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A Bridge and Engine Room Staffing and Scheduling Model for Robust Mission Accomplishment in the Littoral Combat Ships

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A BRIDGE AND ENGINE ROOM STAFFING AND SCHEDULING MODEL FOR ROBUST MISSION ACCOMPLISHMENT IN THE LITTORAL COMBAT SHIPS

by

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ABSTRACT

A BRIDGE AND ENGINE ROOM STAFFING AND SCHEDULING MODEL FOR ROBUST MISSION ACCOMPLISHMENT IN THE LITTORAL COMBAT SHIPS

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Old Dominion University, 2019
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The Navy's Littoral Combat Ships were designed to be relatively small surface vessels for operations near a littoral shore theater. These ships were envisioned to be highly automated, networked, agile, stealthy surface combatants capable of defeating anti-access and asymmetric threats in the littorals with minimum manpower. To date, however, some of these ships have experienced significant engineering and propulsion plant failures that impacted mission accomplishment and were attributable, at least in part, to under staffing and over scheduling the human component of the automation-human operational environment. The critical human components on the Littoral Combat Ship are bridge and engine room staffing. Since the engineering plant has been the source of most major failures to date, this project sought to develop an engine room staffing and scheduling model for the Littoral Combat Ship class given a stated set of minimum mission objectives when operating under normal conditions – called "Condition III Underway Steaming", which is used as the basis for official Navy manning calculations, and to provide recommendations for improved automation-human modeling. A survey of the crew of several LCS ships was conducted and the results were analyzed using exploratory data analysis and multiple joint correspondence analysis. Results of the survey analysis were applied to the design of a joint physical-cognitive-automation workflow analysis of critical procedures and failure modes as they map to four dimensions: fatigue, watch and maintenance tasking, and

automation-human interface. Workflow analysis results were then simulated in an IMPRINT model of a typical watch period, and the results were evaluated against the four dimensions of the survey. The project validated that the four dimensions analyzed are indeed worthy of consideration in manpower models, and that IMPRINT has the potential, with a few modifications, to model joint physical-cognitive-automation workflows as an improvement to the current manpower-only models used in Navy ship design by accounting for human factors.

This Dissertation is dedicated to my wife Gudrun, who cajoled me into pursuing this degree and removed every excuse to allow me to complete it. She sets an example in overcoming adversity that I can only hope to live up to.

It is also dedicated to the Navy and to the Sailors who serve at sea, in hopes that the results will improve their quality of life.

ACKNOWLEDGEMENTS

There are several people who contributed to the successful completion of this work. I extend heartfelt thanks to my committee members who also served as instructors and mentors, with special thanks to my major advisor director who deserves special recognition for nearly 5 years of patience and dedication to its completeness.

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INTRODUCTION

1.1 TECHNICAL FORMULATION

The Navy's Littoral Combat Ships were designed to be relatively small surface vessels for operations near a littoral shore theater. These ships were envisioned to be highly automated, networked, agile, stealthy surface combatants capable of defeating anti-access and asymmetric threats in the littorals with minimum manpower. Most of the mission functions are performed by carried vehicles such as helicopters or unmanned vehicles such as the Spartan Scout, AN/WLD-1 RMS Remote Mine hunting System and MQ-8B Fire Scout as part of the Navy's goal to "unman the front lines." To date, however, some of these ships have experienced significant failures in mission accomplishment which have been, at least in part, attributable to understaffing and overscheduling the human component of the automation-human operational environment. In one case, an LCS had seawater leak into one of its main diesel propulsion systems and was forced to return to port for repairs. In another, an LCS ship suffered propulsion issues after engineers attempted to use gears without adequately oiling them. The subsequent damage cost $23 million to repair, according to the Navy (Gallagher, March 2014). Based on these casualties, this project focused on what appears to be the critical human component of the Littoral Combat Ship: engine room staffing.

The IMPRINT model is designed to start with a defined set of mission requirements as specified by the user and a set of attributes that could influence the ability of the platform (defined as the combination of the ship or "sea-frame", the mission module, and the crew) to accomplish the mission. Measures of effectiveness must be determined and entered into the model to ensure that all nodes are identified and adequately described. As discussed above, engineering is common to all mission areas; in previous Naval Postgraduate School studies (Kerno 2015, Meredith 2016), this module is the most developed, listed as the most likely to be vulnerable to the impact of fatigue and overtasking, and based on this author's experience, the most likely to be capable of being studied in real-life situations. Previous IMPRINT projects have used the Forces Model function, which creates a more global force level manpower study, in which "workload" is just simple engagement with high level activities. This study differs in that it looks at a detailed human performance scenario using Operations Model, where workload is defined as the mental capacity being utilized to perform more definitive tasks. The detailed human performance models allow the analyst measure outcomes such as mission times, mission completion, and errors and their consequences as metrics.

1.2 PROJECT PURPOSE

This project sought to develop a bridge and engine room staffing and scheduling model for the Littoral Combat Ship class given a stated set of minimum mission objectives when operating under normal conditions and varying littoral combat environments. Specific steps of this process:

a. Identifying a stated set of mission objectives under normal and combat littoral environments.
b. Decomposing the set of mission objectives into bridge and engine room functional performance requirements using IMPRINT and modeling tools.
c. Performing root cause analysis of mission accomplishment failure modes in the littoral class of combat ships.

d. Identifying existing staffing and scheduling models and comparing their functional strengths and weaknesses to the engine room functional requirements.

e. Selecting an existing or developing a new staffing and scheduling model that fits the engine room human-automation environment functional requirements.

f. Testing and refining the proposed littoral combat ship engine room staffing and scheduling model in the IMPRINT virtual environment to verify attainment of the identified stated set of mission objectives.

g. Documenting the model, making recommendations for validation of mission objectives accomplishment, and transferring to the Navy for use in normal and combat littoral environments.

The project is designed to assist the Navy in developing a more accurate and precise model for manning the LCS by examining the impact of maintenance, operations, watch standing, and other design factors on the LCS ability to accomplish the mission. In doing so, savings could be realized in the manning of the crew, which is one of the most expensive factors in ship design. Cost for this project was negligible, since much of the shipboard research was already funded and documented by Naval Postgraduate School students and was leveraged for this project. Savings may take time to be realized and may be more in terms of “cost avoidance” than in actual monetary savings. Potential savings could be realized in avoiding future engineering failures through better modeling, which, based on previous failures, could be in excess of several million dollars and hundreds of lost operating days. One could be the cost (once available) of the two past significant failures. Another potential benefit could be an improvement to the design of the ship’s bridge and engineering control station that result in better command and control and perhaps reduce the risk of damage or mission degradation. Finally, if the IMPRINT model proves to be a good fit for such analysis of smaller crewed ships, it could be adopted by the Navy as a design model for future classes such as the new Frigate and the DDG-1000 class of ship, potentially saving significant time, cost, and effort in the design and manning of these vessels. If there is a desire to validate the results of this project using in-situ data collection and actual performance measures, cost estimates are provided Table 1 (rows with no cost have been deleted for space considerations).

Item	Planned Expenditures	Remarks/ Clarifying Explanation
Equipment	22,500	Motion loggers
Contracts	45,000	NRC Postdoc
Travel	8,000	1 visit to sponsor (3 people); 1 underway
Labor		15 days (PI) 25 days (Research Assistant)
FY16Qtr 1 Total		
Equipment	2,000	Equipment and batteries
Labor		15 days (PI) 25 days (Research Assistant)
FY16Qtr 2 Total		
Equipment	2,000	Equipment and batteries
Labor		15 days (PI) 25 days (Research Assistant)
FY16Qtr 3 Total		
Equipment	1,000	Equipment and batteries
Travel	6,000	1 visit to sponsor (3 people)
Labor		15 days (PI) 25 days (Research Assistant)
FY16Qtr 4 Total		
Total Equipment	27,500	
Total Travel	14,000	
Total Labor	114,257.68	60 days (PI) 100 days (Research Assistant)
Total Contract	45,000	
Total Overhead	0	
Grand Total	$200,757.68	

Table 1. Estimated Cost Breakdown of potential in-situ study.

1.3 PROBLEM STATEMENT

This project sought to address the problem: "What is the optimum manning and schedule for Littoral Combat Ship Class engine room personnel to minimize significant failures in mission accomplishment attributable to understaffing and over scheduling the human component in the automaton-human operational environment?"

1.4 SYSTEMIC PROBLEM CONTEXT

The foundational document for all Navy ships is called the Required Operational Capabilities (ROC) and Planned Operational Environment (POE) document (OPNAVINST 3501.352A April 2014). It is a very high-level document and does not provide a detailed task element list beyond the specific supporting elements for each mission area. For the focus areas pertaining to this study, a better set of tasks is found in the Engineering Operating Sequencing System (EOSS), which detail engineering operating procedures and casualty actions. There are several potential methods to decompose these actions into discrete tasks. After considering each during the developmental phase of the project, the Hierarchal Task Analysis method was selected as being to most applicable to IMPRINT modeling, primarily since it has the most attributes that allow analysis of human-equipment interfaces. Hierarchical Task Analysis (HTA) is a systematic method of describing how work is organized in order to meet the overall objective of the job. It involves identifying in a top down fashion the overall goal of the task, then the various sub-tasks and the conditions under which they should be carried out to achieve that goal. In this way, complex planning tasks can be represented as a hierarchy of operations – different things that people must do within a system and plans – the conditions which are necessary to undertake these operations. A short description of the other potential methods considered was taken from Embrey (2000).

a. Operator Action Event Trees (OAET) are tree-like diagrams which represent the sequence of various decisions and actions that the operating team is expected to perform when confronted with a particular process event. Any omissions of such decisions and actions can also be modeled together with their consequences for plant safety.

b. Decision/Action flow diagrams (DA) are flow charts which show the sequence of action steps and questions to be considered in complex tasks which involve decision-making. Decision/Action Flow Diagrams are similar to the flow charts used in computer program development. Both charts are based on binary choice decisions and intervening operations. In general, the binary decision logic in Decision/Action charts expedites communications through the use of simple conventions and provides for easy translation of Decision/Action charts into logic flow charts for computerized sections of the system.

c. Critical Action and Decision Evaluation Technique (CADET) is built on the critical actions or decisions (CADs) that need to be made by the operator usually in response to some developing abnormal state of the plant. A CAD is defined in terms of its consequences. If a CAD fails, it will have a significant effect on safety, production or availability.

d. The Influence Modeling and Assessment Systems (IMAS) technique is used to elicit Subjective Cause-Consequence Models (SCCM) of process abnormalities from personnel, a SCCM is a graphical representation of the perceptions of the operating team regarding the various alternative causes that could have given rise to the disturbance and the various consequences which could arise from the situation.

HTA was selected as the primary framework for the LCS model in this analysis for the following reasons:.

a. HTA is an economical method of gathering and organizing information since the hierarchical description needs only to be developed up to the point where it is needed for the purposes of the analysis.

b. The hierarchical structure of HTA enables the analyst to focus on crucial aspects of the task, which can have an impact on plant safety.

c. When used as an input to design, HTA allows functional objectives to be specified at the higher levels of the analysis prior to final decisions being made about the hardware. This is important when allocating functions between personnel and automatic systems.

d. HTA is best developed as a collaboration between the task analyst and people involved in operations. Thus, the analyst develops the description of the task in accordance with the perceptions of line personnel who are responsible for effective operation of the system.

e. HTA can be used as a starting point for using various error analysis methods to examine the error potential in the performance of the required operations.

Conversely, the two primary disadvantages of Hierarchical Task Analysis are:

a. The analyst needs to develop a measure of skill in order to analyze the task effectively since the technique is not a simple procedure that can be applied immediately. However, the necessary skills can be acquired reasonably quickly through practice.

b. Because HTA has to be carried out in collaboration with workers, supervisors and engineers, it entails commitment of time and effort from busy people

There are other more cognitive approaches that may be better suited to the final analysis, but for the initial deconstruction of the bridge and engine room, HTA is a good technique to establish initial task structure. For this study, the following deconstruction model was used as a baseline, to be tailored to the engineering plant and watch teams. The basic structure is outlined in Figure 1 below.

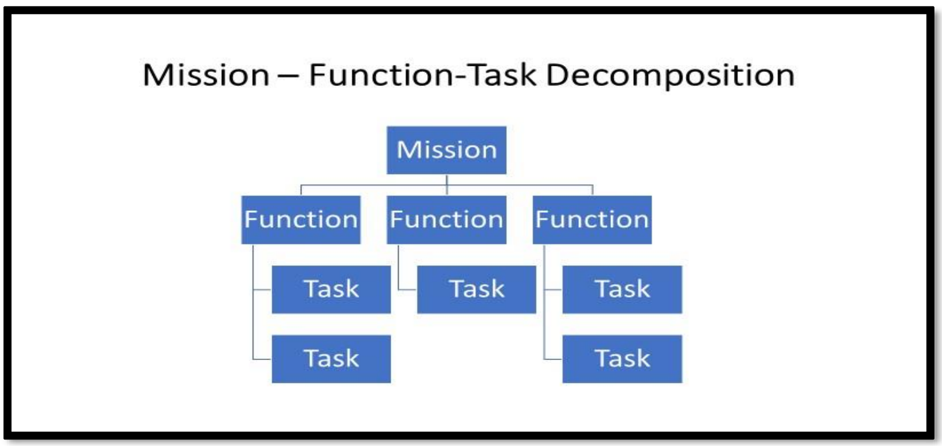


Figure 1. Mission-Task Decomposition

To apply the principles of HTA in IMPRINT, the Operations Analysis is broken into "Missions" which define a finite time period and desired outcome; "Functions", which are large procedures (corresponding to "tasks" in the HTA breakout above); and "Tasks", which are the steps in a procedure and allow for detailed human factors and cognitive analysis. The hierarchy will be apparent in the Results section as IMPRINT graphs are used to validate the workflow models as shown in the below Engineering Task Summary:

Mission: Watch Period: Safely operate the engineering plant

a. Function: Operate Propulsion Equipment

   i. Task: Start up equipment

   ii. Task: Perform periodic maintenance

   iii. Task: Monitor operation

   iv. Task: Secure equipment

b. Function: Operate Electric Plant

   i. Task: Start up equipment

   ii. Task: Perform periodic maintenance

   iii. Task: Monitor operation

   iv. Task: Secure equipment

c. Function: Conduct Casualty Control

   i. Task: Take immediate casualty actions

   ii. Task: Restore equipment to safe condition

   iii. Task: Conduct follow-up actions

   iv. Task: Restore to original condition

There are two primary systemic delimitations for this project. Although there is significant failure data available in the ship's Consolidated Maintenance Database, the data available for causality of the failures is relatively incomplete. There is sufficient data (approximately 6 years' worth) for analysis, and this represents a large focus of effort in defining the ties between failure (quantitative data) and causes of failure (qualitative analysis). Second, this project is tied to similar experiments with the IMPRINT software program, which may not turn out to be the ideal vehicle, but it has the most potential at this stage of development. As one example, Meredith (2016) noted that to date IMPRINT has only been applied to very small crews (5 or less) while the LCS crew size is 50, and IMPRINT has largely been applied to relatively static conditions. Meredith's project expanded the environmental factors to include more dynamic operational events such as unplanned flight or boat operations, and significant casualties. To address these limitations in this research project, a detailed task structure was developed for the IMPRINT model for the engineering watch team and is proposed for the purposes of this product to the Navy representatives. This task model deconstructs the tasks into individual task elements at a detailed level by watch stander, maintainer, and system. If gaps in historical failure data are found, they can be identified and targeted for collection efforts in the follow-on phases of the project during underway periods that are planned. Finally, the intention in this project was to examine possible improvements to the IMPRINT model and to note any areas that may require reconsideration or modification of the model to better fit the scope and purpose of the experiment.

CHAPTER 2
BACKGROUND

2.1 REVIEW OF THE HISTORY OF LITTORAL COMBAT SHIPS (LCS)

The LCS mission is to operate offensively in the high-density, multi-threat littoral environment independently or as an integral member of a carrier strike group (CSG), expeditionary strike group (ESG), or surface action group (OPNAV, LCS Concept of Operations, 2003). A distinguishing feature of LCS is the concept of a modular, reconfigurable ship. There are two ship classes: Freedom class and Independence class. Although the two classes are very different in design, each meets a common set of key performance parameters. The ship is comprised of a ship system (basic hull, mechanical, electrical, and computing systems) and core systems that provide navigation, self-defense, command and communication (C2) and communications capabilities, as well as air, subsurface, and surface vehicle launch, recovery, handling, and control systems. The core systems provide the ship with the capability to detect, identify, track, and defend itself against anti-ship cruise missiles and threat aircraft, but the ship is not designed or intended to operate in a high-intensity air defense environment unless these operations are being conducted under the air defense coverage of a Carrier Strike Group (CSG), Expeditionary Strike Group (ESG), or an air defense asset such as an Aegis cruiser or destroyer. The ship includes a large reconfigurable volume for Mission Packages (MP), which may be exchanged to modify the ship’s focused war fighting capability. Designed as an open architecture ship with tailored MP, LCS provides focused capabilities in the mine countermeasures (MCM), surface warfare (SUW), or antisubmarine warfare (ASW) mission areas. The SUW MP includes a maritime security module, which enables visit, board, search, and seizure (VBSS) compliant and low freeboard non-compliant capability.

