 3 Hours Std. Dev: 1 Hour (Normal Dist.)
Maintenance	All FT and ET planned and corrective maintenance	Every maintenance watch section	2 Hours for every maintenance watch requiring 2 techs. (Normal Dist.)
Training	Training events	Every 10 Hours	1 Hour

2. The Laser Air Warfare System Model Construction and Assumptions

The additional air warfare mission area planned and unplanned events were now added to the previously built baseline VIRGINIA class submarine model. The additional systems were a laser weapon, the laser fire control system, cooperative engagement capability (CEC), and tactical data link 16 (Link 16). The laser weapon and Link 16 were assigned to the Electronic Technicians (ET). The laser fire control system and CEC were assigned to the Fire Control Technicians (FT). The tasking assignments were determined based upon technical rating competency and experience. The overall daily schedule was not changed with the exception of 30 minutes for each maintenance watch section added to both ETs and FTs to conduct maintenance on the additional air warfare systems. The introduction of the new systems for the Laser Weapon System was implemented through either their frequency of operation or a certain periodicity for maintenance and potential issues. Since none of these systems currently exist on a submarine the frequency of occurrence was determined from surface ship combatants and previous operating experience. Table 3 below summarizes the model with the additional inputs to the baseline for the submarine with the laser weapon system suite.

Table C-3. Additional Air Warfare unplanned events

Item	Purpose	Quantity or Frequency	Duration
CEC Issues	System casualty or operator issues responded to by FT	Mean: 2 Days (Poisson Dist.)	Mean: 10 Minutes Std. Dev: 5 Minutes (Normal Dist.)
Link 16 Issues	System casualty or operator issues responded to by ET and FT	Mean: 5 Hours (Poisson Dist.)	Mean: 10 Minutes Std. Dev: 5 Minutes (Normal Dist.)
Laser System Malfunction	Summary of all laser system casualties responded to by ET and FT	Mean: 14 Days (Poisson Dist.)	Mean: 1 Hour Std. Dev: 30 Minute (Normal Dist.)
Laser firing event	AW Team identified from techs and operators to support live firing event responded to by FT	Mean: 17 Days (Poisson Dist.)	Mean: 3 Hours (Poisson Dist.)
WSN-7 Failure	Gyro casualties responded to by ET.	Mean: 1 Day 17 Hours Std. Dev: 6 hours (Normal Dist.)	Mean: 2 Hours Std. Dev: 1 Hour (Normal Dist.)
Maintenance	All FT and ET planned and corrective maintenance	Every maintenance watch section	2.5 Hours for every maintenance watch requiring 2 techs. (Normal Dist.)

3. Model Execution

The baseline model was simulated in order to determine the VIRGINIA class submarine's initial baseline with the assumptions made regarding their current operational profile. The project's goal is not to correct current deficiencies to any facet of the VIRGINIA class submarine's current manning levels, daily tasking, watch rotations, or manpower utilization. The initial step of the project is to use the initial baseline data as the achievable objective when adding the additional air warfare mission area by not failing more events or over utilizing the current manpower. After the baseline has been established the laser system and its associated air warfare supporting systems will be added to the baseline with no additional manpower to determine the impact of the added systems in terms of manpower activity, inactivity, and event success. Once the data is compared to the baseline data the project team will be able to determine if more manpower will be needed for the additional systems or the current baseline manning is enough to absorb the air warfare mission area. If an increase in manning is determined as necessary the model will be simulated again increasing either an FT or ET member in the manning structure as necessary to achieve the baseline event success without over-utilizing a crewmember.

IV. ANALYSIS AND RESULTS

A. BASELINE MODEL RESULTS

The Baseline Model inputs as defined in the methodology section were simulated using the IMPRINT Forces model for a 150 day run. The 150 day run was chosen because it was easier to calculate the necessary statistics from the larger data set than to simulate the model multiple times on a weekly schedule. The project team decided to not restart events that were interrupted due to a higher priority event. If the event could not be resumed and completed in the time remaining after the interruption was satisfied then that event would fail. It was decided to perform the simulation in this manner versus restarting events because in reality on a ship some of the interruptions would get restarted in the schedule and some would be lost or moved to later in the schedule though the team could not exactly figure out how to make this occur. This is typical with shipboard preventative maintenance. If an event interrupts maintenance it will be restarted when a time slot exists, moved farther out, or cancelled. Since the Forces model could not dynamically capture these multiple scenarios, it was decided to fail the event and analytically account for the failure time. The event activity status summary for the Baseline Model produced the following results seen in Table C-4.

Table C-4. Baseline Activity Status Summary

Unplanned Activity	Scheduled	Started	Successful	Interrupted	Delayed	Failed
Electrical Casualty	15	15	15	0	0	0
Fire	5	5	5	0	0	0
Flooding	7	7	7	0	0	0
FT Casualties	10	10	10	0	0	0
Maintenance	964	920	856	64	0	44
Network Issues	144	139	139	0	0	5
Radio Casualties	14	14	14	0	0	0
Training	50	47	47	0	0	3
					Total Failures	52

It can be seen from the activity status summary in Table C-4 that a total of 1209 events occurred with 52 failed events. A two-part analysis is required to achieve an accurate snapshot of the model's performance. The second piece of data to analyze is the utilization of the personnel in the model. Since the project team decided to not restart interrupted events this would intuitively mean that the utilization ratios would only be covering the events actually completed. Multiple techniques were used to analyze the individual resource data to determine utilization. Tables C-5 through C-7 took averages of all personnel, averages of the electronic technicians, and averages of the fire control technicians. The average resource data was normalized to a 168-hour week. This resulted in the following figures of data. It is important to note that not only was the average hours determined for each enlisted rate but the worst case or the extreme was also analyzed.

Table C-5. All personnel average resource data.

All	Total Hours	Avg Hours per Day	Weekly Hours	Normalized Weekly Hours
Off Watch	1134.07	7.56	52.92	48.09
Watch	1098.60	7.32	51.27	46.59
Sleep	941.46	6.28	43.93	39.92
Maint	309.81	2.07	14.46	13.14
Watch Prep	91.58	0.61	4.27	3.88
Training	32.00	0.21	1.49	1.36
Network Issues	27.57	0.18	1.29	1.17
Electrical Casualty	17.14	0.11	0.80	0.73
Flood	9.75	0.07	0.46	0.41
Fire	8.67	0.06	0.40	0.37
Radio Casualties	2.87	0.02	0.13	0.12
FT Casualties	2.94	0.02	0.14	0.12
Eat	285.40	1.90	13.32	12.10
Total Utilization	**Total Personal Hours**	**Personal Hours Per Day**	**Weekly Duty Hours**	**Normalized Weekly Duty Hours**
0.69	1226.86	8.18	127.63	115.98

Table C-6. ET average resource data.