The MP include personnel required to operate and maintain mission specific equipment and to augment the core crew when conducting focused mission operations. In addition to its focused-mission and self-defense capabilities, LCS may be tasked to conduct operations that take advantage of its inherent capabilities, defined as those capabilities enabled by the ship's core systems, sprint speed, agility, mission bay space, and shallow draft. These may include operations such as special operations forces (SOF) support, search and rescue (SAR), freedom of navigation operations, noncombatant evacuation operations (NEO), global fleet station, maritime law enforcement operations, and irregular warfare. LCS is designed to operate in the littoral environment as a focused mission ship, which can be configured with SUW, ASW, or MCM MPs. Mission Packages (MPs) are integrated with the ship's services, data links, unmanned vehicle controls and command, control, communications, computers and intelligence infrastructure. The MPs are transportable by ship or air, built for rapid reconfigurability and must be changed out in port. The MPs include personnel to support mission capabilities and to augment the core crew for tasks such as FP, watch standing, and administration. LCS provides self-defense against anti-ship cruise missiles, threat aircraft and surface threats. Due to its core systems, speed, agility and shallow draft characteristics, LCS provides the inherent capability to conduct a number of secondary missions on a limited basis, including Special Operations Forces (SOF) support, Search and Rescue (SAR), afloat forward staging base, freedom of navigation operations, global fleet station, maritime law enforcement operations, and irregular warfare. Engineering performance is critical to mission accomplishment across all MP's and is thus a viable target outcome as a failure in this area would impact or even eliminate mission accomplishment.

In breaking down the task analysis, this research focused on specific operational conditions and subsets for modeling. The LCS Concept of Operations (CONOPS) defines three operating conditions for conducting operations:

a. Condition I: Battle Readiness. While in Condition I, the ship shall meet the following criteria:

  (1) Able to perform assigned focused mission area (SUW, ASW, or MCM) when configured with respective MP and perform limited non-MP related mission areas, or inherent capabilities, simultaneously.

  (2) Able to keep the required systems manned and operating for maximum effectiveness.

  (3) Required to accomplish only maintenance associated with mission critical repairs.

  (4) Evolutions such as replenishment, law enforcement, or non-mission helicopter operations are not applicable.

  (5) The maximum expected continuous crew endurance for Condition I is 24 hours.

b. Condition II: Modified Battle Readiness. Condition II is Condition I modified to meet particular probable threats that are situation-dependent. As such, Condition II is a subset of condition I that stands up particular Condition I capabilities at the discretion of the commanding officer. While in Condition II, the ship shall meet the following criteria:

  (1) Able to perform focused mission (SUW, ASW, or MCM) areas when configured with respective MP.

(2) Able to simultaneously perform those offensive and defensive functions necessary to counter specific probable, limited threats.

(3) Able to keep required operational systems continuously manned and operating.

(4) Able to perform other command and control (C2) functions relevant to the threats which are not required to be accomplished simultaneously.

(5) Able to accomplish mission critical maintenance and support functions.

(6) The maximum expected continuous duration for Condition II is 10 consecutive days, with a minimum of 4 to 6 hours of rest provided per crewmember per day.

c. Condition III: Wartime/Increased Tension/Forward Deployed Cruising Readiness. Reduced defensive systems are manned to a level sufficient to counter possible threats. While in condition III, the ship shall meet the following criteria:

(1) Able to keep installed and embarked focused mission (SUW or ASW or MIW) systems manned and operating as necessary to conform with prescribed ROCs.

(2) Able to accomplish all underway maintenance, support and administrative functions.

(3) To determine manpower requirements, the maximum expected crew endurance for Condition III is 21 consecutive days underway, with opportunity for 8 hours of rest provided per man per day, followed by 4 days in port.

Since the key failures appear to have occurred during Condition III, this is the most applicable condition and was used for the analysis in this project.

2.2 OPERATIONAL PERFORMANCE LIMITATIONS

The IMPRINT program has been applied in the past to smaller combat equipment such as tanks. Its application to the complex shipboard environment is not yet proven, although a previous phase of this experiment has shown it to be capable of mapping basic LCS crew functionality and operations under Condition III as described in paragraph 2.1.c. In a more global force level manpower study, “workload” is just simple engagement with high level activities. In a detailed human performance model, workload is the mental capacity being utilized to perform more definitive tasks. The detailed human performance models allow observation of outcomes such as mission times, mission completion, and errors and their consequences as metrics. The modeling of complex operations under varying conditions was challenging, but the measures of effectiveness in the Required Operational Capabilities (ROC) and Planned Operational Environment (POE) document provides a stable set of criteria with a well-defined structure that seems to lend itself to the IMPRINT model’s capabilities. Data collection during real live operations may be subject to operational and funding limitations, but the initial plan does account for a great deal of flexibility in the conduct of the study. The IMPRINT Operations Model allows the operator to analyze the performance (such as time, accuracy, and workload) of a new weapon system by helping build models of each mission that the weapon system is capable of accomplishing. Models are built by breaking down the mission into a network of procedures defined as “functions”. Each of the functions is then further broken down into a network consisting of individual “tasks”. When the program executes the mission model simulation, the analyst can study the range of results that occur in the mission. A description of the variability of each element can be obtained for further analysis. IMPRINT Pro performs the simulation model based on how long it takes (based on programmer input) to perform each task in the mission. In addition, with each task, the analyst can estimate accuracy levels and assign workload values that reflect the amount of effort the Warfighters will have to expend to perform the task. During the simulation, IMPRINT Pro predicts task performance and calculates how much workload each Warfighter experienced throughout the mission. In this way, it is possible to determine whether the Warfighter were overloaded, and if so, how changes can be made to reduce the workload to an acceptable level. At the completion of the simulation, IMPRINT Pro can compare the minimum acceptable mission performance time and accuracy to the predicted performance. This method was used to determine whether the mission met its performance requirements. Past researchers have modeled the LCS crews in a macro sense using the Force Unit model, which looks at how a Force Unit, a structured set of resources comprised of people and equipment, can succeed in meeting an emergency which demands those resources. Using the model developed by previous researchers, this analysis utilized the Operations Model and a small subset of tasks in detail to investigate the effects of the aforementioned dimensions.

CHAPTER 3

PROJECT METHODOLOGY

3.1 PROJECT DESIGN

Data collection plan: Since this engineering effort did not have direct access to the LCS automation-human operational environment, a directed, nonrandom survey was conducted to assess potential automation, human, and environmental variables contributing to observed failures. Once the key attributes were decided upon for the chosen mission, and the attributes to be entered determined, the method of measuring data was submitted and approved by the Old Dominion University Batten College of Engineering and Technology Internal Review Board as IRB 921238-2, Littoral Combat Ship Staffing Model using IMPRINT, on 15 August 2016. Inputs included objective (mission hours, mission objectives, achievement of specific milestones from the ship's Required Operating Condition (ROC) document), and specific parameters that pertain to the mission itself – ranges, success in mine location, etc. Finally, the crew was surveyed in terms of skills, experience, training level, proficiency, and in terms of performance – fatigue, workload, error rate, etc. Due to the focused scope of the project, although surveys were completed by a variety of shipboard personnel, the focus was on a single key node, the engine room, since this is the area where the majority of decision-making occurs with the most severe potential consequences. These parameters were fed into the model and refined to see if the results are repeatable and predictable to a degree that the model was validated.

In-Situ measurements: Although this project does not include an in-situ research aspect, the authors had access to significant data that was collected in numerous Naval Postgraduate

School studies (Kerno 2015, Meredith 2016). This data was reviewed and referenced as necessary to support or refute the findings of the LCS survey and other aspects of the analysis.

Recommendations and adjustments: Based on the validated model, the opportunity existed to adjust several of the attributes already inherent in the IMPRINT program to more closely tailor them to actual Navy parameters and use the results to formulate recommendations for changes to the model itself. One final desired outcome was the ability to modify the IMPRINT model so that it can be used in a predictive fashion for new ships such as the next generation Frigate FFG(X), which is the follow-on class to the LCS, and even the DDG-1000 class, which will face many of the same challenges. The challenge is that unlike LCS, these are more multi-mission ships and may require several iterations of the IMPRINT analysis, as well as analyzing the interactions between mission areas.

3.2 MISSION PERFORMANCE DECOMPOSITION

The LCS bridge is composed of a system of systems that integrate to provide command and control (in Navy terminology, "C2" that includes radars, cameras and visual operators to build a coherent surface and air picture of land, obstructions, and other air and surface vessels to support safe navigation and safe operations. Unlike other classes of ship, the bridge system was designed from the ground up as an integrated "open architecture" system, with automated computer-controlled functions augmenting the human crew and in many cases replacing crew members required on other surface ships. This includes such systems as surface and air search radars, electronic navigation systems, and propulsion control systems that all culminate in a central Bridge Control Station from which an Officer of the Deck can change displays and control the ship with commands from a joystick and computer touch screen. In designing the LCS Crew Survey, visits were made to actual LCS ships and to the LCS simulator/trainer to examine the human-automation interface and provide familiarization with the procedures and construct of the Integrated Bridge System (IBS).

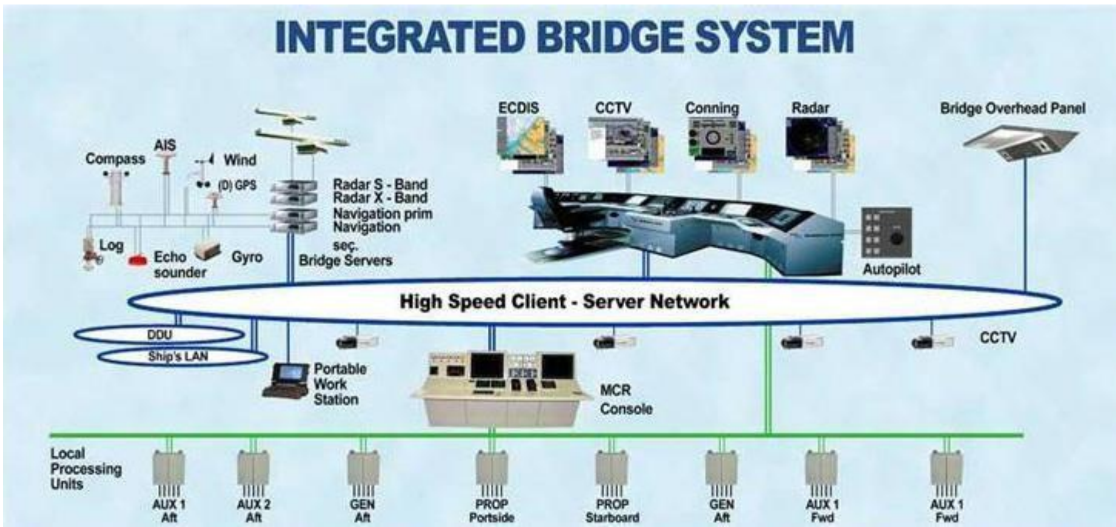


Figure 2. Schematic of LCS Integrated Bridge System (IBS) (Source: US Navy)

3.3 ANALYSIS OF BRIDGE AND ENGINEROOM ARCHITECTURES

The Engine room of the LCS ships is designed for minimal manning, with most control functions residing at a watch station on the bridge. Since the majority of engineering functions are automated, only one individual is assigned to roam the engineering spaces as a monitor and casualty responder for fires, flooding, etc. One class is a combined gas turbine and diesel propulsion system with a reduction gear (called a “combining gear in LCS) and the other with a rotating water jet propulsion system. The systems are unique to the LCS platform and are supported by a robust simulator training program called Train to Qualify (TTQ) such that almost all functions required to operate the engineering plant can be performed on a simulator exactly as they work on the ship. While the control station is located on the bridge, that individual is not considered an integral member of the bridge watch team and is focused exclusively on engineering plant control. The functional interface for both the IBS and the Engineering systems are separate but similar in design. The majority of functions are controlled by an operator sitting in front of a series of computer monitors with touch-screen capability, using "soft buttons" on the screen to perform most actions such as starting and stopping pumps, closing and opening breakers, and aligning valves. A large number of alarms relay the status of doors, valves, machines, and casualties such as fire and flooding via installed sensors. The displays are essentially detailed "status boards" from which the operator can monitor parameters such as temperature, pressure, RPM, etc., selected by a series of menus and buttons on the screen. Most operating procedures are contained in paper booklets that are maintained at the watch station for reference during routine operations and casualties. Engineering roving watch standers can also perform some corrective and planned maintenance while on or off watch, and the bridge watch stander is often assigned corrective and planned maintenance, as well as other administrative duties, when not on watch. While the two LCS classes have different designs display styles, the overall concept – relying heavily on automation controlled at an interface – is very similar.

Figure 3. Photograph of LCS Bridge showing Human-Automation Interface equipment (IBS) (Source: U. S. Navy)

3.4 LCS SURVEY DESIGN

The concept of operations for the LCS program relies on highly trained operators (often spending 12-18 months in a “train to qualify” program) that may or may not have served on LCS ships in the past. They use both bridge and engineering simulators for training as well as classroom instruction with qualified and experienced trainers. A significant portion of planned and corrective maintenance is performed by civilian operators, contracted for periods when the ship is in home port. Shipboard control systems make extensive use of automation as part of the Navy's goal to reduce shipboard manpower requirements. For this reason, the survey treated the LCS ship as an environment, with three integrated sub systems (human and automation) operating the bridge, engineering, and combat systems respectively. While there is little interaction between the three subsystems, the degree of automation and interaction is similar for each. Although there are the two variants of LCS, the Freedom and Independence class, the design and level of automation is essentially the same between the two. To date, some LCSs have experienced significant failures in mission accomplishment which have been attributable potentially to under staffing and over scheduling the human component of the automation-human LCS operational environment. Initial analysis of failure modes seems to indicate that the critical human components on the Littoral Combat Ship are bridge and engine room staffing.

The design of this survey was to determine the extent to which the dimensions of fatigue, maintenance tasking, watch tasking, and automation-human activity integration are perceived by LCS bridge and engine room personnel to impact the performance of their duties. Survey results were used to inform the design of automation-human cognitive task and activity workflow analyses of LCS bridge and engine room activities. Results of the workflow analyses, in turn, were applied to modify current LCS manpower models to optimize the integration of the automation-human operational environment for each operational state: peace-time steaming, war-time steaming, and combat operations. Optimized LCS manpower models were programmed into the Naval Postgraduate School's IMPRINT discrete event modeling tool and simulated to verify automation human operational performance. For the survey, the following problem statement was investigated:

> *What is the degree to which Littoral Combat Ship Class bridge and engine room personnel perceive that they are impacted in their watch and maintenance performance by understaffing and over scheduling the human component of the automation-human LCS operational environment as measured by the dimensions of fatigue, maintenance tasking, watch tasking, and human-automation activity integration?*

The survey was designed to measure four dimensions identified as potentially contributing to failures of mission accomplishment. Each dimension was defined as follows:

a. Fatigue - state of human awareness as measured by the level of fatigue.

b. Maintenance tasking - actual versus specified maintenance activities accomplishment.

c. Watch tasking - actual versus specified watch task accomplishment.

d. Automation-human activity integration - the extent to which littoral class ship automation-human cognitive-task and activity workflows have been designed to minimize the potential for operational errors.

This survey was focused on bridge and engineering personnel. The category “other” includes Combat Information Center and other support personnel that alternated standing watch or performing maintenance tasks. The survey opened with nine demographic questions directly related to littoral class ship personnel performance of duties. Questions are listed below by number:

1. Primary group; E-7 or above, E-6 or below.
2. Location of primary duties; bridge, engineering spaces, other.
3. Number sea tours completed; first, second, third, fourth, five or more.
4. Primary ship types of past tours; amphibious, cruiser/destroyer, no previous sea tours.
5. LCS class variant; Freedom, Independence.
6. Last underway period, hours per day standing watch; do not stand watch, less than 2, 2 to 4, 4 to 6, 6 to 8, 8 to 10, more than 10.
7. Average hours/day of planned preventive maintenance; do not perform maintenance, less than 2, 2 to 4, 4 to 6, 6 to 8, 8 to 10, more than 10.
8. Average hours/day of corrective maintenance; do not perform maintenance, less than 2, 2 to 4, 4 to 6, 6 to 8, 8 to 10, more than 10.
9. Last underway period, hours per day normally slept; less than 4, 4 to 6, 6 to 8, 8 to 10, more than 10.

The survey questions were formatted in a 7-unit Likert scale: 1. Extremely unlikely, 2. Moderately unlikely, 3. Slightly unlikely, 4. Neither unlikely or likely, 5. Slightly likely, 6. Moderately likely, 7. Extremely likely.

Survey questions were originally presented in random order, as indicated by the question number, but are grouped by measurement dimension for ease of reference:

Dimension: Fatigue

10. How likely are you to sleep at the same time each day?

15. What is the likelihood that you will be fatigued while standing watch?

16. What is the likelihood that you will be fatigued while performing maintenance?

Dimension: Maintenance Tasking

11. On an average day underway, what is the likelihood that you will have sufficient time to perform assigned preventive maintenance?

12. On an average day underway, what is the likelihood that you will have sufficient time to perform assigned corrective maintenance?

Dimension: Watch Tasking Workload

14. What is the likelihood that you will be able to perform all scheduled tasks on your watch station?

17. What is the likelihood that you will encounter more tasks than you have time to perform?

26. What is the likelihood that you will be distracted by other tasks (i.e., planned or corrective maintenance, administrative) while standing watch?

Dimension: Automation-Human Activity Integration

18. What is the likelihood that you will clearly understand the difference between automated functions and those you are expected to perform?

19. What is the likelihood that operating procedures are sufficiently detailed for you to operate your equipment?
20. What is the likelihood that the automated features of your watch station make standing watch easier than on other ships?
22. What is the chance that, when an automated alarm occurs, you trust that it is a real event?
23. What is the likelihood that your watch station displays provide all the information you need to stand watch?
24. What is the chance that I will clearly understand all the information displayed on the control panels for my watch station?
27. What is the chance that modifications to the information display and automation could mitigate effects of overtasking or fatigue at your watch station?

Questions 13, 21, and 25 were inserted to test internal consistency and are not listed above. Questions 13 and 25 were randomly assigned as positive restatements of questions 11 and 15 respectively. Question 21 was randomly assigned as a negative restatement of question 20. The results of the survey will be discussed in Chapter 4.

3.5 PERFORMANCE INTEGRATION DESIGN

Once the data was collected and analyzed from the LCS Crew Survey, the IMPRINT modeling tool was used to build a model of the operational and maintenance tasking of a typical watch section consisting of the Remote Console Operator (RCO) and the Engineering Plant Technician (EPT). The watch period "mission" was populated with a set of operating and maintenance procedures knows as "Functions" and the tasks associated with each function. These tasks were then programmed into IMPRINT with the appropriate time, workflow "swim lanes" of manual, automatic, and cognizant functionality, and the model was run a number of times to simulate different conditions in terms of workload, fatigue, and automation across the spectrum of functions for the two operators. The next sections describe the project results including survey results, construction of the IMPRINT model, and the tabular and graphical outcomes under various conditions. Finally, conclusions are drawn from the results and recommendations made for improvements to the model and for further research.

CHAPTER 4
PROJECT RESULTS

4.1 LCS CREW SURVEY RESULTS.

The LCS Crew Survey was sponsored by the US Navy, and the survey design and methodology were reviewed and approved by the Old Dominion University Batten College of Engineering and Technology Internal Review Board. The survey was conducted in May-August 2017 and was open for a period of 3 months. E-mail invitations requesting participation were sent to crews on two Littoral Combat Ships (LCS) that had completed recent deployments. These two ships provided a sample of approximately 80 personnel; The directed, non-random survey was voluntary and was conducted using Qualtrics™ survey software. Participants remained anonymous. There were 35 responses out of a population of 80, representing a response rate of 44 percent. Based on hypergeometric probabilities, this response rate yields a 90% confidence of detecting a 5% difference and a 99% confidence of detecting a 10% difference in opinion on any given question. This was considered sufficient, since the population is relatively homogeneous for navy crew members of a single class of ship). (Pearson Education, Probability Distribution, 2010). Respondents' demographics were as follows.

- 18 (51%) were E-7 or above and 17 (49%) were E-6 or below.
- 10 (29%) primary duty location was on the bridge, 11 (31%) was in engineering spaces, and 14 (40%) were in other personnel.
- 7 (20%) were on their first sea tour, 10 (29%) their second tour, 9 (26%) their third tour, 3 (8%) their fourth tour, and 6 (17%) on their fifth or greater tour.
- 9 (26%) had prior tours on an amphibious ship, 20 (57%) on a cruiser/destroyer, and 6 (17%) no prior tours.

- 27 (77%) served on the LCS Freedom class and 8 (23%) on the LCS Independence class.
- 4 (11%) did not stand watch, 2 (6%) stood watch 4 to 6 hours, 2 (6%) stood watch 6 to 8 hours, 16 (46%) 8 to 10 hours, and 11 (31%) 10 or more hours.
- 8 (23%) did not perform preventive maintenance, 6 (17%) less than 2 hours/day performing preventive maintenance, 11 (31%) 2 to 4 hours/day, 4 (12%) 4 to 6 hours/day, and 6 (17%) 6 to 8 hours/day.
- 10 (28%) did not perform corrective maintenance, 8 (23%) less than 2 hours/day performing preventive maintenance, 8 (23%) 2 to 4 hours/day, 8 (23%) 4 to 6 hours/day, and 1 (3%) 6 to 8 hours/day.
- 4 (11%) slept less than 4 hours/day, 24 (69%) 4 to 6 hours/day, 5 (14%) 6 to 8 hours/day, 2 (6%) 8 to 10 hours/day.

Kendall's tau was estimated to test internal consistency between positive questions 11 and 13 and questions 15 and 25 and between negative questions 20 and 21. Table 2 reports Kendall's tau and corresponding p-values. Overall, the tau signs and p-values support internal consistency.

Questions	Relationship	tau	p-value
11 – 13	Positive	+0.794	2.22e-16
15 – 25	Positive	+0.772	3.58e-07
20 - 21	Negative	-0.375	0.0067

Table 2. Internal consistency Kendall's tau statistics.

Exploratory analysis was used to examine the survey response data in each dimension for trends and anomalies in the LCS automation-human operational environment that may have to be considered in the subsequent design of the cognitive-task-automation workflow analysis. Three delimitations apply to this statistical analysis: (1) While the survey size was relatively small relative to pure research surveys, the survey purpose was only to assess potential automation, human, and environmental variables contributing to observed LCS failures. (2) The use of the SCREE plot, Kendall's tau analyses, and Multiple Joint Correspondence Analysis were used as supporting analyses of potential variables contributing to observed LCS failures. (3) While it may have been appropriate to collapse the results into smaller anchored bins if the survey had been designed as a primary research measurement instrument, the 7-node Likert Scale was preserved to more clearly show the fidelity of the answers. For this survey, exploratory analysis was performed within each measurement dimension:

Dimension: Fatigue. This section focused on the respondents' perception of sleep and fatigue, and their impact on watch standing and maintenance. The responses to question 10, likelihood of sleeping at the same time each day, resulted in a bi-modal distribution. Thirty-four percent (34%) reported that it was unlikely, with the mode at 14% moderately likely, and forty-nine percent (49%) likely, with the mode at 34% moderately likely. The question then arose as to whether this bi-modal distribution was related to primary duty station. Table 5 indicates that a relationship exists between the likelihood of sleeping the same time each and primary duty station. Bridge and Other personnel displayed bimodal distributions with 8 bridge personnel responding unlikely and 2 likely and 7 other personnel responding unlikely, 1 neither, and 6 likely. Engineering personnel tended more strongly toward unlikely with 9 responding unlikely, 1 neither, and 1 slightly likely. Table 3 shows fatigue responses.

Score*	1	2	3	4	5	6	7
Bdg	3	2	3	0	1	1	0
Eng	5	2	2	1	1	0	0
Oth	5	1	1	1	1	4	1

Table 3. Count of sleep-same-time to primary duty station.
*Likert Scale Score where 1 = Very Unlikely and 7 = Very Likely

Responses to question 15 indicated that ninety-two percent (92%) of respondents were likely to be fatigued while on watch with seventy-seven percent (77%) percent reporting moderately or extremely likely. Similarly, responses to question 16 indicated that seventy-one percent (71%) of respondents were likely to be fatigued while performing maintenance with fifty-seven percent (57%) reporting moderately or extremely likely. Of note, none (0%) of the respondents chose “Moderately Unlikely or “Extremely Unlikely” in either of these categories. This result tends to suggest that fatigue is considered a significant factor in both activities, and merits further research. For the discussion of determination of outliers, reference section Multiple Joint Correspondence Analysis.

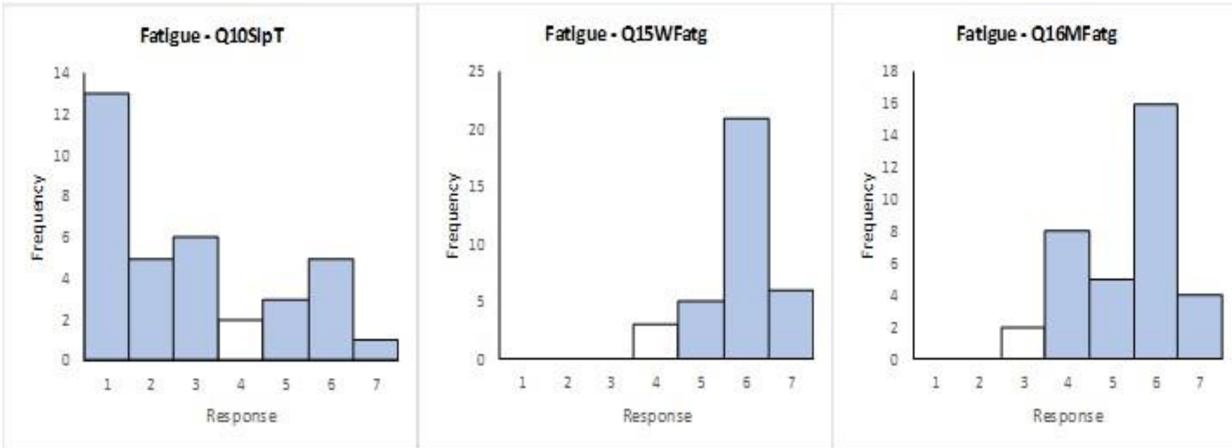


Figure 4. Fatigue Response Distributions (Likert Scale where 1 = Very Unlikely and 7 = Very Likely; Outliers – no fill.)

Dimension: Watch Tasking Workload**.** This section focused on the respondents' perception of the potential for "overtasking" as it related to the time available to complete assigned tasks. Question 14 measured watch tasking workload balancing. Here respondents formed either a bi-modal distribution. Eighty-three percent (83%) reported neither or likely ability to perform all scheduled tasks at their watch station. Of the 17% reporting unlikely to perform all scheduled tasks, four were in Engineering, and two in the Other category. Question 17 was designed to determine the sufficiency of watch tasking workload design. Eighty-three percent (83%) reported that it was likely that they encountered more tasks than they had time to perform with sixty-eight percent (68%) reporting that encountering unplanned task was moderately or extremely likely. Of the 83% reporting likely, twenty percent (20%) were bridge personnel and 31.5% each were Engineering and Other personnel. Question 26, distraction by other tasks, was designed to assess the randomness of unplanned task arrivals versus the ability of personnel to control when they could respond to unplanned tasks. The response distribution was negatively skewed with seventy-four percent (74%) of respondents reporting that it was likely that unplanned tasks were a distraction. Of the 74% reporting likely, thirty-one percent (31%) were Other personnel, twenty-nine percent (29%) were Engineering personnel, and fourteen percent (14%) were Bridge personnel. Responses to questions 17 and 26 suggest that personnel feel overtasked in both watch and maintenance. Figure 5 graphically summarizes these results.

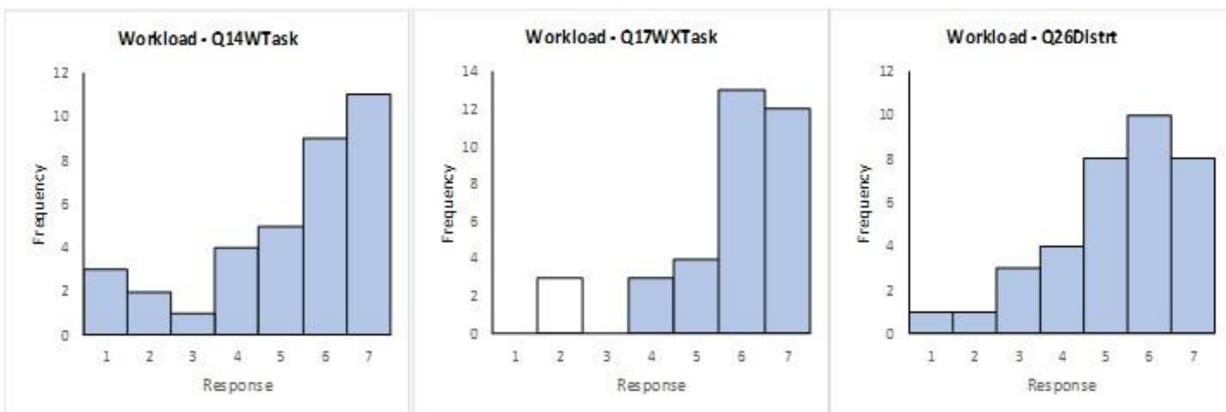


Figure 5. Watch tasking Response Distributions (Likert Scale where 1 = Very Unlikely and 7 = Very Likely; Outliers – no fill)

Dimension: Maintenance Tasking. This section examined the respondents' perception of their ability to perform both assigned corrective and preventive maintenance tasks. The distributions for both questions 11 and 12 were negatively skewed with respective modes at response 5 for question 11, preventive maintenance tasks, and 4, corrective maintenance tasks. For question 11, preventive maintenance tasks, forty-six percent (46%) responded that it was likely that they had sufficient time to complete preventive maintenance tasks, but a substantial minority of thirty-four percent (34%) responded that it was unlikely. For question 12, corrective maintenance tasks, forty-three percent (43%) responded that it was likely that they had sufficient time to complete corrective maintenance tasks, but, again, a substantial minority of twenty-six percent (26%) responded that it was unlikely. For question 11, the likely-unlikely combinations were Bridge 14% - 6%, Engineering 14% - 14%, and Other 17% - 11%. For question 12, the likely-unlikely combinations were Bridge 11% - 6%, Engineering 14% - 14%, and Other 20% - 6%. Combining these response rates with those of Watch tasking questions 17 and 26 suggests that planned preventive and corrective maintenance tasks are not level loaded across watches and that personnel have to deal with unplanned tasks on an overload basis. Figure 6 summarizes maintenance task responses.

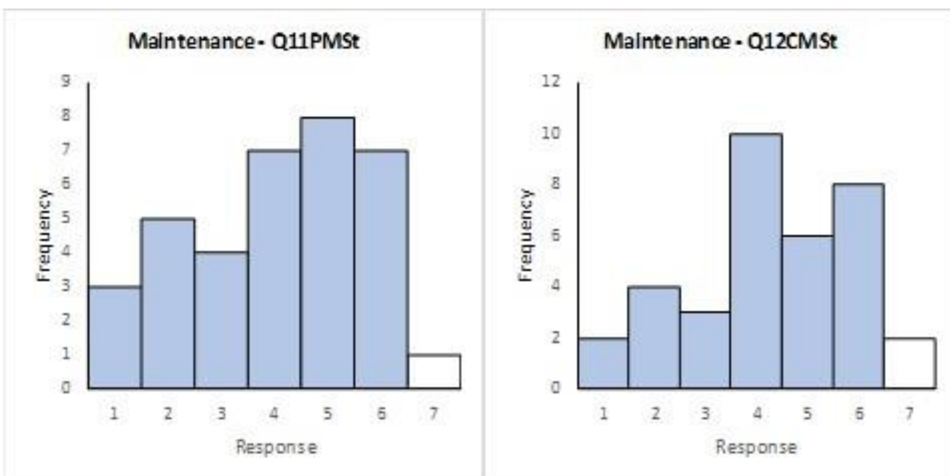


Figure 6. Maintenance Response Distributions (Likert Scale where 1 = Very Unlikely and 7 = Very Likely; Outliers – no fill)

Dimension: Automation-Human Integration**.** This area explored the impact of automation and human integration as it relates to the watch station. Questions 18, 19, and 20 sought to measure the effectiveness of the automation-human workflow design. As shown in Figure 7, eighty-six percent (86%) responded that it was likely that they clearly understood the difference between automated functions and those they are expected to perform. The responses to question 19, operating procedures are sufficiently detailed for you to operate your equipment, resulted in a bimodal distribution. Seventy-one percent (71%) responded that operating procedures were sufficient, but twenty-six percent (26%) responded that procedures were not sufficient. Table 4 indicates that engineering and other personnel were more likely to respond that operating procedures were sufficient, but Bridge personnel were more evenly divided on procedures sufficiency. Responses to question 20, automated features make standing watch easier, resulted in a negatively skewed distribution with forty-five percent (45%) responding likely and thirty-four percent (34%) responding unlikely. Table 5 indicates that bridge personnel tended to view automation assistance more positively than engineering personnel and other personnel.