Electronic Technician (ET)	Total Hours	Daily Hours	Weekly Hours	Normalized Weekly Hours
Off Watch	968.65	6.46	45.20	43.22
Watch	1098.99	7.33	51.29	49.04
Sleep	956.66	6.38	44.64	42.69
Maint	305.80	2.04	14.27	13.64
Watch Prep	92.18	0.61	4.30	4.11
Training	27.50	0.18	1.28	1.23
Network Issues	11.82	0.08	0.55	0.53
Electrical Casualty	15.62	0.10	0.73	0.70
Flood	9.72	0.06	0.45	0.43
Fire	7.58	0.05	0.35	0.34
Radio Casualties	2.87	0.02	0.13	0.13
Eat	267.81	1.79	12.50	11.95
Total Utilization	**Total Personal Hours**	**Personal Hours Per Day**	**Weekly Duty Hours**	**Normalized Weekly Duty Hours**
0.67	1224.47	8.16	118.57	113.36

Table C-7. FT average resource data.

Fire Control Technician (FT)	Total Hours	Daily Hours	Weekly Hours	Normalized Weekly Hours
Off Watch	1354.62	9.03	63.22	53.98
Watch	1097.70	7.32	51.23	43.74
Sleep	921.19	6.14	42.99	36.71
Maint	315.15	2.10	14.71	12.56
Watch Prep	90.20	0.60	4.21	3.59
Training	36.50	0.24	1.70	1.45
Network Issues	49.63	0.33	2.32	1.98
Electrical Casualty	19.17	0.13	0.89	0.76
Flood	9.80	0.07	0.46	0.39
Fire	10.11	0.07	0.47	0.40
FT Casualties	2.94	0.02	0.14	0.12
Eat	308.84	2.06	14.41	12.31
Total Utilization	**Total Personal Hours**	**Personal Hours Per Day**	**Weekly Duty Hours**	**Normalized Weekly Duty Hours**
0.71	1230.04	8.20	139.34	118.98

The worst case individual resource utilizations can be seen in Tables C-8 and C-9. This was done as a way to prevent the averages from essentially smoothing over the extremes in the data sets. Therefore, the worst case individual was determined by finding the crewmember who obtained the least amount of sleep. Although it is simple to say that this would be the worst case member but this does not account for all of the slight differences in the crewmembers in terms of the job roles that held and qualifications that had. The averages and worst cases will be summarized as a way to determine in which situation the values exceeded or did not meet the presumed threshold of the Navy Standard Work Week.

Table C-8. ET worst case resource data.

Electronic Technician (ETC)	Total Hours	Daily Hours	Weekly Hours
Off Watch	1597.30	10.65	74.54
Watch	0.00	0.00	0.00
Sleep	843.09	5.62	39.34
Maint	746.71	4.98	34.85
Watch Prep	0.00	0.00	0.00
Training	15.00	0.10	0.70
Network Issues	16.18	0.11	0.76
Electrical Casualty	35.36	0.24	1.65
Flood	13.65	0.09	0.64
Fire	12.13	0.08	0.57
Radio Casualties	2.09	0.01	0.10
Eat	318.48	2.12	14.86
Total Utilization	**Total Personal Hours**	**Personal Hours Per Day**	**Weekly Duty Hours**
0.68	1161.57	7.74	113.79

Table C-9. ET worst case resource data.

Fire Control Technician (FTSN)	Total Hours	Daily Hours	Weekly Hours
Off Watch	1610.38	10.74	75.15
Watch	0.00	0.00	0.00
Sleep	854.79	5.70	39.89
Maint	744.74	4.96	34.75
Watch Prep	0.00	0.00	0.00
Training	16.00	0.11	0.75
Network Issues	0.00	0.00	0.00
Electrical Casualty	27.19	0.18	1.27
Flood	13.65	0.09	0.64
Fire	12.13	0.08	0.57
FT Casualties	0.00	0.00	0.00
Eat	321.12	2.14	14.99
Weekly Utilization	**Total Personal Hours**	**Personal Hours Per Day**	**Weekly Duty Hours**
0.67	1175.91	7.84	113.12

The resource data was then summarized into duty hours and personal hours to determine the weekly utilization and compared to the prescribed Navy Standard Work Week (NSWW). The NSWW is simply defined by 81 duty hours and 87 non-duty hours which includes personal time, sleep, messing and Sunday free time. The Baseline utilization summary can be seen below in Table C-10.

Table C-10. Baseline utilization summary.

Submarine Baseline	Navy Standard Work Week (Hours)	Average All		Average ET		Average FT		Worst Case ET		Worst Case FT	
		Weekly Hours	% of NSWW	Weekly Hours	% of NSWW	Weekly Hours	% of NSWW	Weekly Hours	% of NSWW	Weekly Hours	% of NSWW
Duty	81	115.98	143.2%	113.36	140.0%	118.98	146.9%	113.79	140.5%	113.12	139.7%
Personal Time (Sleep, Personal Time, Eating)	87	52.02	59.8%	54.64	62.8%	49.02	56.3%	54.21	62.3%	54.88	63.1%
Utilization	0.48	0.69	143.2%	0.67	140.0%	**0.71**	146.9%	**0.68**	140.5%	0.67	139.7%

The utilization summary shows that the worst case ET was actually the worst utilization of 0.68 for ETs and the average FT was the worst utilization of 0.71 for FTs. Each of these values are highlighted in a bright yellow in figure 7. It can also be seen that each rating is more than 40% over utilized compared to the NSWW. Since duty time is indirectly proportional to non-duty time, when duty time increases non-duty time decreases. This is evident in that each rating is over 40% deficient in personal time which accounts for all sleep. In fact in the model, sleep accounts for all personal or non-duty time outside of eating which means if the 2 prescribed NSWW hours of messing and 2 prescribed hours of personal time are subtracted from the total personal or non-duty time in figure 2 of 8.2 hours it can be seen that each crewmember is sleeping for approximately 4 hours on average. 4 hours is clearly not meeting the expected NSWW.