Station	Unlikely	Likely
Bridge	11% (4/35)	17% (6/35)
Engineering	6% (2/35)	26% (9/35)
Other	9% (3/35)	28% (10/35)
Totals	26% (9/35)	71% (25/35)

Table 4. Relationship procedures sufficiency.

Station	Unlikely	Likely
Bridge	9% (3/35)	17% (6/35)
Engineering	11% (4/35)	14% (5/35)
Other	14% (5/35)	14% (5/35)
Totals	34% (12/35)	45% (16/35)

Table 5. Relationship automation to watch ease.

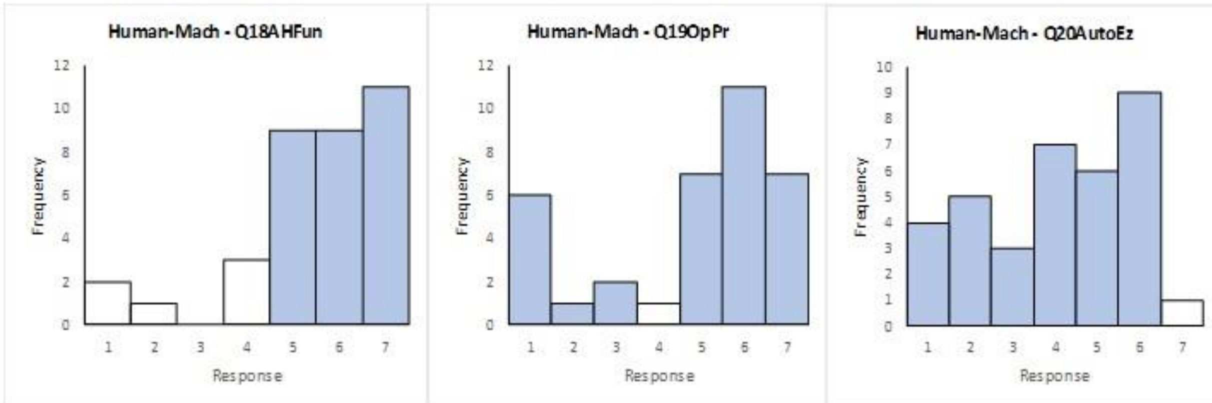


Figure **7**. Q18, 19, 20; Human-Automation Distributions. (Likert Scale where 1 = Very Unlikely and 7 = Very Likely; Outliers – no fill)

Questions 22, 23, 24, and 27 sought to measure the effectiveness of automation-human information exchange and comprehension. As shown in Figure 8, question 22, trust in automation alarms, resulted in a bimodal distribution with forty-three percent (43%) responding they were likely to trust automation alarms and forty-six percent (46%) responding that they were unlikely to trust automation alarms. Questions 23, 24, and 27 resulted in predominantly likely responses. Question 23, your watch station displays provide all necessary information, resulted in seventy-one percent (71%) likely and twenty percent (20%) unlikely responses. Of the unlikely responses, two were bridge personnel, one was engineering, and four were other personnel. Question 24, chance that I will clearly understand all display information, resulted in seventy-four percent (74%) responding that they were likely and eleven percent (11%) responding that they were unlikely to understand. Of the unlikely responses, one each was bridge and engineering personnel, and two were other personnel. Question 27, chance that modifications to the information display and automation could mitigate effects of overtasking or fatigue, resulted in a negatively skewed distribution with sixty-six percent (66%) responding likely and fourteen percent (14%) unlikely.

Of the unlikely responses, one was from the bridge and two each were engineering and other personnel.

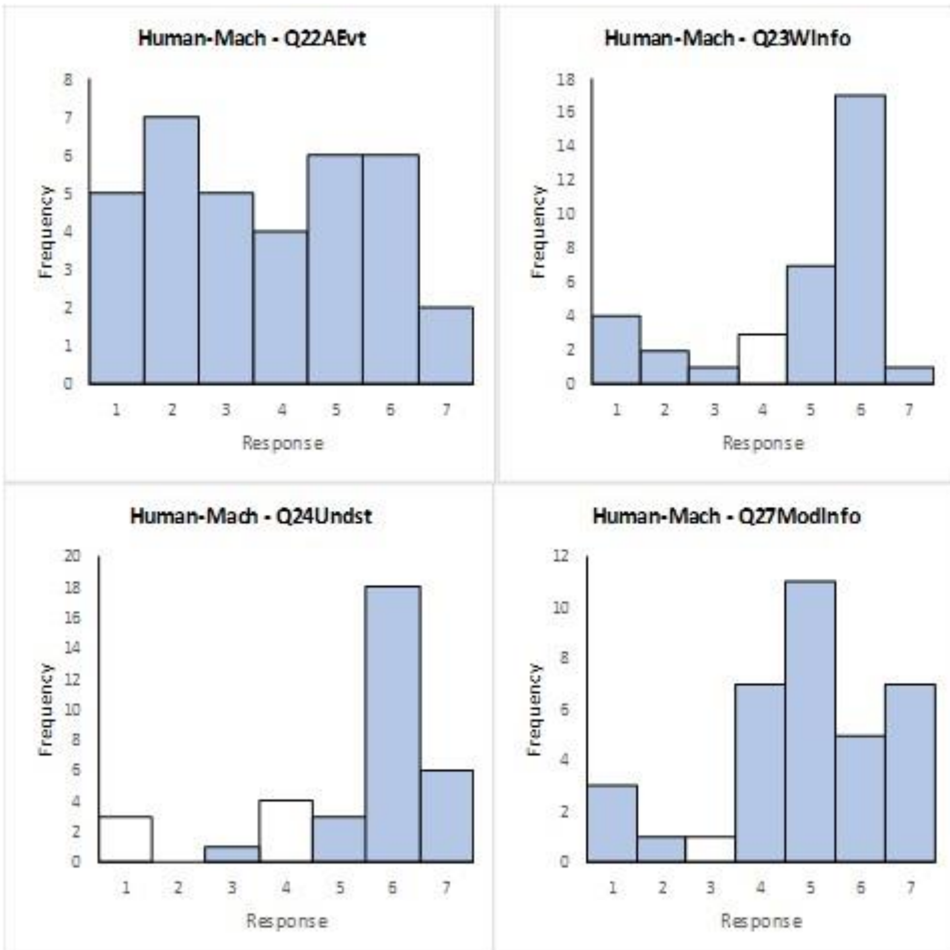


Figure 8. Q22, 23, 24, 27 Human-Automation Distributions (Likert Scale where 1 = Very Unlikely and 7 = Very Likely; Outliers – no fill).

Multivariate Joint Correspondence Analysis (MJCA). Multivariate Joint Correspondence Analysis (MJCA) is a method of determining whether a survey's responses demonstrate homogeneity or heterogeneity. Survey frequency responses are plotted in a unit-normalized, Chisquare distance cloud of points which is then analyzed in the geometric space to partition the survey information into cluster centers of mass, noise, and outliers, which are the structural information in the geometry. Analysis of the LCS survey data using the R statistical application "ca" showed that the first four dimensions were responsible for 49.0% of the cumulative principle inertia (eigenvalues), with the fifth dimension raising the cumulative inertia to 54.8% (Table 8). Camiz and Gomes (2015) note that only the eigenvalues larger than the "trivial average ½" are interpreted as significant. Thus, multivariate correspondence analysis was limited to the mapping of the survey dimensions to the first four principal component dimensions.

Dimension	**Inertia**	**Percent**	**Cum Percent**	**Scree Plot**
1	0.179731	18.3	18.3	******
2	0.156112	15.9	34.1	*****
3	0.086036	8.7	42.9	***
4	0.060173	6.1	49.0	**
5	0.056722	5.8	54.8	**

Table 6. SCREE Plot of First 4 Dimensions from LCS Survey

Dimension 2 Versus 1 Analysis

The biplot in Figure 9 of the full survey response data on dimension 2 versus dimension 1 coordinates with a bivariate normal 95% confidence ellipse yield a coefficient of correlation of -0.00914 and show that the mass of the data is identically, independently distributed (IID). The data within the 95% confidence interval do not clearly map to either dimension 1 or 2. This

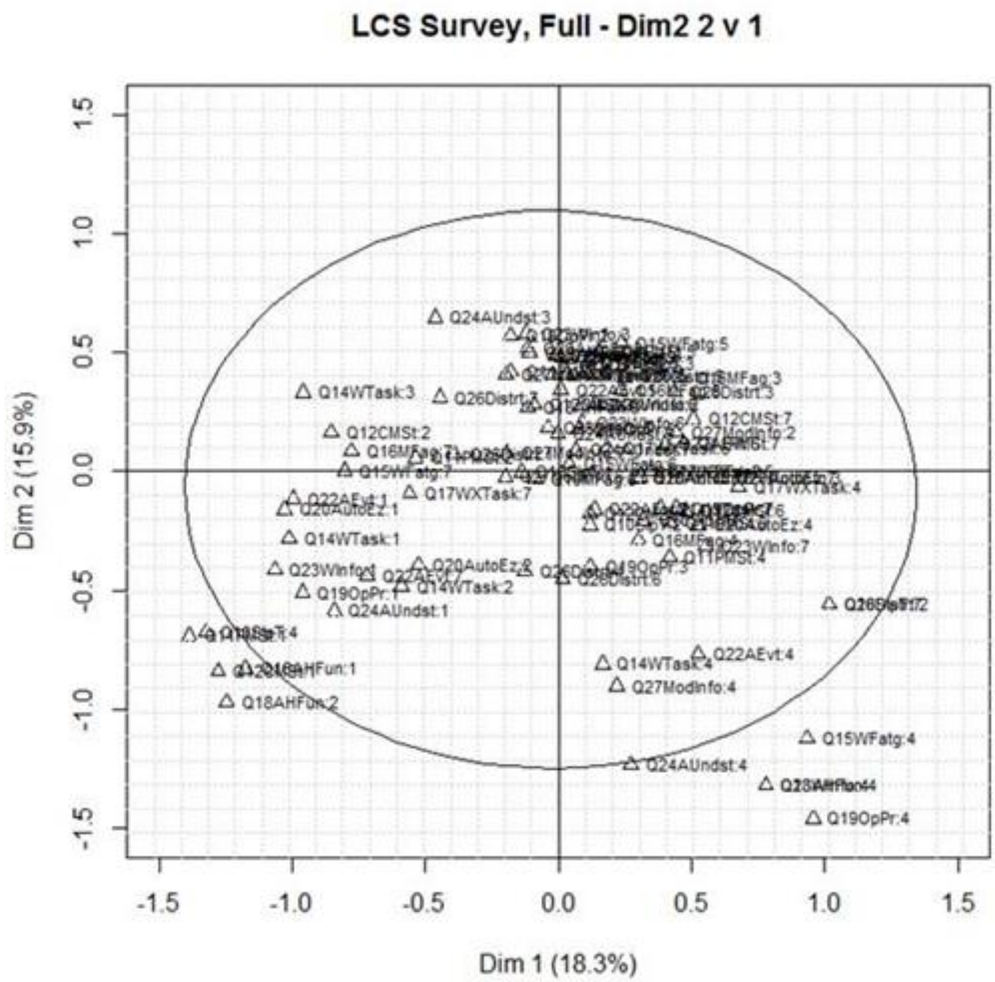


Figure 9. LCS Survey, Full – Dim 2 v 1.

observation along with the observation that dimension 1 explains 18.3% of the variation and dimension 2 an additional 15.9% (cumulatively 34.1%) leads to the conclusion that there is no structural information in the IID data. Examination of the biplot indicates that the survey responses partitioned into three clouds, the IID data plus two outlier clouds. Table 7 reports the mass, quality, inertia, coordinates, and contributions of the data in outlier cloud in the lower right corner of the biplot, and Table 8 reports those of the outlier cloud in the lower left corner.

name	mass	qlt	inr	cor1	ctr	cor2	ctr
15-4	6	687	16	935	282	-1122	405
18-4	6	689	17	778	178	-1318	511
19-4	2	572	11	956	172	-1457	400
23-4	6	689	17	778	178	-1318	511
24-4	8	655	17	272	31	-1231	625

Table 7. Full – Dim 2 v 1 Lower Right Outlier Cloud

Question 15 asked "… likelihood that you will be fatigued while standing watch …," and the response 4 was "neither." Examination of the Figure 1 "Fatigue – Q15WFag" frequency plot and Table 6 indicates that a response of 4 was low mass and medium quality whose inertia is due primarily to it large coordinate distances. Thus, response 4, shown with no fill color, should be considered as not belonging to the mass of the response 5 – 7. The interpretation is that fatigue is an important predictor of watch performance. Similar analysis of question 18, "… likelihood that you will clearly understand the difference between automated functions and those you are expected to perform …," shows that response 4 does not belong to the mass of response 5 – 7, which further supports that LCS personnel understand the difference. Analysis of question 19, "… likelihood that operating procedures are sufficiently detailed …," question 23, "… likelihood that your watch station displays provide all the information you need …," and question 24, "… clearly understand all the information displayed …," yield the same conclusion. The 4 Neither response does not belong to the mass of either the unlikely or likely subgroups. Responses to questions 19 and 23 should be considered as two separate subgroups, and the 9 and 7 unlikely number of responses indicate some procedures may not be sufficiently detailed to provide all the information needed to stand watch. Of the personnel responding unlikely to question 19, 4 were bridge personnel, 2 engineering, and 3 “other”. Of personnel responding unlikely to question 23, 2 were bridge personnel, 1 engineering, and 4 other personnel. Responses to question 24 should be considered as supporting LCS personnel understanding of display information.

name	mass	qlt	inr	cor1	ctr	cor2	ctr
10-4	4	668	12	-1324	531	-673	137
11-1	6	758	16	-1386	608	-690	151
12-1	4	612	14	-1278	428	-838	184
18-1	4	503	15	-1177	246	-828	167
18-2	2	396	12	-1246	246	-971	150

Table 8. Full – Dim 2 v 1 Lower Left Outlier Cloud

Question 10, “… How likely are you to sleep at the same time each day …,” response 4 exhibited the same low mass and medium quality with its inertia due primarily to its large coordinate distances. The two neither responses do not belong to either the unlikely or likely subgroups. As with questions 19 and 23, the responses to question 10 should be considered as from two separate subgroups. Of those responding unlikely to question 10, 8 were bridge personnel, 9 were engineering, and 7 were Other. Of those responding likely, 2 were bridge personnel, 1 was engineering, and 6 were other personnel. Questions 11 and 12 response 1 and question 18 responses 1 and 2 exhibit similar low mass and medium quality with their respective inertia due primarily to large coordinate distances. Questions 11, having "… sufficient time to perform assigned preventive maintenance …" and 12, having "… sufficient time to perform corrective maintenance …" both response 1 each indicate that the extremely unlikely responses are outliers not belonging the population mass in Figure 6.

Dimension 3 Versus 2 Analysis

Figure 10 presents the biplot of the full survey response data on dimension 3 versus dimension 2 coordinates, again with a bivariate normal 95% confidence ellipse. The coefficient of correlation between the response frequencies was -0.09505. Like dimension 2 versus dimension 1, the mass of the data is normally IID with some outliers and do not clearly map to either dimension 2 or 3. Dimension 3 adds only 8.7% explanation of the variation (cumulatively 42.9%). Again, this leads to the conclusion that there is no structural information in the IID data of the first three dimensions. Question 17 with response 2, questions 18 and 24 with response 1, question 20 with response 7, and question 27 with response 3 form one set of outliers near the bottom of the confidence ellipse. From Figure 2, Question 17, "… likelihood that you will encounter more tasks than you have time to perform," the three unlikely responses 2 were clearly not members of the dominant likely population. It is noteworthy that all response 2's were bridge personnel. From Figure 4, Question 18, "… understand the difference between automated functions and those you are expected to perform," and from Figure 5 Question 24, "… clearly understand all the information displayed on the control panels for my watch station," response 1's do not belong to the negatively skewed distributions. The one response 3 for Question 24 is not statistically different from the negatively skewed distribution. The two responses 1 for Question 18 were other personnel, and the three responses 1 for Question 24 were one bridge personnel and two other personnel. From Figure 4, the one response 7 for Question 20, "…automated features of your watch station make standing watch easier…,” does not belong to the 1-6 response distribution. The 7 response was a bridge personnel. From Figure 5, the one response 3 to Question 27, “…chance that modifications to the information display and automation could mitigate effects of overtasking or fatigue…,” does not belong with the 1-2 or the 4-7 responses and was from a bridge personnel. The other three outlier response 4’s in the upper left quadrant of Figure 4 were Question 18, Question 19, “…operating procedures are sufficiently detailed…,” and Question 23, “… watch station displays provide all the information you need….” This indicates that the responses for these questions are bimodal with the 4 responses not belonging to either mode. The three 4 responses for Question 18 were one bridge and two other personnel. For question 19, it was one other personnel, and, for question 23, it was one bridge and two other personnel.