The final takeaway from the baseline data is when failed events are compared to utilization. If the events were allowed to restart it would significantly impact utilization. Utilization would increase and personal time would decrease directly impacting sleep time. This impact will be analyzed in more depth later in this analysis.

The Baseline results set the objective for the project model runs. The baseline seems to indicate that the VIRGINIA class submarine is over utilized in the current state before the additional air warfare systems. It is not the goal of the project to correct current deficiencies in the already designed and operational VIRGINIA class submarine. The IMPRINT model goal is to meet or exceed the baseline; in other words, no additional failed events and no utilization higher than the identified worst utilizations when compared to the initial baseline model. It is also important to note here that the project team was unable to obtain every specific detail regarding such factors as maintenance time, expected casualty frequency, and training time and therefore, the as designed

VIRGINIA class submarine platform may be manned sufficiently; however, the assumptions that were made for this project do not prove that to be the situation.

B. SUBMARINE LASER SYSTEM MODEL RESULTS

The IMPRINT Forces model was simulated with the additional inputs for the air warfare laser system with the existing manning from the VIRIGINA class ship's manning document. The event activity status summary for the Submarine Laser System Model produced the following results seen in Table C-11.

Table C-11. Submarine Laser System activity summary.

Unplanned Activity	Scheduled	Started	Successful	Interrupted	Delayed	Failed
CEC Issues	74	72	72	0	0	2
Electrical Casualty	14	14	14	0	0	0
Fire	5	5	5	0	0	0
Flooding	6	6	6	0	0	0
FT Casualties	10	10	10	0	0	0
Laser Firing Event	6	6	6	0	0	0
Laser System Malfunction	6	6	6	0	0	0
Link-16 Issues	146	144	144	0	0	2
Maintenance	1031	947	816	131	0	84
Network Issues	146	142	138	4	0	4
Radio Casualties	14	14	14	0	0	0
Training	51	47	45	0	0	4
WSN-7 Failure	6	6	6	0	0	0
					Total Failures	52

The activity summary shows that 1,519 events started but resulted in a total of 96 failures. This is 44 more failures than the 52 failed events seen in the baseline model. The individual resource data was analyzed similarly to the baseline in Tables C-12 through Table C-16 by taking the averages and worst case individual data sets. The data sets are provided as a reference source in the discussion to follow.

Table C-11. All personnel Laser System average resource data.

All	Total Hours	Avg Hours per Day	Weekly Hours	Normalized Weekly Hours
Off Watch	1108.97	7.39	51.75	46.95
Watch	1097.51	7.32	51.22	46.46
Sleep	947.72	6.32	44.23	40.12
Maint	316.18	2.11	14.76	13.38
Watch Prep	91.97	0.61	4.29	3.89
Training	30.30	0.20	1.41	1.28
Network Issues	29.17	0.19	1.36	1.23
Electrical Casualty	19.74	0.13	0.92	0.84
Flood	8.12	0.05	0.38	0.34
Fire	11.00	0.07	0.51	0.47
Radio Casualties	1.93	0.01	0.09	0.08
FT Casualties	1.98	0.01	0.09	0.08
Eat	279.22	1.86	13.03	11.82
Laser Firing Event	4.00	0.03	0.19	0.17
WSN-7 Failure	4.01	0.03	0.19	0.17
Link-16 Issues	5.82	0.04	0.27	0.25
CEC Issues	7.92	0.05	0.37	0.34
Laser System Malfunction	3.03	0.02	0.14	0.13
Total Utilization	**Total Personal Hours**	**Personal Hours Per Day**	**Weekly Duty Hours**	**Normalized Weekly Duty Hours**
0.69	1226.95	8.18	127.94	116.06

Table C-13. ET Laser System average resource data.

Electronic Technician (ET)	Total Hours	Daily Hours	Weekly Hours	Normalized Weekly Hours
Off Watch	957.96	6.39	44.70	42.71
Watch	1098.56	7.32	51.27	48.98
Sleep	960.65	6.40	44.83	42.83
Maint	292.42	1.95	13.65	13.04
Watch Prep	92.61	0.62	4.32	4.13
Training	27.66	0.18	1.29	1.23
Network Issues	12.50	0.08	0.58	0.56
Electrical Casualty	20.77	0.14	0.97	0.93
Flood	7.84	0.05	0.37	0.35
Fire	10.03	0.07	0.47	0.45
Radio Casualties	1.93	0.01	0.09	0.09
Eat	264.61	1.76	12.35	11.80
Laser Firing Event	4.67	0.03	0.22	0.21
WSN-7 Failure	4.46	0.03	0.21	0.20
Link-16 Issues	8.51	0.06	0.40	0.38
Laser System Malfunction	2.60	0.02	0.12	0.12
Total Utilization	**Total Personal Hours**	**Personal Hours Per Day**	**Weekly Duty Hours**	**Normalized Weekly Duty Hours**
0.67	1225.26	8.17	118.65	113.37

Table C-14. FT Laser System average resource data.

Fire Control Technician (FT)	Total Hours	Daily Hours	Weekly Hours	Normalized Weekly Hours
Off Watch	1310.32	8.74	61.15	52.17
Watch	1095.05	7.30	51.10	43.60
Sleep	930.49	6.20	43.42	37.05
Maint	347.86	2.32	16.23	13.85
Watch Prep	90.46	0.60	4.22	3.60
Training	32.94	0.22	1.54	1.31
Network Issues	52.51	0.35	2.45	2.09
Electrical Casualty	18.37	0.12	0.86	0.73
Flood	8.48	0.06	0.40	0.34
Fire	12.30	0.08	0.57	0.49
FT Casualties	1.98	0.01	0.09	0.08
Eat	298.71	1.99	13.94	11.89
Laser Firing Event	3.33	0.02	0.16	0.13
WSN-7 Failure	3.42	0.02	0.16	0.14
Link-16 Issues	1.51	0.01	0.07	0.06
CEC Issues	7.92	0.05	0.37	0.32
Laser System Malfunction	3.64	0.02	0.17	0.14
Total Utilization	**Total Personal Hours**	**Personal Hours Per Day**	**Weekly Duty Hours**	**Normalized Weekly Duty Hours**
0.71	1229.20	8.19	139.54	119.06

Table C-15. ET Laser System worst case resource data.