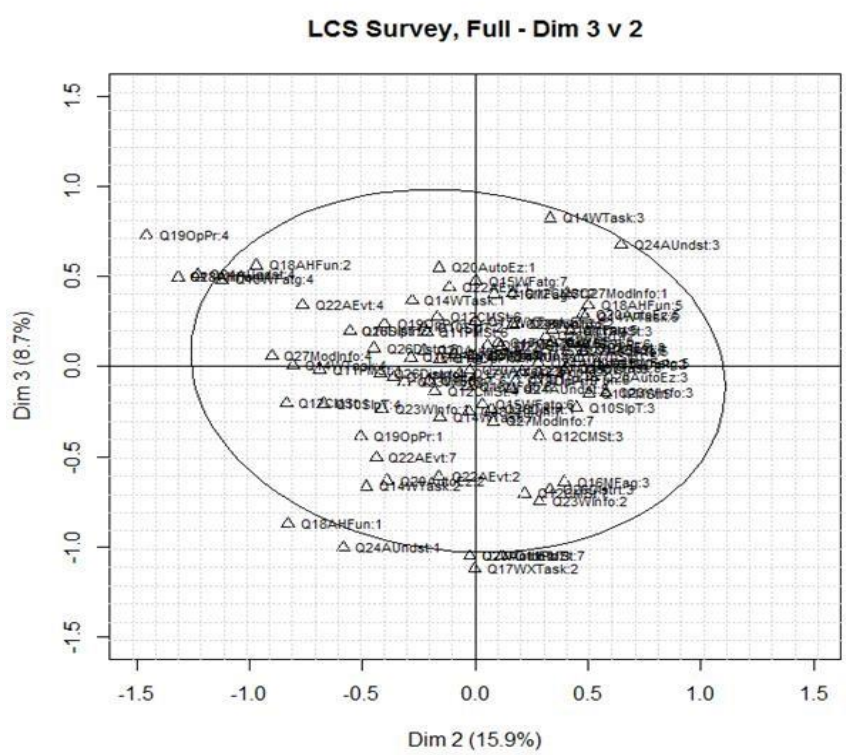


Figure 10. LCS Survey, Full – Dim 3 v 2

Dimension 4 Versus 3 Analysis

Figure 11 presents the biplot of the full survey response data on dimension 4 versus dimension 3 coordinates, again with a bivariate normal 95% confidence ellipse. The coefficient of correlation between the response frequencies was -0.07381. Like the prior dimensions, the mass of the data is normally IID and do not clearly map to either dimension 3 or 4. Dimension 4 adds only 6.1% explanation of the variation (cumulatively 49.0%). Again, this leads to the conclusion that there is no structural information in the IID data of the first four dimensions. Examination of the biplot indicates that the survey responses are now distributed about the confidence ellipse rather than being partitioned into distinct clouds. Outlier responses to questions 17 response 1, 18 responses 1 and 2, 20 response 7, and 24 response 1 were identified and discussed for prior biplots. Questions 11 and 12, "…sufficient time to perform assigned preventive (corrective) maintenance…" response 7's do not belong to the negatively skewed distributions in Figure 6. Likewise, question 16, "… be fatigued while performing maintenance …," response 3 does not belong to the 4-7 likely response distribution of Figure 4.

Demographics

Figure 12 presents the biplot of full survey demographics data on dimension 2 versus 1 coordinate, with the bivariate normal 95% confidence ellipse for only the demographics. There are two outliers. Last underway period, hours per day normally slept, Q9_HrsSleepL6_8, for normally sleeping 6 to 8 hours per day, maps primarily to the Dimension 2 negative axis. This demographic data point is most closely associated with the Figure 9, dimension 2 versus 1, outlier cloud responses fatigued 15-4, understanding automated functions 18-4, detailed operating procedures 19-4, and watch station information 23-4, which suggests an association between 6 to 8 hours sleep daily to being optimally alert while standing watch.

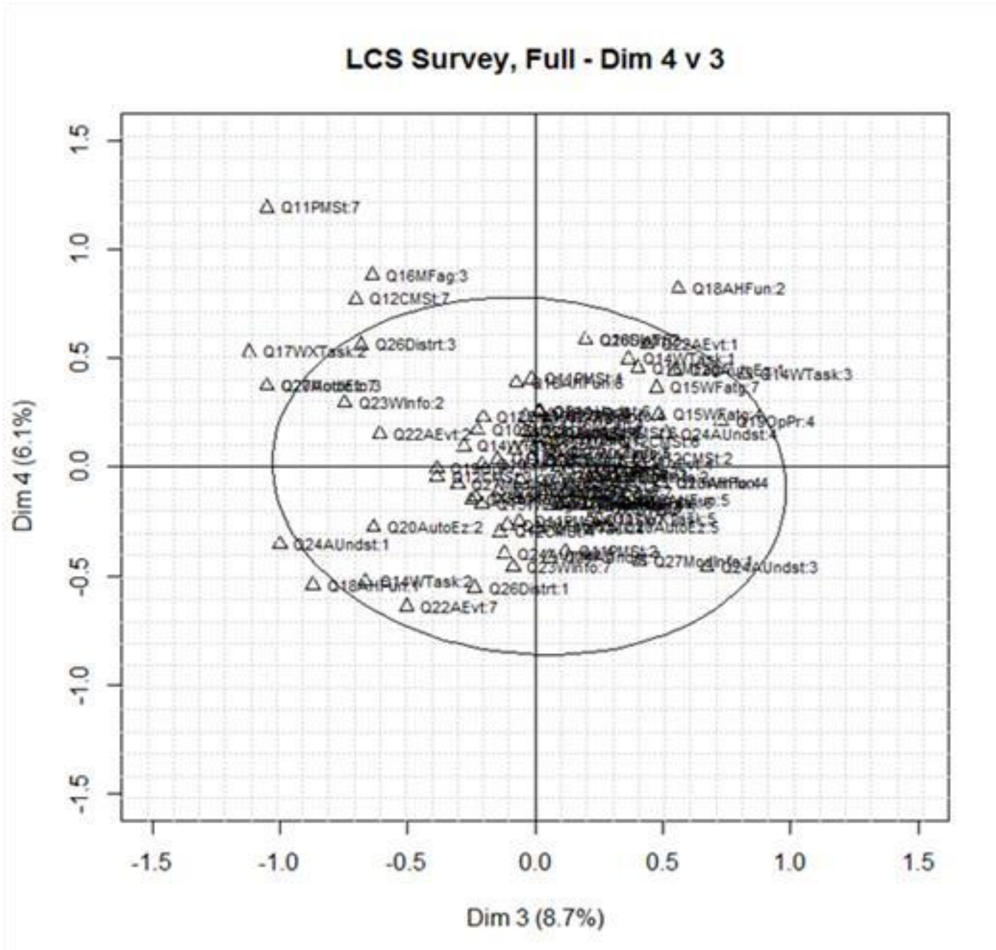


Figure 11. LCS Survey, Full – Dim 4 v 3.

The outlier for number sea tours completed, Q3_ToursFourth, maps primarily to the negative dimension 1 axis. Again, this demographic is most closely associated with the Figure 6, dimension 2 versus 1, outlier cloud responses sleep time 10-4, preventive maintenance time 11-1, corrective maintenance time, and understanding automated functions 18-1 and 18-2. This association may be due to the low mass of the 3 personnel (8%) responding that this was their fourth tour. Conversely, 6 personnel (17%) responded that they were on their fifth or greater tour. This conflicting evidence does not allow any conclusion regarding an association between prior sea duty experience and transition training before being assigned sea duty on a highly automated vessel such as an LCS.

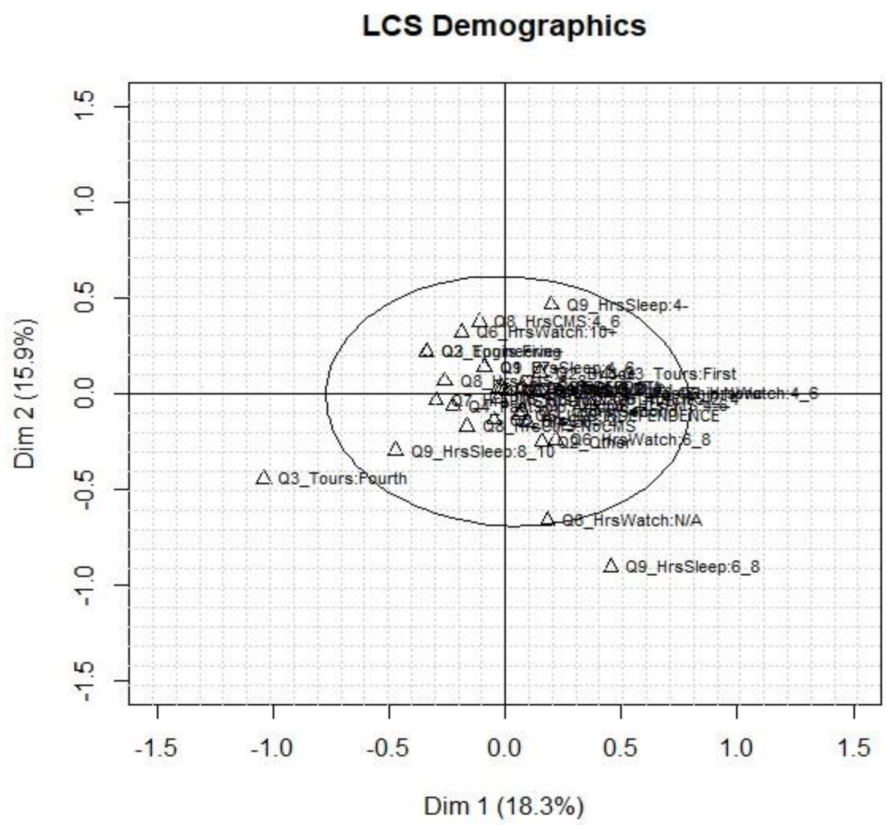


Figure 12. LCS Demographics – Dim 2 v 1.

Figure 13 presents the biplot of demographics data on dimension 3 versus 2 coordinates with the bivariate normal 95% confidence ellipse for only the demographics. Again, only responses Q9_HrsSleepL6_8 and Q3_ToursFourth displayed as outliers. Figure 13 presents the biplot of demographics data on dimension 4 versus 3 coordinates with the bivariate normal 95% confidence ellipse for only the demographics. One additional demographic outlier for last underway period, hours per day normally slept, Q9_HrsSleep4-, for normally sleeping less than four hours per day, maps primarily to the Dimension 4 negative axis. There are no response outliers in the lower right quadrant of Figure 8, Dimension 4 versus 3, with which this demographic outlier maps.

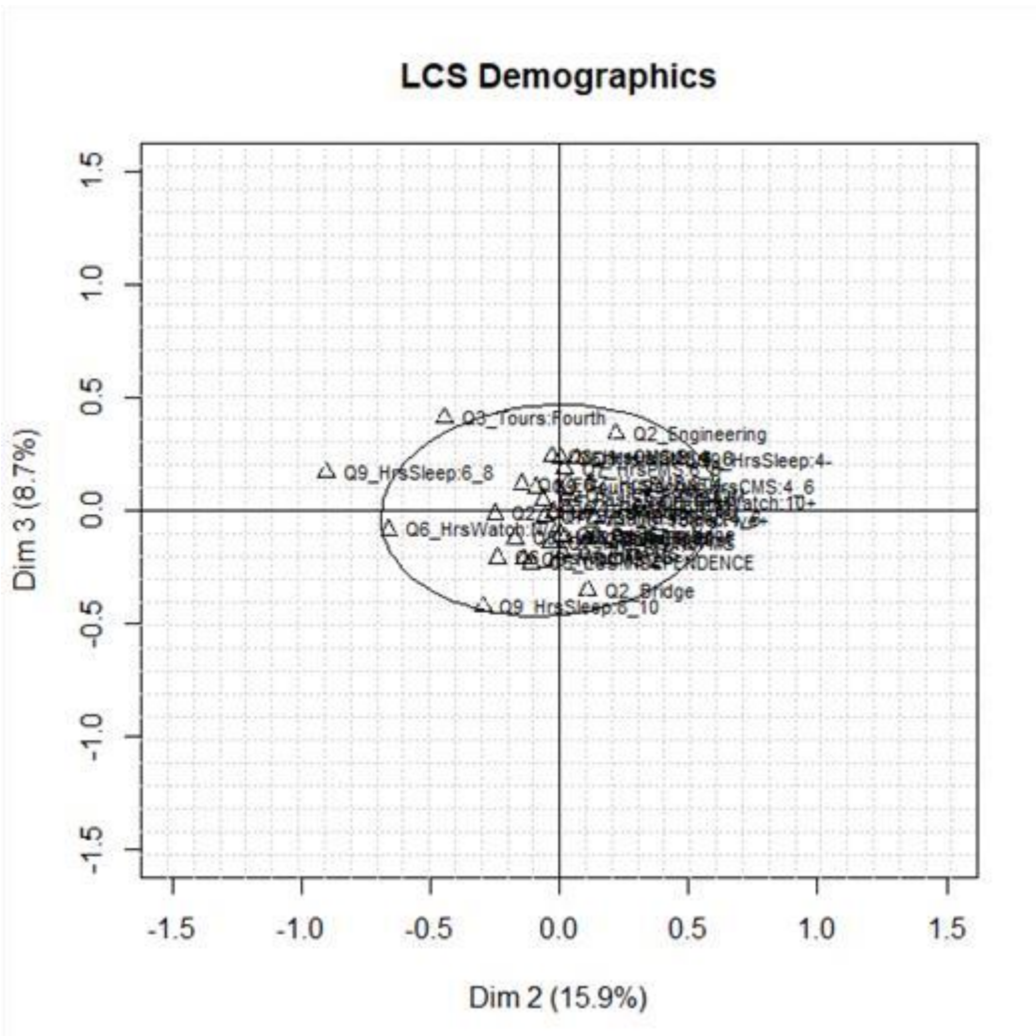


Figure 13. LCS Demographics – Dim 3 v 2

Survey Discussion

The goal of the survey was to determine if, in the opinion of experienced LCS crewmembers, there is a perception that their ability to perform their watch standing and maintenance duties is impacted by the highly automated LCS environment. Integration of response frequency histograms and multiple joint correspondence analysis partitioning of responses into cluster centers of mass, noise, and outliers revealed response patterns that support the conclusion that the LCS automation environment does impact performance of watch standing and maintenance duties. Analysis of the demographics (Supervisory Duties, Primary Duty, and Experience) support that survey results were consistent across all three variables, with one outlier being those with four tours, which is not unexpected given the Navy's sea shore rotation of 3-5 years – someone in this category would be very senior, and not many personnel at this level are assigned to a single ship. Question 9 (Hours of Sleep) seemed very concentrated for all demographics between 4 and 6 hours (69%), which is not surprising given that most of the individuals surveyed stand the same watch schedule. This amount of sleep reported by the respondents is significantly below that recommended in Navy Policy (7 hours) and is consistent with the results of the Fatigue section of the survey; it stands to reason that there is a relationship between low hours of sleep, not sleeping at the same time (lack of a circadian rhythm) and operators being fatigued while performing maintenance and standing watch.

Returning to Figure 4, Fatigue Response Distributions, responses to question 10, likelihood of sleeping at the same time each day, partition into two groups, seventy-seven percent (77%) are unlikely to do so. and twenty-six percent (26%) likely to do so. This sleep pattern is negatively associated with the responses to question 15 likely of being fatigued while standing watch and question 16 likely of being fatigued while performing maintenance tasks.

Returning to Figure 5, Watch tasking Response Distributions, only the three response 3's were outliers for question 17, strengthening support for the perception of encountering more tasks than having time to perform. The likely responses to question 14, performing all scheduled tasks, and question 26, being distracted by other tasks, suggests that LCS personnel prioritize accomplishment of assigned tasks and response to other unplanned tasks as they can. This may or may not be the best prioritization plan given the criticality and potential impact of other unplanned events. The distribution of responses to having sufficient time to perform preventive and corrective maintenance tasks in Figure 3 are negatively skewed with adjusted 35% unlikely and 44% likely for preventive maintenance tasks and 21% unlikely and 42% likely for corrective maintenance tasks. Again, as with watch tasking, there may be unplanned tasks impacting some engineering personnel's ability to complete maintenance tasks. Evaluation of the automation-related question 20 indicated that a slight majority of respondents, 44%, seem to feel that the automation on LCS made their watch standing easier than on other ships, but 35% responded that automation made watch standing more difficult. After omitting outliers for question 18, understanding the difference between automated and manual functions, all responses were likely. After omitting the outlier for question 19, sufficiently detailed operating procedures, responses partitioned into two groups; 26% unlikely and 74% likely.