Electronic Technician (ETC)	Total Hours	Daily Hours	Weekly Hours
Off Watch	1469.19	9.79	68.56
Watch	0.00	0.00	0.00
Sleep	868.80	5.79	40.54
Maint	832.56	5.55	38.85
Watch Prep	0.00	0.00	0.00
Training	17.88	0.12	0.83
Network Issues	16.88	0.11	0.79
Electrical Casualty	42.74	0.28	1.99
Flood	11.36	0.08	0.53
Fire	12.18	0.08	0.57
Radio Casualties	4.06	0.03	0.19
Eat	291.87	1.95	13.62
Laser Firing Event	8.00	0.05	0.37
WSN-7 Failure	9.78	0.07	0.46
Link-16 Issues	14.49	0.10	0.68
Laser System Malfunction	0.19	0.00	0.01
Total Utilization	**Total Personal Hours**	**Personal Hours Per Day**	**Weekly Duty Hours**
0.68	1160.67	7.74	113.84

Table C-16. FT Laser System worst case resource data.

Fire Control Technician (FTSN)	Total Hours	Daily Hours	Weekly Hours
Off Watch	1672.66	11.15	78.06
Watch	0.00	0.00	0.00
Sleep	853.93	5.69	39.85
Maint	669.92	4.47	31.26
Watch Prep	0.00	0.00	0.00
Training	24.00	0.16	1.12
Network Issues	0.00	0.00	0.00
Electrical Casualty	26.45	0.18	1.23
Flood	9.14	0.06	0.43
Fire	12.18	0.08	0.57
FT Casualties	0.00	0.00	0.00
Eat	326.52	2.18	15.24
Laser Firing Event	0.00	0.00	0.00
WSN-7 Failure	1.91	0.01	0.09
Link-16 Issues	0.00	0.00	0.00
CEC Issues	0.00	0.00	0.00
Laser System Malfunction	3.30	0.02	0.15
Total Utilization	**Total Personal Hours**	**Personal Hours Per Day**	**Weekly Duty Hours**
0.67	1180.45	7.87	112.91

The utilizations for each resource table was summarized and compared to the Navy Standard Work Week (NSWW). Table C-17 shows the Submarine Laser System utilization summary:

Table C-17. Submarine Laser System utilization summary.

Submarine with Laser System	Navy Standard Work Week (Hours)	Average All		Average ET		Average FT		Worst Case ET		Worst Case FT	
		Weekly Hours	% of NSWW	Weekly Hours	% of NSWW	Weekly Hours	% of NSWW	Weekly Hours	% of NSWW	Weekly Hours	% of NSWW
Duty	81	116.06	143.3%	113.37	140.0%	119.06	147.0%	113.84	140.5%	112.91	139.4%
Personal Time (Sleep, Personal Time, Eating)	87	51.94	59.7%	54.63	62.8%	48.94	56.3%	54.16	62.3%	55.09	63.3%
Utilization	0.48	0.69	143.3%	0.67	140.0%	**0.71**	147.0%	**0.68**	140.5%	0.67	139.4%

The utilization summary shows that the worst utilization is equal to the worst utilization seen in the baseline model. However this model failed 44 more events than the baseline. Had the events been able to restart it would have significantly impacted the utilization in order to pass more events. This indicates that the VIRGINIA class submarine will require additional manning augments in order to absorb the additional air warfare systems. This is the basis for augmenting the submarine with additional personnel since as explained previously their utilization remains the same but the number of events that they fail increases with an increasing level of work.

C. SUBMARINE LASER SYSTEM WITH AUGMENTED MANNING

The project team started with 1 additional crewmember and increased that manning number until a value was achieved that met or exceeded the failed events of the initial baseline model's results. It was determined that the required augment needed to achieve the baseline was 4 personnel - 2 ETs and 2 FTs. The event activity status summary for the 4 persons Augmented Model produced the following results seen in Table C-18.

Table C-18. Augmented manning activity summary.

Unplanned Activity	Scheduled	Started	Successful	Interrupted	Delayed	Failed
CEC Issues	74	72	74	0	0	0
Electrical Casualty	14	14	14	0	0	0
Fire	5	5	5	0	0	0
Flooding	6	6	6	0	0	0
FT Casualties	10	10	10	0	0	0
Laser Firing Event	6	6	6	0	0	0
Laser System Malfunction	10	10	10	0	0	0
Link-16 Issues	146	146	146	0	0	0
Maintenance	969	922	853	69	0	47
Network Issues	142	142	142	0	0	0
Radio Casualties	14	14	14	0	0	0
Training	52	52	49	3	0	0
WSN-7 Failure	6	6	6	0	0	0
					Total Failures	47

The activity summary shows that 1,454 events started and resulted in a total of 47 failures. This is 5 less failures than the 52 failed events seen in the baseline model. It is again important to note that these events take place over a period of 150 days and therefore provide a good statistical average of the most probable numbers to expect based upon the assumptions used in the submarine model. The individual resource data was analyzed similarly to the baseline and is shown in Tables C-19 through C-24 by taking the averages and worst case individual data.

Table C-19. All personnel augmented model average resource data.

All	Total Hours	Avg Hours per Day	Weekly Hours	Normalized Weekly Hours
Off Watch	1357.04	9.05	63.33	54.93
Watch	1099.27	7.33	51.30	44.50
Sleep	937.84	6.25	43.77	37.96
Maint	248.53	1.66	11.60	10.06
Watch Prep	92.18	0.61	4.30	3.73
Training	29.11	0.19	1.36	1.18
Network Issues	22.55	0.15	1.05	0.91
Electrical Casualty	15.35	0.10	0.72	0.62
Flood	6.31	0.04	0.29	0.26
Fire	8.56	0.06	0.40	0.35
Radio Casualties	1.93	0.01	0.09	0.08
FT Casualties	1.65	0.01	0.08	0.07
Eat	311.60	2.08	14.54	12.61
Laser Firing Event	3.00	0.02	0.14	0.12
WSN-7 Failure	3.75	0.02	0.17	0.15
Link-16 Issues	4.51	0.03	0.21	0.18
CEC Issues	4.93	0.03	0.23	0.20
Laser System Malfunction	2.43	0.02	0.11	0.10
Total Utilization	**Total Personal Hours**	**Personal Hours Per Day**	**Weekly Duty Hours**	**Normalized Weekly Duty Hours**
0.70	1249.43	8.33	135.38	117.43

Table C-20. ET augmented model average resource data.

Electronic Technician (ET)	Total Hours	Daily Hours	Weekly Hours	Normalized Weekly Hours
Off Watch	1201.26	8.01	56.06	50.78
Watch	1099.56	7.33	51.31	46.48
Sleep	950.10	6.33	44.34	40.16
Maint	247.56	1.65	11.55	10.46
Watch Prep	92.80	0.62	4.33	3.92
Training	27.53	0.18	1.28	1.16
Network Issues	10.02	0.07	0.47	0.42
Electrical Casualty	15.44	0.10	0.72	0.65
Flood	6.87	0.05	0.32	0.29
Fire	7.87	0.05	0.37	0.33
Radio Casualties	1.93	0.01	0.09	0.08
Eat	295.85	1.97	13.81	12.51
Laser Firing Event	4.00	0.03	0.19	0.17
WSN-7 Failure	4.37	0.03	0.20	0.18
Link-16 Issues	6.99	0.05	0.33	0.30
Laser System Malfunction	2.27	0.02	0.11	0.10
Total Utilization	**Total Personal Hours**	**Personal Hours Per Day**	**Weekly Duty Hours**	**Normalized Weekly Duty Hours**
0.69	1245.96	8.31	127.33	115.33

Table C-21. FT augmented model average resource data.

Fire Control Technician (FT)	Total Hours	Daily Hours	Weekly Hours	Normalized Weekly Hours
Off Watch	1551.77	10.35	72.42	59.75
Watch	1098.61	7.32	51.27	42.30
Sleep	922.50	6.15	43.05	35.52
Maint	249.75	1.66	11.65	9.62
Watch Prep	90.73	0.60	4.23	3.49
Training	30.70	0.20	1.43	1.18
Network Issues	38.65	0.26	1.80	1.49
Electrical Casualty	15.24	0.10	0.71	0.59
Flood	5.61	0.04	0.26	0.22
Fire	9.41	0.06	0.44	0.36
FT Casualties	1.65	0.01	0.08	0.06
Eat	331.28	2.21	15.46	12.76
Laser Firing Event	6.20	0.04	0.29	0.24
WSN-7 Failure	2.60	0.02	0.12	0.10
Link-16 Issues	0.96	0.01	0.04	0.04
CEC Issues	4.93	0.03	0.23	0.19
Laser System Malfunction	2.60	0.02	0.12	0.10
Total Utilization	**Total Personal Hours**	**Personal Hours Per Day**	**Weekly Duty Hours**	**Normalized Weekly Duty Hours**
0.71	1253.78	8.36	145.11	119.72

Table C-22. ET augmented model worst case individual resource data.

Electronic Technician (ET2 #4A)	Total Hours	Daily Hours	Weekly Hours
Off Watch	1593.25	10.62	74.35
Watch	0.00	0.00	0.00
Sleep	856.34	5.71	39.96
Maint	713.90	4.76	33.32
Watch Prep	0.00	0.00	0.00
Training	27.88	0.19	1.30
Network Issues	12.40	0.08	0.58
Electrical Casualty	33.66	0.22	1.57
Flood	11.36	0.08	0.53
Fire	12.18	0.08	0.57
Radio Casualties	2.81	0.02	0.13
Eat	311.22	2.07	14.52
Laser Firing Event	0.00	0.00	0.00
WSN-7 Failure	11.39	0.08	0.53
Link-16 Issues	11.77	0.08	0.55
Laser System Malfunction	1.84	0.01	0.09
Total Utilization	**Total Personal Hours**	**Personal Hours Per Day**	**Weekly Duty Hours**
0.68	1167.56	7.78	113.51

Table C-23. FT augmented model worst case individual resource data.

Fire Control Technician (FT2 #4A)	Total Hours	Daily Hours	Weekly Hours
Off Watch	1414.11	9.43	65.99
Watch	0.00	0.00	0.00
Sleep	898.12	5.99	41.91
Maint	872.03	5.81	40.69
Watch Prep	0.00	0.00	0.00
Training	17.00	0.11	0.79
Network Issues	53.24	0.35	2.48
Electrical Casualty	22.01	0.15	1.03
Flood	9.23	0.06	0.43
Fire	10.46	0.07	0.49
FT Casualties	3.19	0.02	0.15
Eat	285.69	1.90	13.33
Laser Firing Event	2.00	0.01	0.09
WSN-7 Failure	1.91	0.01	0.09
Link-16 Issues	2.61	0.02	0.12
CEC Issues	7.18	0.05	0.34
Laser System Malfunction	1.22	0.01	0.06
Total Utilization	**Total Personal Hours**	**Personal Hours Per Day**	**Weekly Duty Hours**
0.67	1183.81	7.89	112.76

The utilizations for each resource table was summarized and compared to the NSWW. Table C-24 shows the predictions of the augmented model.

Table C-24. Augmented submarine Laser System utilization summary.

Submarine with Laser System and 4 Manning Augments	Navy Standard Work Week (Hours)	Average All		Average ET		Average FT		Worst Case ET		Worst Case FT	
		Weekly Hours	% of NSWW	Weekly Hours	% of NSWW	Weekly Hours	% of NSWW	Weekly Hours	% of NSWW	Weekly Hours	% of NSWW
Duty	81	117.43	145.0%	115.33	142.4%	119.72	147.8%	113.51	140.1%	112.76	139.2%
Personal Time (Sleep, Personal Time, Eating)	87	50.57	58.1%	52.67	60.5%	48.28	55.5%	54.49	62.6%	55.24	63.5%
Utilization	0.48	0.70	145.0%	0.69	142.4%	**0.71**	147.8%	**0.68**	140.1%	0.67	139.2%

The utilization summary shows that the Augmented Submarine worst utilization is equal to the worst utilization seen in the baseline model which was expected as explained thoroughly earlier in this project report. However this model failed 5 less events than the baseline. This shows that 4 augmented personnel, 2 ETs and 2 FTs, are required for the VIRGINIA class submarine to absorb the air warfare weapons systems without increasing the workload on the already existing over-utilized crew-members.