Returning to Figure 8, question 22, trusting automated alarms, resulted in a relatively uniform response rate with 49% responding unlikely and 40% responding likely. After adjustment for the three outliers, question 23, workstation displays supply sufficient information, the responses partitioned into two subgroups with 22% responding unlikely and 78% responding likely.

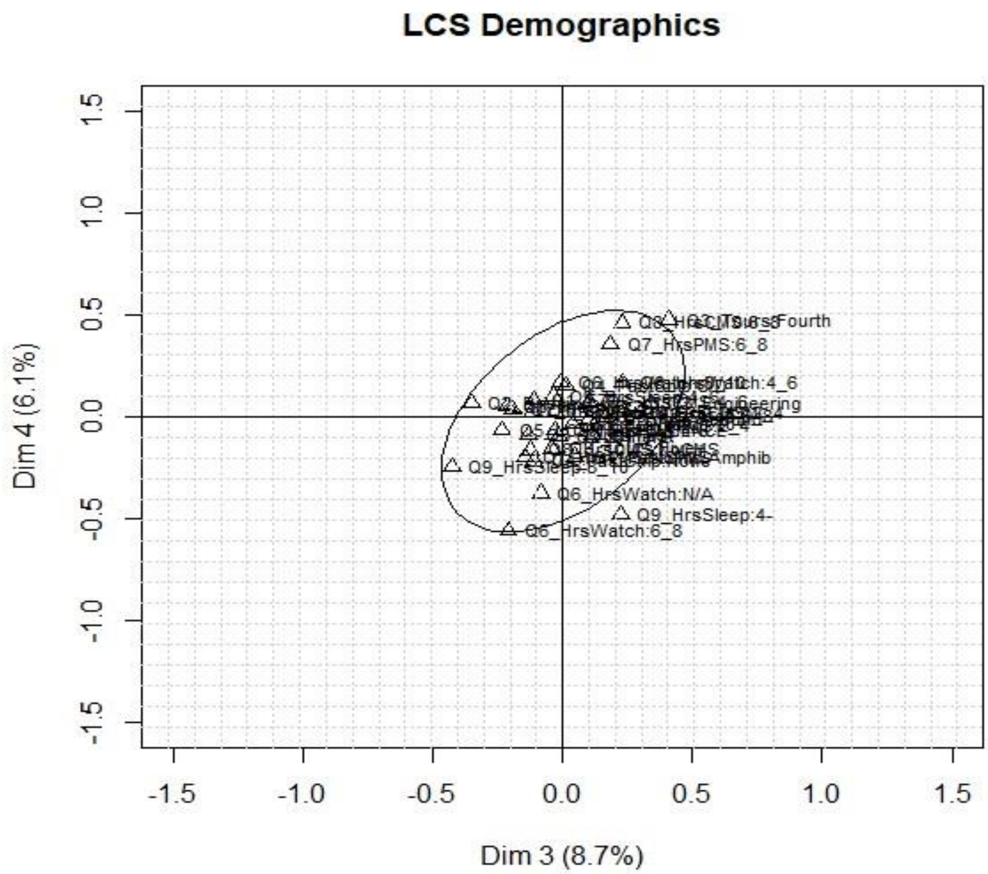


Figure 14. LCS Demographics – Dim 4 v 3

Closer evaluation of the automation-related questions indicated that a slight majority of respondents (54 percent) seem to feel that the automation on LCS made their watch "more challenging" than on other ships (question 21). Conversely, the distribution for a similar question (20) was much closer to a standard bell curve, about the same majority responding that the automation made their watch "easier" than on other ships. The responses to these questions did show a bit of a dichotomy in that while the answers to the more positive questions (18, 19 and 20) were skewed heavily toward the "likely" side, the more negative question (21) was also skewed toward the "likely" direction. Questions 24, clearly understanding display information, and 27, display modification could mitigate overtasking and fatigue, provide insight into the LCS automation-human interface design. An adjusted 96% responded likely to question 24 that they understood display information. Conversely, 68% responded likely to question 27 and 12% responded unlikely indicating a small proportion of LCA personnel find that display information contributes to overtasking and fatigue. Given that the demographic biplots (Figure 14 is the final one, included for continuity) were statistically homogeneous but multiple outliers were observed in the response biplots, it can be concluded that the design of and training for the LCS automation-human operational environment assumes a standard Navy personnel profile and does not account for natural differences in human capabilities. This strongly suggests a need to revise the design of the human component in the manning model of the LCS environment to identify and integrate management of failure risk due to variance in natural human capabilities.

4.2 PERFORMANCE DECOMPOSITION

Workflow Analysis: Workflow analysis is a process in which businesses examine the progression of workflows to improve efficiency**.** Workflow analysis identifies areas for improvement; for example, by improving workflows, resources are used more efficiently, and staff is better able to work to capacity. There are myriad techniques and software programs for workflow analysis, including IMPRINT, but most have a rather deterministic approach (as seen earlier in the HTA section of this paper). Some researchers have maintained that in looking at systems that may include a high degree of automation, as well as human-automation interfaces, a cognitive element is required. As noted by Karwowski and Ward (P.513): “Work measurement models must be based on both work and job design in addition to a paradigm of human performance” and that “a systematic description of human performance covers a wide range of work situations, from routine performance to stressful encounters with accidental events, is needed" (Karwowski and Ward, 2016).

Using the approach above, the set of critical selected for analysis, are broken down into task elements with a matrix to capture both the task and the applicable "swim lane" using a task analysis worksheet, which categorizes the elements of each step as follows:

a. Physical Elements: Those elements which are dependent upon human sensing (i.e., auditory, tactile, etc.)
b. Cognitive Elements: Those elements that depend on human thinking and decision making (i.e., weigh alternatives, make decision)
c. Automation Elements: Those elements associated with automated functions (i.e., display status, calculate function.

The task analysis worksheet in Figure 15 displays all the elements and is an example of a completed form for one of the operational tasks:

Page: ____1__ of _1___

Operation Name: Parallel Bus to Bus Tie Operation Number: CAEPA
Operation Description: Operational Procedure to align Electric Plant

Shift: Operations Time: 8 min Analysis By: Cordle

Physical Element Codes:	Cognitive Element Codes:	Automation Element Codes
PA: Auditory PC: Cognitive PF: Fine Motor PG: Gross Motor PS: Speech PT: Tactile PV: Visual	RN: Realize Need for Decision GI: Gather Information MA: Model Alternatives WE: Weigh Evidence SA: Select Alternative RD: Review Decision AC: Act on Decision DT: Distracted/Inattentive	AD: Delay AL: Control Action AS: Display Status AE: Execute Action AX: Calculate Function

Start Time	End Time	CE Code	PE Code	AE Code	Initiating Event	Task Element Description	Terminating Event
0000	01:00		PA		Order to execute	Verify System Alignment	Verified
01:00	01:30	AD			System alignment verified	Press "Initiate Bus Tie" on HMI	Pushed "Initiate Bus Tie
01:30	1:45			AS	"Are you sure" pops up	When "are you sure?" pops up press "yes"	Pushed "yes"
1:45	2:30	WE			Pressed "yes"	Ensure 3S/4S and 1S/2S Breaker Close	Verified
2:30	7:30		PV		Observed closing on display	Perform Visual Inspection of SSDG	Inspection Complete
7:30	8:00	RD			Inspection Complete	Reverify System Alignment	Verified

Figure 15: Sample Time-Motion Analysis Worksheet

A similar Time-Motion Analysis Worksheet was prepared for each of the nine "critical tasks" as part of the proof of concept. These are included as Appendix G.

Failure Mode Analysis: Once the high-risk procedures had been identified and broken down into discrete tasks for workflow analysis, a FMEA risk analysis (Figure 16) was performed to identify potential failure modes, occurrence distributions, and impacts. This allowed for the generation of a failure action plan (FAP) for each failure mode (human or automation) using standard Failure Mode Analysis techniques. To support this process, the author developed a tailored worksheet (Figure 17) to capture the critical failure tasks identified in the Time-Motion Analysis Worksheet, determine the degree of risk by applying a 1-10 scale to the Severity (SEV), Frequency of Occurrence (OCC) and Detectability (DET), resulting in a final Risk Process

Number (RPN) that can then be used to determine the tasks within each procedure that present the highest risk of impacting mission (including severe injury/death and major equipment damage).

Once steps are identified, recommended actions can be hypothesized to reduce the risk, by addressing one of the three factors (SEV, OCC, or DET) that will result in a lower RPN if implemented.

Procedure:____________________ Date:______ Analyst:_____

Process Step	Potential Failure Mode	Potential Failure Effect	SEV	Potential Cause	OCC	Current Process Controls	DET	RPN	Action Recommended	SEV (Revised)	OCC (Revised)	DET (Revised)	RPN (Revised)

Figure 16: Failure Analysis Worksheet (Page 1 of 2)

The spreadsheet above can be filled in for each task to by analyzed using the below key, modified from a standard FMEA spreadsheet which was slightly tailored to address the Navy-specific parameters that would apply to normal at-sea operations based on operator experience. While there could be other interpretations of the gradients, the below table is used for consistency and conforms to the norms used in Navy Operational Risk Analysis processes (OPNAVINST 3500.39C, July 2010).

Ranking	SEV Severity	OCC Frequency	DET Detectability	SEV Severity	OCC Frequency	DET Detectability
	Qualitative Condition			Quantitative Condition		
1	Minor	Remote	Very High	Inconvenience, Cosmetic Damage, Mission Delay	Once in ship's lifetime	100%
2	Very Low	Very Low				
3	Low	Low	High			<75%
4	Moderate	Moderately Likely		Minor Mission Degradation or Minor Equipment Damage	Once per deployment Cycle (3 year)	
5			Moderate			<50%
6						
7	High	Highly Likely	Low	Severe Injury, major Equipment Damage Loss of secondary Mission	Once per Deployment (6 months)	<10%
8						
9	Extreme	Very Likely	Very Low	Death or Loss of Primary Mission	Monthly or higher	<1%
10						

Figure 17: Failure Analysis Worksheet Key (Page 2 of 2)

From the Time Motion Analysis Worksheets prepared for each critical task, a FEMA worksheet was prepared to address the critical failure modes, causes, and recommended solutions from each one, and the resulting (potential) improvement in risk were these recommendations to be implemented. When the tasks are plugged into IMPRINT, an attempt will be made to insert these mitigations and compare mission performance results before and after to see if performance improvements or degradations can be noted. In addition, the IMPRINT models can be used to identify areas of overloading, issues with the human-automation interface, and at varying levels of fatigue for comparison. A discussion of the "Reports" function of IMPRINT and example results from this analysis are presented in the following section.

4.3 IMPRINT FUNCTIONAL INTERFACE MODELING

The current models used to model shipboard manning are based on calculations of gross workload, such as watch, maintenance, training, etc. but do not provide a level of detail that allows any type of workload analysis or modeling of anticipated working conditions such as fatigue, overtasking, or the effects of automation. The use of modeling software for The IMPRINT program was developed by the Army as a means to model workload in individuals and teams and is ideally suited for military crews since they often work in small teams, even if they are a subset of a larger force. The Navy could easily adapt the IMPRINT model for shipboard manning, adding a layer of fidelity to the model that has not been possible and allowing manpower planners to assess risk to mission and impact of external factors to the process, allowing for better informed decisions.

IMPRINT is a software program based on the C# code protocols, and allows for a series of models by Force, Operators, and Maintainers, as well as Support Personnel. It can be used to construct a series of missions, functions, and tasks, and is also capable of identifying operations and tasks performed by humans as well as by machines, or automation. Once the basic tasks are constructed into a network "function", the individual tasks can be simulated using a series of defined parameters, including time, accuracy, and assigned parameters for degree of difficulty in areas including auditory, visual, cognitive, etc. Once the operators are built, and the mission defined as a network, specific taxons can be added to simulate fatigue, levels of training and experience, and other "human" variables that can influence the outcome. A sample network display (in this case, an Army tank mission) is shown in Figure 18.

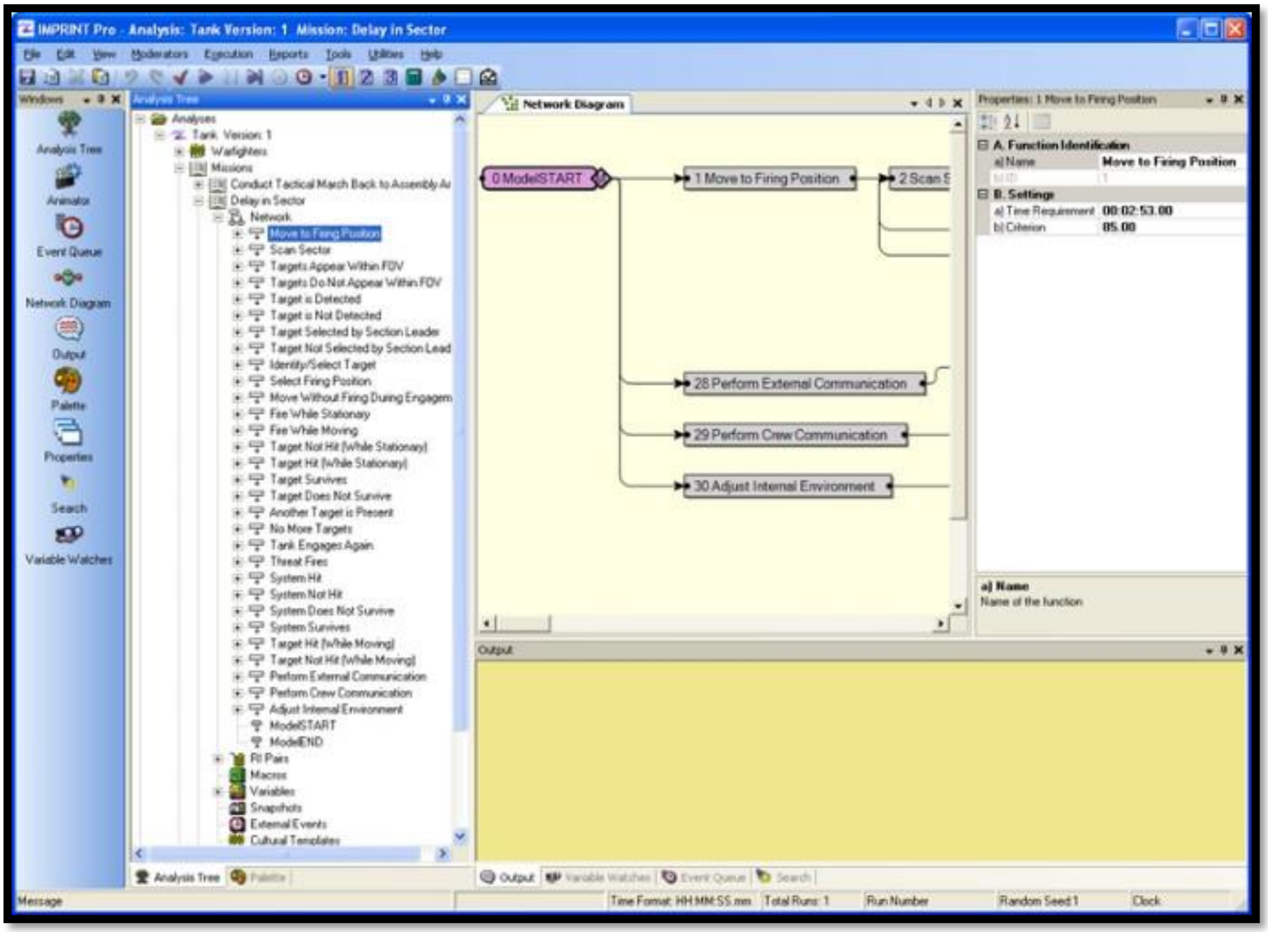


Figure 18. Sample IMPRINT Workflow Diagram (Function Level).

The settings (time requirements, accuracy criterion, shown in the upper right corner) are based on either experience and/or information about the specific system, educated assumptions, or a distribution of a type selected by the analysist. The mission can then be run in real time and compared against specific desired or acceptable outcomes, such as acceptable failure rate or a specific outcome. This information is supplied to the operator as a table and/or graph and can be compared to various outcomes as parameters are varied based on experience. In practice, this method has been utilized by the United States Army to simulate the crew of an Abrams M1A1 tank and support manning decisions for future consideration.