D. PERSONNEL LIFECYCLE COST

The increased augment of 4 personnel would have a significant cost impact. The project assumed that each augment would be an E-5 with 6 years of service. This assumption is very reasonable since the qualifications expected to be either a maintainer or an operator of an advanced combat system such as a laser would be expected that the individual have an adequate experience level. This would result in base pay, basic housing allowance (BAH), basic allowance for sustenance (BAS), submarine pay, and sea pay. There would also be a significant cost for healthcare, support services, and training. For simplicity the project ignored these costs and only used pay and allowances to project a lifecycle cost. Table C-25 is a summary of the pay and allowance costs for 4 augmented personnel for 48 ships over a lifecycle of 33 years. The VIRGINIA class submarine program has planned to build 48 ships in this class and each ship has an expected service life of 33 years. Table C-25 provides all of the individual cost drivers used to predict the overall cost impact to the VIRGINIA class program for its 33-year lifecycle to be approximately $518 million.

Table C-25. Lifecycle cost for augmented personnel.

PO2 (6 yrs)	Monthly Cost ($)	Annual Cost ($)
Base Pay	2761.80	33141.60
BAH (HI)	2994.00	35928.00
Sea Pay	406.00	4872.00
Sub Pay	275.00	3300.00
BAS	376.92	4523.04
	Cost of 1 Sailor	81764.64
	Cost per Boat	327058.56
	33 Life of Ship	10792932.48
	48 Ships	**518,060,759.04**

E. FAILED EVENT IMPACTS ON UTILIZATION

The Forces model was set to fail events over restarting as previously stated because it does not impact increasing utilization accurately as stated in the previous sections of this report. Therefore it's pertinent to determine what the impact of these failed events would have on the resources of the personnel assigned. The failed events are summarized in Table C-26 below and separated into three columns of each of the characteristic models that were analyzed in this project.

Table C-26. Failed event summary.

Failures	**Submarine Baseline**	**Submarine with Laser**	**Submarine Laser with 4 Augments**
CEC Issues	0	2	0
Electrical Casualty	0	0	0
Fire	0	0	0
Flooding	0	0	0
FT Casualties	0	0	0
Laser Firing Event	0	0	0
Laser System Malfunction	0	0	0
Link-16 Issues	0	2	0
Maintenance	44	84	47
Network Issues	5	4	0
Radio Casualties	0	0	0
Training	3	4	0
WSN-7 Failure	0	0	0
Total Failures	52	96	47

Using the mean time for each failed event's distribution an overall resource value for the failed events can be determined. In doing this a daily and weekly resource impact to each individual can be determined by taking the total weekly or daily hours of the failed events and dividing them by the total manning compliment. This is a rough calculation because the event durations are normally distributed and not every technician is qualified to respond to every event, but it does give a rough indication of the failed events impact to the human resources. The resource impact to personnel had they covered the failed events can be seen in Table C-27 below.

Table C-27. Personnel time versus failed events.

Personal Time vs Event Failures (Hours)	Submarine Baseline	Submarine with Laser	Submarine Laser with 4 Augments
Event Failure Total Time	201	449.67	235
Event Failure Daily Time	1.34	3.00	1.57
Event Failure Weekly Time	9.38	20.98	10.97
Daily Impact to All Personal Time	-0.10	-0.21	-0.09
Weekly Impact to All Personal Time	-0.67	-1.50	-0.61

Table C-27 shows the weekly impact to every person's personal or non-duty time. For instance, in the Submarine with Laser model, had the personnel actually successfully accomplished the failed events every person in the model would have forfeited 1.5 hours of personal time. In other words these personnel would achieve 1.5 hours less sleep. In the Submarine Baseline model section of this report it was determined that all personnel were getting approximately 4 hours of sleep per day. This increased utilization of successfully accomplishing the failed events would cause that previously predicted 4 hours of sleep per day for every person to drop to approximately only 3 hours and 40 minutes per day. This amount of sleep is unsustainable for an individual for any significant period of time.

V. CONCLUSION

The results provided an interesting perspective into the current VIRGINIA class submarine manning. Based upon the assumptions that were made in this project, it was clearly evident that the two enlisted ratings there were reviewed were undermanned for their expected number of potential activities that they might need to respond to. This was not a completely unexpected outcome at the start of the project though it is very important to highlight this initial workload manning deficit.

The focus of this project was to determine if the hypothesis that adding the air warfare mission area to a submarine would create the need to add additional personnel to the submarine to manage the increased workload. The hypothesis was clearly validated from the simulations conducted based upon the submarine models created. The results concluded that 4 additional personnel, 2 from each enlisted rate studied would be needed when a High Energy Laser weapon system suite is integrated into a VIRGINIA class submarine platform.

This project provided a broader learning perspective that must be considered when any sub-system is introduced to an already built system. The broader learning perspective is that human factors engineering must be considered when integrating a sub-system into an already built system and not simply assume that the current operators and maintainers will be capable of absorbing the additional workload. While this project did not introduce the peculiarities of a crewmember's training or education for the newer sub-system, it is easy to understand how important these would be when introducing a new sub-system. Not only would it be necessary to study and analyze the level of training and education necessary for the new sub-system, it would be equally important to analyze the effects of what that time for the new sub-system would take away from the training and education that the members already get for the current sub-systems they are responsible for.

VI. FURTHER AREAS FOR RESEARCH

Research should be further conducted looking into current VIRGINIA class submarine manning levels without the laser weapon system. This additional research and analysis will help to determine the potential of the crew to absorb any additional workload from the integration of any sub-system. In this project, 4 additional crewmembers were determined to be necessary for the integrated laser weapon system; however, the project was scoped in such a way to not conduct analysis into the additional impacts from these personnel such as berthing, messing, and all standard habitability requirements.

Another approach for further analysis for the integration of a laser weapon system onto a submarine platform would be to model the entire submarine crew. This would provide a more robust understanding of the entire crew's personal utilization rates and which crewmembers may be able to absorb an increase in workload more than the enlisted rates that were studied in this project. Also, not only should all of the current VIRGINIA class enlisted rates be reviewed and studied to determine which may be the best candidates to be trained in the use and maintenance of the systems needed for the conduct of air warfare but additional enlisted rates not currently onboard a submarine should be included in the study. An additional rate that could be very useful for a submarine with an integrated air warfare weapon system might be an Operational Specialist (OS). The OS rate might prove to be an enlisted member that could be well trained and provide valuable experience for the current submarine enlisted ratings. Furthermore, additional analysis might be very useful in the area of different watch-standing conditions such as battle-stations or condition 1, general quarters. This will help to provide additional understanding as to the more specific effects of personal utilization in various conditions of battle.

VII. FINAL IMPRINT SOFTWARE DISCUSSION / RECOMMENDATIONS

The IMPRINT software tool was used to conduct this analysis and was found to be extremely effective though it was not particularly user-friendly. The analysis began by building the submarine model using the Littoral Combat Ship model (LCS_FREEDOM_40.imprint) built by the thesis team of Renaldo N. Hollins and Kelly M. Leszczynski of December, 2014. Using the LCS model the analysis team was able to quickly and effectively read the format and structure of the software. After a short period of learning (about 4-6 hours of use) some of the requirements and limitations of the software was found to be more than sufficient for our needs to the point that a significant amount of extra data entry was necessary to meet the software requirements but had no bearing on the problem that was being researched. Specifically, highly detailed watch schedules were needed to be crafted and used but ultimately were not variable in the research. Additionally, a more user-friendly watch-section interface would have been helpful, as the current program requires each event to be scheduled sequentially starting at 0000 on the first day and continuing until the end of the watch period length. On that note, when typing in a data field it would seem that the presence of a blinking cursor to indicate the location of where typing will occur was sporadic at best.

Positive points of the software include the fact that much of the personnel information, such as detailed rates and specialties are pre-programmed. An example of this is the fact that while there is one Electronics Technicians (ETs) rate in the Navy, the specialty of an ET on a submarine is very different than an ET in the Nuclear Field and significantly different than an ET in the advanced electronics field, and all three different ETs are selections in the software. Furthermore, the software provided flexibility in allowing user-defined job roles to personnel regardless of rate and specialty, thus allowing multiple different rated personnel to be required to respond to different planned and unplanned casualties. In this project the job role capability was used to define specific qualifications or skills so that some of the ETs were qualified to be radio technicians while others are not.

Another significant difficulty was discovered in the handling of maintenance onboard a submarine. Maintenance for a submarine is handled by off-watch personnel who will complete the maintenance during the scheduled period. Any maintenance that for some reason is not accomplished during that time period would be either passed on to the next off-watch personnel or would be accomplished during the designated sleeping period. As there was no way found to do this in IMPRINT, the choice was made to make maintenance an unplanned event with duration corresponding to assumed average maintenance length. The loophole that was found in the program is that when maintenance is interrupted, realistically it will take additional time to accomplish as the stopping and starting of the procedures are not instantaneous. This additional time for resuming work after a break cannot be added into each of the events, thus, resuming maintenance continues throughout the deployment with no requirement for scheduling or any ‘drop dead’ dates.

Overall, IMPRINT was found to be a very powerful and effective tool to accomplish what was needed to be done. While it is possible that this could have been accomplished using some familiar but intense programming in Microsoft Excel, IMPRINT was the right choice in this circumstance. The team did not have sufficient time during the course of research to fully dive into what the program could do, leaving many questions as to whether or not the limitations encountered could have been resolved with additional time or training in the software, though learning all of the finer details of the software was not the intent of the project.

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APPENDIX D: PRESENTATION OF THE STUDY CONDUCTED BY ROBISON ET AL. (2015)

Introduction

- **PROBLEM:** OPNAV N97 is interested in integrating a High Energy Laser onto a Virginia Class Submarine

- **HYPOTHESIS:** Current Virginia class submarine manning is not suitable to manage the increased workload of a new High Energy Laser Weapon system

Literature Review

- Capstone Project (LCS crew manning, use of IMPRINT)
- Final Project (Adjustments to initial IMPRINT model)
- Navy total force manpower policies and procedures (Navy Standard Work Week)
- Ship's Manning Documents (surface ships, VIRGINIA class submarine)
- Laser weapon system (Harney, Vol. 1, Ch. 17)

Objectives

- To determine
  1. if, from a manning perspective, the additional laser weapon system is feasible
  2. the projected manning requirements for the system
  3. the potential lifecycle cost of personnel for the system

Methodology / Data Collection

1. Baseline (Forces IMPRINT) model for submarine control room
   1. Force numbers / rates and their schedule
   2. Planned and Unplanned activities
2. Evaluate baseline IMPRINT model for “as-is” workload
3. Add additional Laser Weapon systems activities to the submarine baseline model
4. Evaluate the updated model’s overall workload
5. Add additional personnel to manage the increased workload
6. Analyze and compare the updated system’s workload to the initial baseline and the NSWW

Primary Assumptions

1. Only rated personnel examined are affected by changes
2. Only specified enlisted rates will be trained
3. No additional rates will be added
4. Experience levels have no affect on performance
5. Additional personnel could not negatively affect performance
6. Maintenance is an unplanned event
7. Laser firing events would occur during normal manning conditions with augmented watch team

Primary Assumptions (Watch Rotation)

Activities | Force Models | Warfighters | Unplanned | Schedules

Special Evolution Team | WATCH SECTION 1 OF 3 | WATCH SECTION 2 OF 3 | WATCH SECTION 3 OF 3

Activity	Start Time	End Time	Total Activity Time
Sleep	00:00	05:00	05:00
Watch Preparation	05:00	05:30	00:30
Eat	05:30	06:00	00:30
Watch	06:00	11:30	05:30
Eat	11:30	12:00	00:30
Off Watch	12:00	17:30	05:30
Eat	17:30	18:00	00:30
Sleep	18:00	23:00	05:00
Watch Preparation	23:00	23:30	00:30
Eat	23:30	1 00:00	00:30
Watch	1 00:00	1 05:30	05:30
Eat	1 05:30	1 06:00	00:30
Off Watch	1 06:00	1 11:30	05:30
Eat	1 11:30	1 12:00	00:30
Sleep	1 12:00	1 17:00	05:00
Watch Preparation	1 17:00	1 17:30	00:30
Eat	1 17:30	1 18:00	00:30
Watch	1 18:00	1 23:30	05:30
Eat	1 23:30	2 00:00	00:30
Off Watch	2 00:00	2 05:30	05:30
Eat	2 05:30	2 06:00	00:30
Sleep	2 06:00	2 11:00	05:00
Watch Preparation	2 11:00	2 11:30	00:30
Eat	2 11:30	2 12:00	00:30
Watch	2 12:00	2 17:30	05:30
Eat	2 17:30	2 18:00	00:30
Off Watch	2 18:00	2 23:30	05:30
Eat	2 23:30	3 00:00	00:30