IMPRINT can also be used in conjunction with other software simulations such as Fatigue Avoidance Scheduling Tool (FAST), a model used to predict operator effectiveness based on sleep and work schedules. The assumption inherent in this paper is that IMPRINT, combined with FAST and informed by in-situ measurements and surveys of crew members will validate its potential as a planning tool in determining future manpower requirements for Navy ships. A schematic of this process is shown in Figure 19, and a FAST graph is shown in Figure 20.

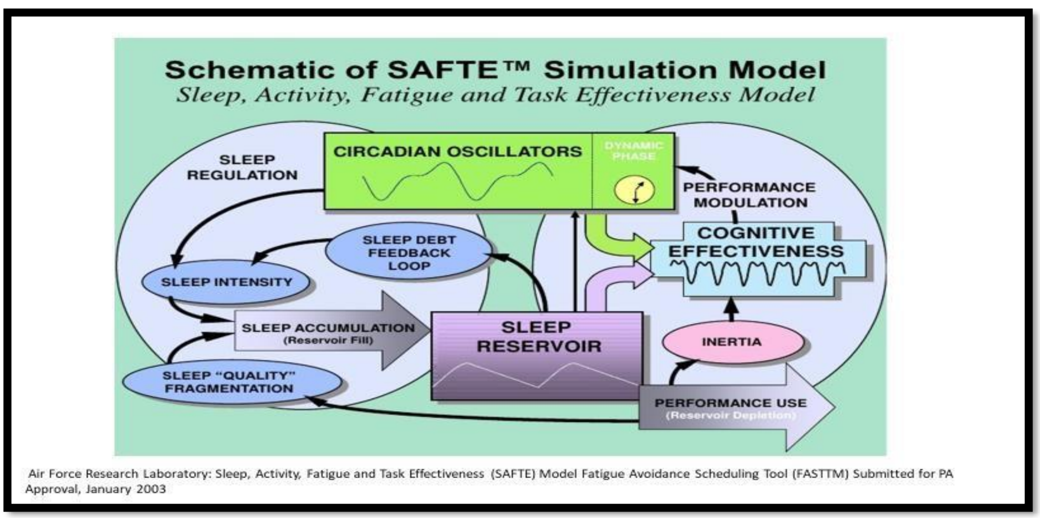


Figure 19. SAFTE Simulation Model (IMPRINT User's Guide, 2007, pg. 3, Reproduced with permission)

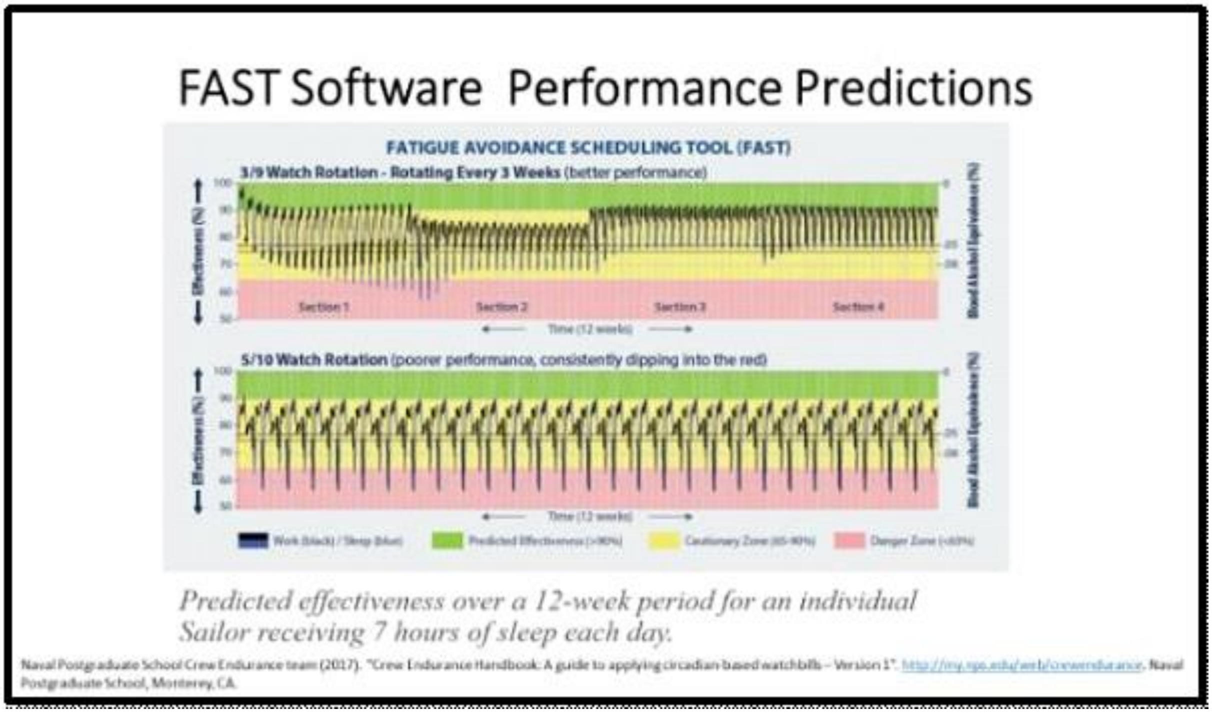


Figure 20: FAST Software Graph of Predicted Effectiveness (Source: Naval Postgraduate School Crew Endurance Handbook, 2017, Pg. 3)

IMPRINT has been used in small crew situations, for example a 4-person Tank crew, to determine the feasibility of combining workload tasks and reducing the number of operators. In one case, predicted failure rates of the proposed manpower reductions were sufficient to inform the decisionmakers and influence the outcome of a tank crew manning study (Allender, 2014).

4.4 IMPRINT PERFORMANCE DESIGN

The Naval Postgraduate School has created a detailed model of the LCS FREEDOM class crew using the Forces Model in IMPRINT, which forms the basis for this study. In conducting initial research for this study, it was apparent that the predominance of mechanical failures in the program have been in the engineering department, for this reason this study focuses on a small team of individuals who stand watch and maintain equipment in the Engineering Department, using a watch and work schedule designed around the Standard Navy Work Week (now called the Naval Allowance Factor). This reference gives a notional breakdown of each major element of a workday. For this analysis, key portions of the day were defined as a "mission" and various "functions" assigned to the crew members during these periods. As previously noted, the Operations Model of IMPRINT allows a detailed analysis of specific functions and tasks as they relate to cognitive function and performance. A schematic of the NAF is shown Figure 21.

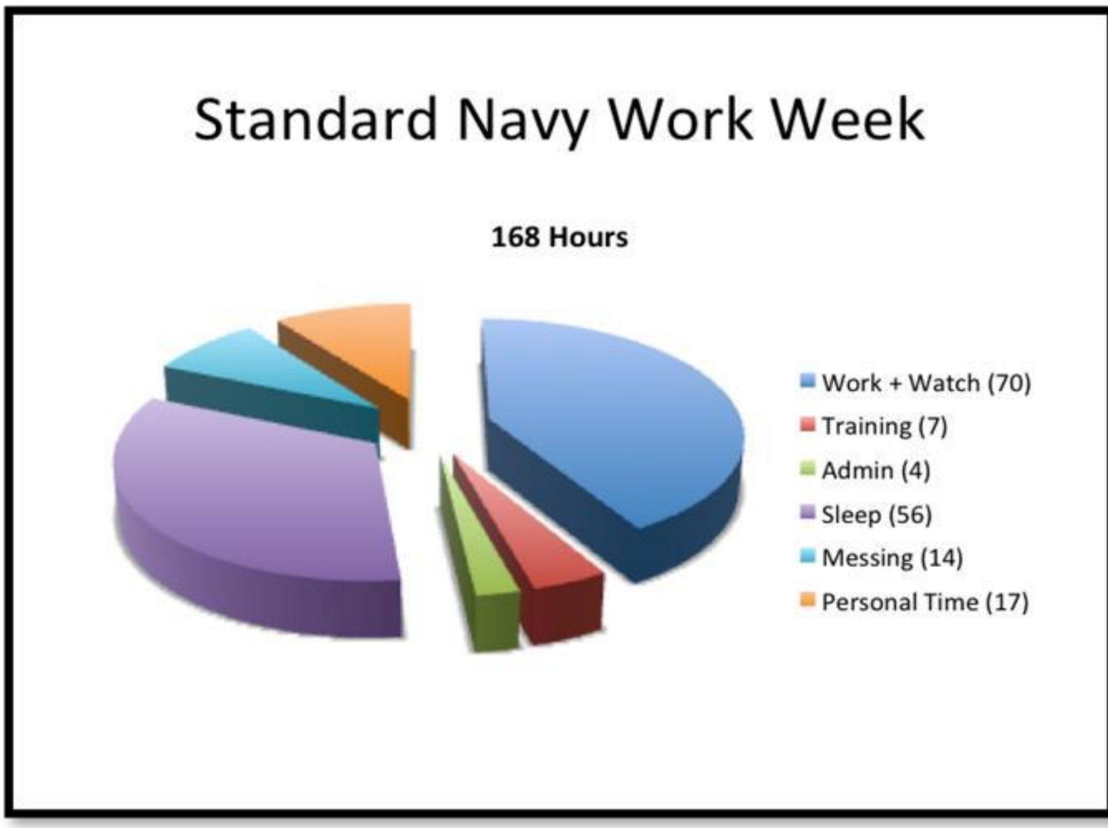


Figure 21: Standard Navy Work Week (after OPNAVINST 1000.16L, NAVY TOTAL FORCE MANPOWER POLICIES AND PROCEDURES, June 2014)

Numerous studies have shown that the actual hours worked and slept vary somewhat for the crew members in actual ships at sea, and these empirical numbers could easily be used in future studies to determine impact of manning shortfalls, excessive workload, or reduced effectiveness of automation. For the purpose of standardization for comparison, and since there are multiple initiatives underway to better align manning and workload to the design parameters, this study used the Navy standard as the baseline.

LCS Study Impact. Based on the aforementioned survey of two LCS crews discussed in section 1 of this chapter, the following conclusion applies:

> *"The four dimensions of human cognizance, task workload, maintenance, and automation-human integration are important for consideration in refining the IMPRINT model in the next phase of this research. Specifically, a majority of those surveyed feel that fatigue, overtasking, and the degree of automation inherent in the current manning model for LCS present significant challenges. This leads to the conclusion that these areas merit further detailed research cognitive/physical task workflow analysis, refinements to the existing IMPRINT modeling algorithms, and possible modifications to the overall manning construct to address identified potential deficiencies. Additionally, an examination of specific areas of automation and the human system interface may be appropriate. Based on the survey results, the researchers performed cognitive/physical task workflow analysis of bridge and engineering tasks, as well as examining past failures, and build an initial IMPRINT crew model that accounts for the four survey dimensions in the next stage of research."*

The IMPRINT program has embedded algorithms to apply some of these factors, but as limitations are encountered, some recommendations for modification may follow. The following breakdown addresses the domains addressed in the workflow analysis.

Watch: There are several required functions on a ship that are performed around the clock by a specifically qualified individual called a “watch stander”. In order to perform these functions, an individual must be “on watch” for a given period. Since the Navy manning model uses a 3-section rotation underway as a baseline for manning calculations, this was used as the basis for the breakdown of hours in this study as well. An individual on watch has a relatively discrete list of duties during this period, consisting of monitoring equipment parameters, patrolling the workspace (in this case, the engine room), starting, stopping, and operating various pieces of equipment, and responding to casualties. IMPRINT allows the analyst to build a set of Functions based on these duties, each with a discrete set of tasks to accomplish that function. For a watch stander, the basic reference for most activities is called Engineering Operating System (EOSS), which consists of a series of operating procedures in relatively discrete activities and a set of defined tasks. These are sorted by type, either by Operating Procedure or Casualty Procedure. There are hundreds of individual procedures, and it would be possible to model each one of them in IMPRINT, but since a given operator is unlikely to perform more than a few per watch period, a reasonable model can be developed, based on experience, to simulate a notional watch period with a defined set of functions. The specific operating and casualty EOSS procedures chosen for the model was defined later in the paper and explained in detail. Overall, the combination of a sequence of operations can simulate a “normal” watch period, and casualty procedures can be inserted into the model to determine their impact on the crew members both individually and as a team. For example, a single individual may be able to perform a sequence of normal operating procedures by himself over a watch, but he may have to give and receive reports to other members of the watch team or coordinate some actions with them or with personnel outside the watch team. He may also have to use automated functions to complete some tasks that support a particular function. If a casualty occurs, the watch stander may have to leave his station or turn his attention to the casualty, and another crew member may have to take over the responsibilities of the normal watch. This could, in turn, impact that individual's ability to perform other tasks, depending on where he or she was in the workday – maintenance left unaccomplished, loss of sleep resulting in fatigue, etc. could result in other impacts in that individual's model. The casualty could also result in a loss of certain equipment or loss of automation, making subsequent watches more complex and perhaps increasing the probability of other failures. IMPRINT has the ability to model each of these situations, but in order to validate the model, some assumptions must be made to build a "reasonable" set of parameters to simulate one set of situations, and a determination must be made as the value of building multiple scenarios versus the time and effort/cost involved. A sample "Function" is modeled Figure 22 as an example (detailed IMPRINT protocols used in this model are described in Appendix F).

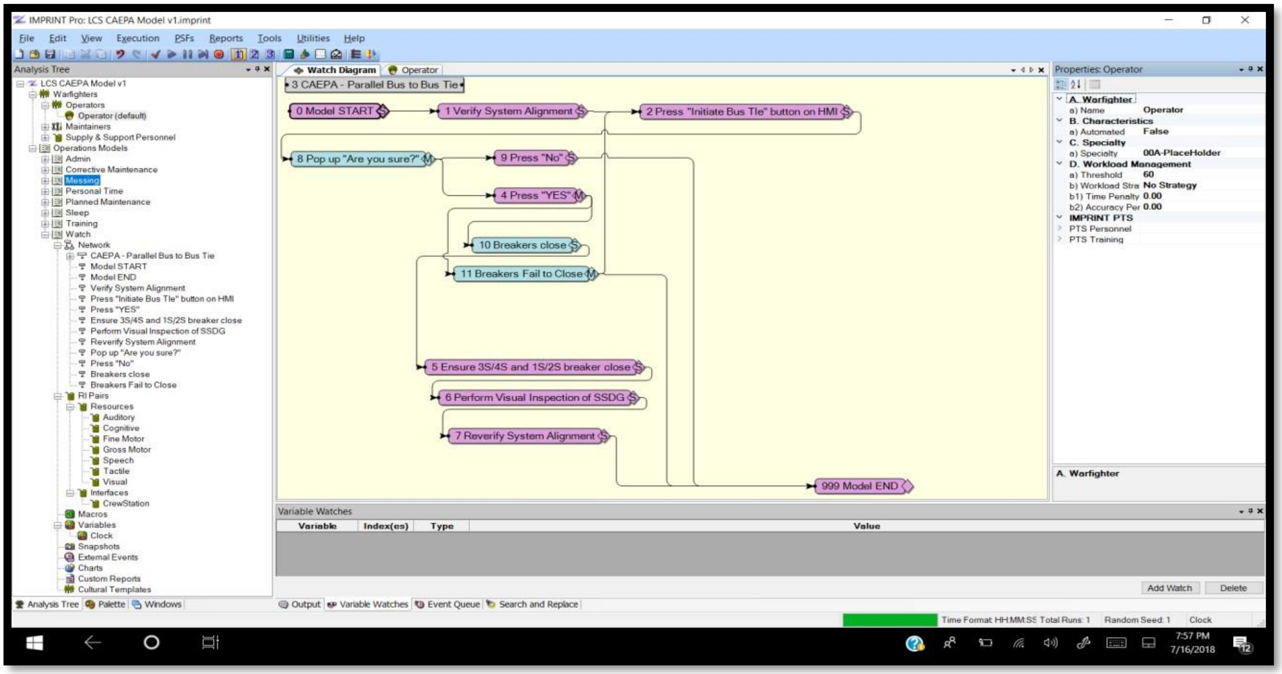


Figure 22. IMPRINT Workflow Example (Task Level)

Maintenance: The Navy recognizes two distinct types of maintenance, Planned and Corrective. Planned maintenance is based on several historical models, including expected failure rates and modes, mean time between failure, degree of automation in monitoring, and other engineering factors. It is built around a series of Maintenance Requirement Cards (MRC) performed on a specific piece of equipment at a specified periodicity. The majority of these procedures area relatively short in duration (0.5-3 hours) and while most are performed by a single operator, some require multiple personnel for part of the task or to act a safety observer. Each MRC includes discrete sections for safety precautions, tools and materials, notes and warnings, and a step-by-step procedure. The experience level and type of individual (called “rating”) is designated on each MRC, as is the amount of time expected to perform the maintenance in increments of 0.1 hr. There are various categories of MRCs, including periodic (performed per a calendar schedule, such as daily, weekly, monthly, annual, etc.); Situational (performed when a specific event occurs, such as getting underway, shooting a gun, etc.) and Unscheduled (performed when a minor discrepancy is discovered and can be repaired on the spot in a short amount of time). Other types exist in the maintenance deck, but they occur either with limited frequency or are associated with long in port periods and are thus unlikely to be performed during underway periods used for this analysis. To determine a realistic set of MRC "functions" to be performed as subsets of this mission, historical data was examined by experienced operators and maintainers and a reasonable set of MRCs was chosen. As with the EOSS procedures, there are hundreds of individual procedures, and future analyses could use the same process to eventually model each of them in IMPRINT to cover most possible combinations. There are other assumptions associated with Planned Maintenance, such as the amount of preparation time required to assemble tools and materials, secure and tag out the system, and restore the system to full capability. These are captured in Navy documentation for manning calculations and can be entered into the IMPRINT model as well. Finally, there is a certain amount of time dedicated to data entry and scheduling, as well as periodic manager spot checks which would be part of a normal routine. The model also accounts for the means by which an operator interacts with the automated systems, defined as "Resources"; for each of these areas, common values can be entered to assist in calculating the overall workload, any interferences, and overall impact on mission success. These resources are shown in Table 9.