Primary Assumptions (Event Priority List)

Activities

Priority	Name	Type
0	Watch	Planned
5	Laser Firing Event	Unplanned
10	Flooding	Unplanned
15	Fire	Unplanned
20	Electrical Casualty	Unplanned
90	WSN-7 Failure	Unplanned
100	LINK-16 Issues	Unplanned
100	CEC Issues	Unplanned
105	Radio Casualties	Unplanned
110	Network Issues	Unplanned
115	FT Casualties	Unplanned
130	Laser System Malfunction	Unplanned
135	Sleep	Planned
190	Watch Preparation	Planned
200	Eat	Planned
215	Maintenance	Unplanned
220	Training	Unplanned
225	Off Watch	Planned

Analysis Process

- Obtain the data output from IMPRINT
  - Baseline model
  - Laser system model
  - Augmented model
- Analyze average work hours per person and their utilization
- Analyze worst case utilization
- Compare hours worked to NSWW
- Examine the difference between the initial baseline model and the adjusted model with the new warfare area
  - Adjusted model was not intended to correct deficiencies of the baseline model
- Examined the impact to personnel
- Determined lifecycle cost of additional personnel

Results (Event Failures)

Failures	Submarine Baseline	Submarine with Laser	Submarine Laser with 4 Augments
CEC Issues	0	2	0
Electrical Casualty	0	0	0
Fire	0	0	0
Flooding	0	0	0
FT Casualties	0	0	0
Laser Firing Event	0	0	0
Laser System Malfunction	0	0	0
LINK-16 Issues	0	2	0
Maintenance	44	84	47
Network Issues	5	4	0
Radio Casualties	0	0	0
Training	3	4	0
WSN-7 Failure	0	0	0
Total Failures	52	96	47

Results (Utilization)

Submarine Baseline	Navy Standard Work Week (Hours)	Average All		Average ET		Average FT		Worst Case ET		Worst Case FT	
		Weekly Hours	% of NSWW	Weekly Hours	% of NSWW	Weekly Hours	% of NSWW	Weekly Hours	% of NSWW	Weekly Hours	% of NSWW
Duty	81	115.98	143.2%	113.36	140.0%	118.98	146.9%	113.79	140.5%	113.12	139.7%
Personal Time (Sleep, Personal Time, Eating)	87	52.02	59.8%	54.64	62.8%	49.02	56.3%	54.21	62.3%	54.88	63.1%
Utilization	0.48	0.69	143.2%	0.67	140.0%	0.71	146.9%	0.68	140.5%	0.67	139.7%

Submarine with Laser System	Navy Standard Work Week (Hours)	Average All		Average ET		Average FT		Worst Case ET		Worst Case FT	
		Weekly Hours	% of NSWW	Weekly Hours	% of NSWW	Weekly Hours	% of NSWW	Weekly Hours	% of NSWW	Weekly Hours	% of NSWW
Duty	81	116.06	143.3%	113.37	140.0%	119.06	147.0%	113.84	140.5%	112.91	139.4%
Personal Time (Sleep, Personal Time, Eating)	87	51.94	59.7%	54.63	62.8%	48.94	56.3%	54.16	62.3%	55.09	63.3%
Utilization	0.48	0.69	143.3%	0.67	140.0%	0.71	147.0%	0.68	140.5%	0.67	139.4%

Submarine with Laser System and 4 Manning Augments	Navy Standard Work Week (Hours)	Average All		Average ET		Average FT		Worst Case ET		Worst Case FT	
		Weekly Hours	% of NSWW	Weekly Hours	% of NSWW	Weekly Hours	% of NSWW	Weekly Hours	% of NSWW	Weekly Hours	% of NSWW
Duty	81	117.43	145.0%	115.33	142.4%	119.72	147.8%	113.51	140.1%	112.76	139.2%
Personal Time (Sleep, Personal Time, Eating)	87	50.57	58.1%	52.67	60.5%	48.28	55.5%	54.49	62.6%	55.24	63.5%
Utilization	0.48	0.70	145.0%	0.69	142.4%	0.71	147.8%	0.68	140.1%	0.67	139.2%

Results (Impact to Personnel)

Personal Time vs Event Failures (Hours)	Submarine Baseline	Submarine with Laser	Submarine Laser with 4 Augments
Event Failure Total Time	201	449.67	235
Event Failure Daily Time	1.34	3.00	1.57
Event Failure Weekly Time	9.38	20.98	10.97
Daily Impact to All Personal Time	-0.10	-0.21	-0.09
Weekly Impact to All Personal Time	-0.67	-1.50	-0.61

- **NSWW:** Personal time (NSWW = 12 hrs) accounts for:
  - Sleep: 8 hrs daily per NSWW
  - Non-duty Time: 2 hrs daily per NSWW
  - Messing: 2 hrs daily per NSWW
- **IMPRINT Model:**
  - Personal time per model: ~ 8 hrs daily
  - Sleep time per model: ~ 4 hrs daily

Lifecycle Cost

- How much does it cost to add 4 people to each boat over the lifecycle of the VIRGINIA class submarine program?

PO2 (6 yrs)	Monthly Cost ($)	Annual Cost ($)
Base Pay	2761.80	33141.60
BAH (HI)	2994.00	35928.00
Sea Pay	406.00	4872.00
Sub Pay	275.00	3300.00
BAS	376.92	4523.04
	Cost of 1 Sailor	81764.64
	Cost per Boat	327058.56
	33 Life of Ship	10792932.48
	48 Ships	**518,060,759.04**

Conclusions

- Virginia class submarine manning in the rates analyzed appears over-utilized
  - Sleep time is very limited for the provided ship's manning
- Virginia class submarine cannot absorb an additional air warfare mission area as manned
- 4 additional personnel are needed to manage new weapon system at current utilization rates

Future Considerations

- Further address the challenges imposed on current manning on Virginia class submarines
  - Current manning is ~46% over-utilized causing a drastic reduction in the standard crew-member's ability to get sleep
- Expand the study to include the entire ship's manning, not only the two rates considered in this project
- Investigate the specific details of the proposed laser weapon system
  - Look into the training aspects of the rates
  - Look into augmenting the submarine with new rates (NEC's)
- Further iterations of IMPRINT models will most likely improve results performance and provide better future predictions

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