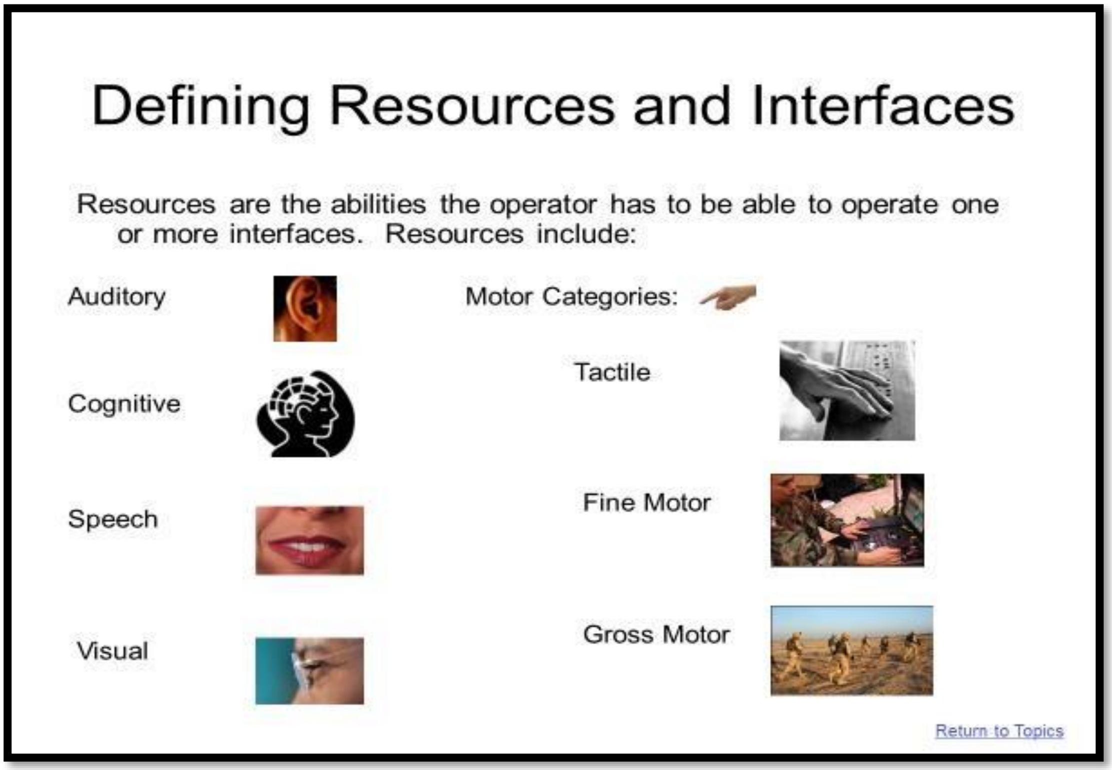


Table 9. Resources and Interfaces. (Source: IMPRINT User's Guide 2012, pg. 73. Reprinted with permission)

The remaining "missions" from the standard Navy Work Week (Sleep, Messing, Admin, Training, Personal Time) would not require the detailed operations modeling, as the missions, functions and tasks associated with these are essentially singular in nature and can me simulated with a fairly simple model. These include sleeping, eating, training, admin and personal time. They have distinct periods represented in the standard Navy Work Week and would have to be assigned priority in the case of other unplanned events; a crew member responding to a drill may miss training for example, which could detriment future level of knowledge, or sleep, resulting in increased fatigue. Other "missions" such as personal and admin time, may be simply with minimal impact, and thus detailed modeling of these periods missed is not required. A sample work day might resemble that in Table 10.

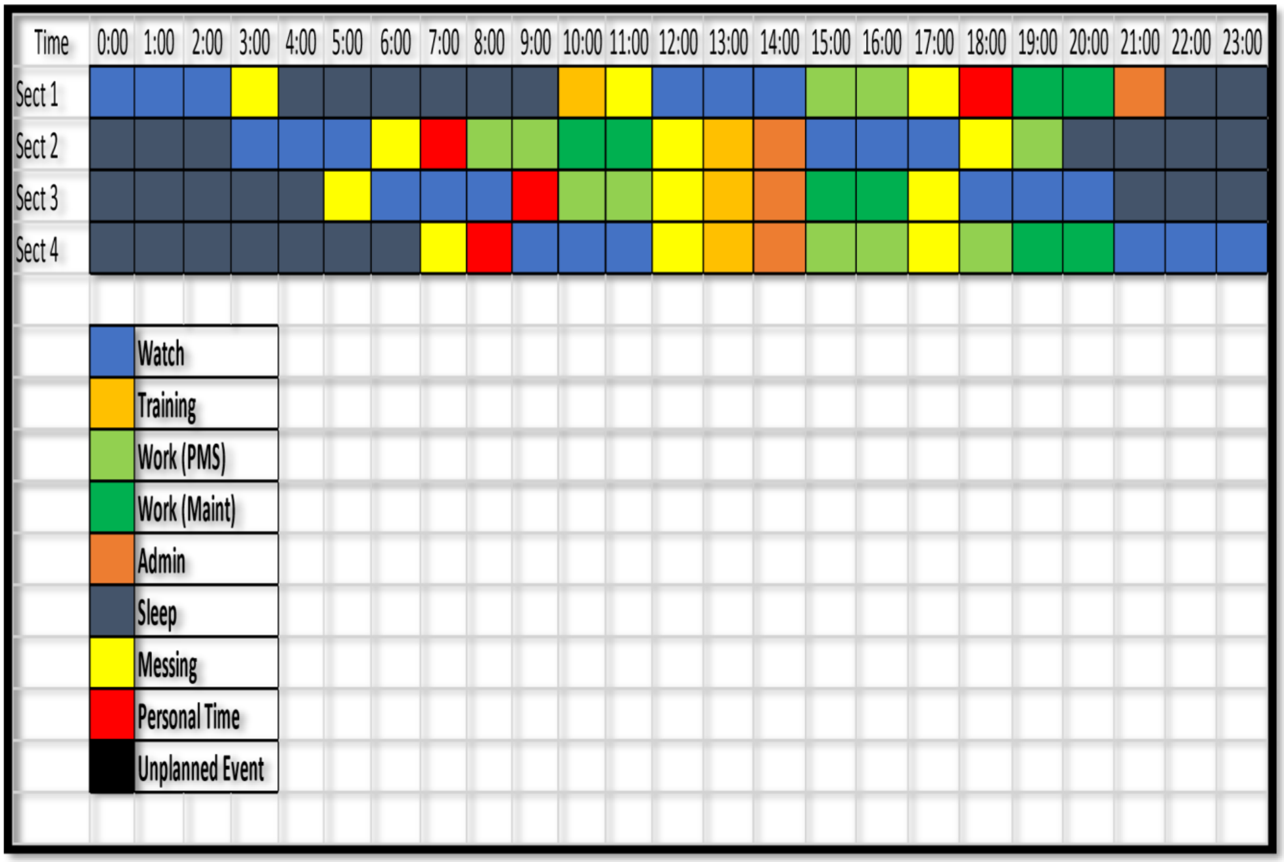


Table 10. Breakdown of 24-hour day by work domain.

By "modeling" the members of a watch section for a 24-hour period, the individual missions and tasks can be examined for workload and probability of failure. By varying the schedule (for instance, 3 section watch instead of 4, as shown above. The IMPRINT model can be tailored to various schedules and the results compared. Previous studies have shown that there is a significant difference in fatigue levels for watch standers in a circadian, 4 section fixed schedule as compared to 3 sections in a rotating schedule. This is normally depicted using FAST data (based on a correlation between predicted and observed levels) which shows clear differences. The goal of an IMPRINT model would be to capture the effect of these increased fatigue levels induced by reduced number of watch sections and translate that into a risk of failure for a given set of tasks. A comparison of these watch rotations and the resulting levels of effectiveness is shown Figure 23.

Figure 23. Predicted Effectiveness of a 5-on/10-off, 3-section watch rotation. (Hollins and Leszczynski, 2014, p. 28)

In the above graph, the gradient between yellow and red represents what standard military planners define as “acceptable” level of effectiveness, or roughly the level of impairment corresponding to a Blood Alcohol Level (BAC) of 0.08, or legally drunk.

Modeling every possible mission, function and task for a 50-plus person crew under several operating conditions would create a model with an almost endless variety of layers and outcomes. While this is obviously the most robust option, a series of informed decisions, based on either existing policy or operator experience, can reduce the family of missions and functions required to be modeled to a more reasonable number, allowing the model to run as a "proof of concept" and showing its viability. Tailoring these results based on the input of real operators as seen in the 2016 survey results can further refine the problem and support the thesis that this model is representative of the larger space, and perhaps justify the expense and time of creating a more complete model. A summary of the project delimitations is related below.

Operators: The Littoral Combat Ship has a base crew of 50 personnel, divided into 3 major Departments: Engineering. Combat Systems, Operations. The Modules (designed for a specific warfare area) have a separate crew with operators and maintainers. For this study, Engineering Department was chosen since the majority of the known failures have occurred on Engineering Equipment. Engineering Department is further divided into two divisions, Electrical and Mechanical. Since individuals from both divisions stand watch and perform planned and corrective maintenance on the equipment in this department, one individual from each division was modeled. In addition to performing maintenance, these individuals stand watch as part of a 2-person team, with one Officer or Chief Petty Officer acting as the supervisor, and one Mechanic and one Electrician as subordinate watch standers. Officers are not modeled in IMPRINT and rarely operate equipment, so the model is limited to the two enlisted crew members. The watch rotation is shown in Table 11.

Condition III					
WATCHSTATION	Section I	Section 2	Section 3	Section I	Section 2
WATCH HOURS	0300-0700	0700-1200	1200-1800	1800-2200	2200-0300
OOD	ACPS	EMO	MPA	ACPS	EMO
JOOD	CMC	BMC	CMC	CMC	BMC
RCO	GSE1	ENCS	DCC	GSE1	ENCS
EPT	ENC-1	GSM2	EM1	ENC-1	GSM2
TAO	CHENG	CPS	CSO	CHENG	CPS
FNS	OSC-1	OSC-2	OS1	OSC-1	OSC-2
DSO	ETCS	FC1	FC2	ETCS	FC1
TSC	IT1-1	ET1	IT1-2	IT1-1	ET1
COM	FCC	ET2-1	ET2-2	FCC	ET2-1
ACT	OSC-1	OSC-2	OS1	OSC-1	OSC-2

Table 11: LCS Underway Watch (Condition III) Rotation - Red circle shows Engineer Team. (A LITTORAL COMBAT SHIP MANPOWER ANALYSIS, Mckinnya J. Williams-Robinson, Naval Postgraduate School, March 2007 p.30)

Equipment: The major components that provide propulsion and electric power are main engines (two gas turbine and two diesel), two diesel generators for electric power, and associated support systems including lube oil, cooling water, air conditioning, and electrical distribution system. Since known failures have occurred in several of these components, all were considered for the analysis, although only a selection of operating and maintenance procedures was modeled for proof of concept.

Operating Condition: Since the majority of the failures have occurred during normal steaming underway, and since this is basis for existing Navy manpower models, the LCS is considered underway in condition III, in three watch sections for the analysis.

Procedures: There is a very large set of procedures related to maintenance and operation of the LCS platform. In order to conduct a proof of concept and modeling to the detail required, a sampling process is necessary. While many options are available to select a final set of procedures for a proof of concept, the process defined below is based on a combination of experience, available procedures, failure data, and risk analysis. A process map of this procedure is shown in Figure 24.

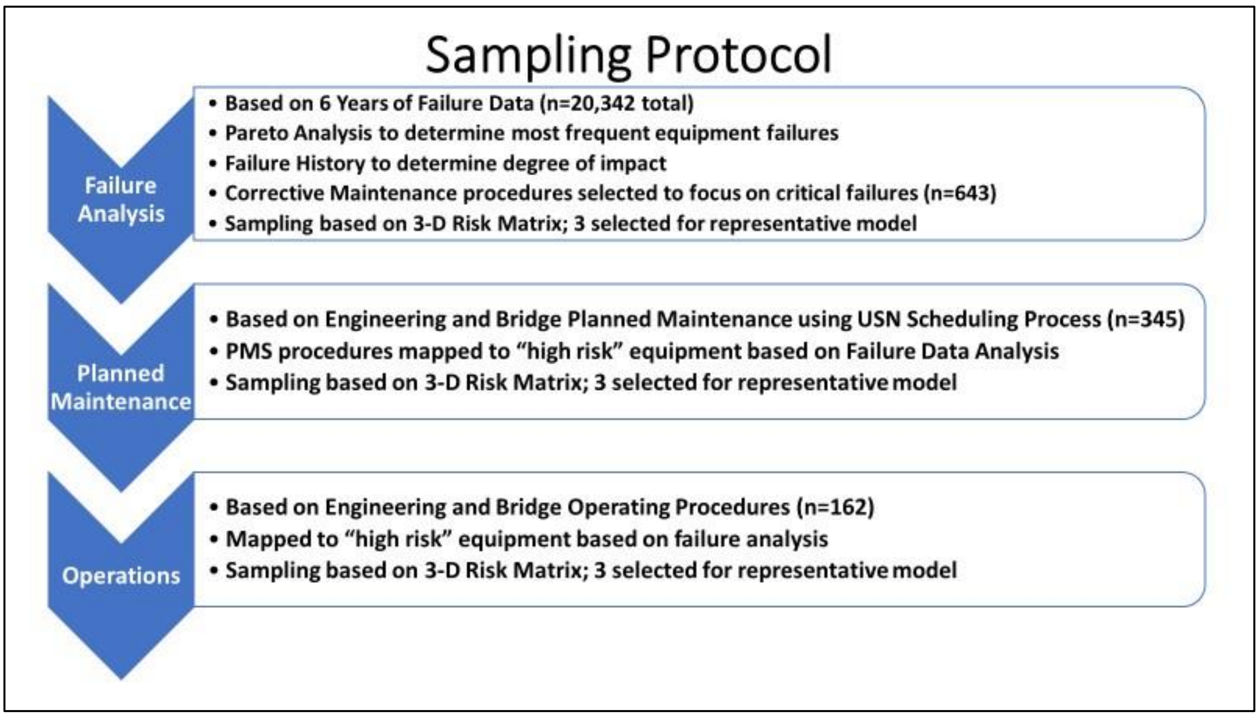


Figure 24. Overview of Sampling Protocol

The procedures used by the crew generally fall into one of 3 categories.

1. Corrective Maintenance: The procedures for corrective maintenance are usually developed on a case by case basis, but they are generally based on failure data stored

in a document called the Consolidated Ships Maintenance Project, or CSMP. The entries in this system are sorted by system and component, often referred to as “parent” and “Child”. There is an entry for each failure and each one includes the following data fields:

Entry Block	**Information**
Hierarchal Sequence Number	A discrete identifier for the system and component
Location	The physical location of the component
Problem Description	A freeform paragraph describing the failure – cause, severity, impact
Recommended Solution	The ship’s recommendation for a repair procedure
Reference	Technical Manual or Maintenance Procedure
Priority	1 through 4 based on mission impact (1 is highest)
Date	The date discovered

Table 12. Navy Corrective Maintenance Job Description Criteria

A typical LCS ship has approximately 1200 total entries at any given time, and they can be sorted by system to find the systems with the highest number of failures. For this analysis, a 6-year data set was analyzed consisting of 20,245 entries, of which some 10% were “placeholders” for scheduling of inspections, etc. The remaining discrepancies were sorted by Hierarchal Sequence Number (HSC) which separates them into categories by type of equipment (i.e., Diesel Engine, Navigation, etc.). This was then graphed as a Pareto chart, as shown in Figure 25 and Appendix B.

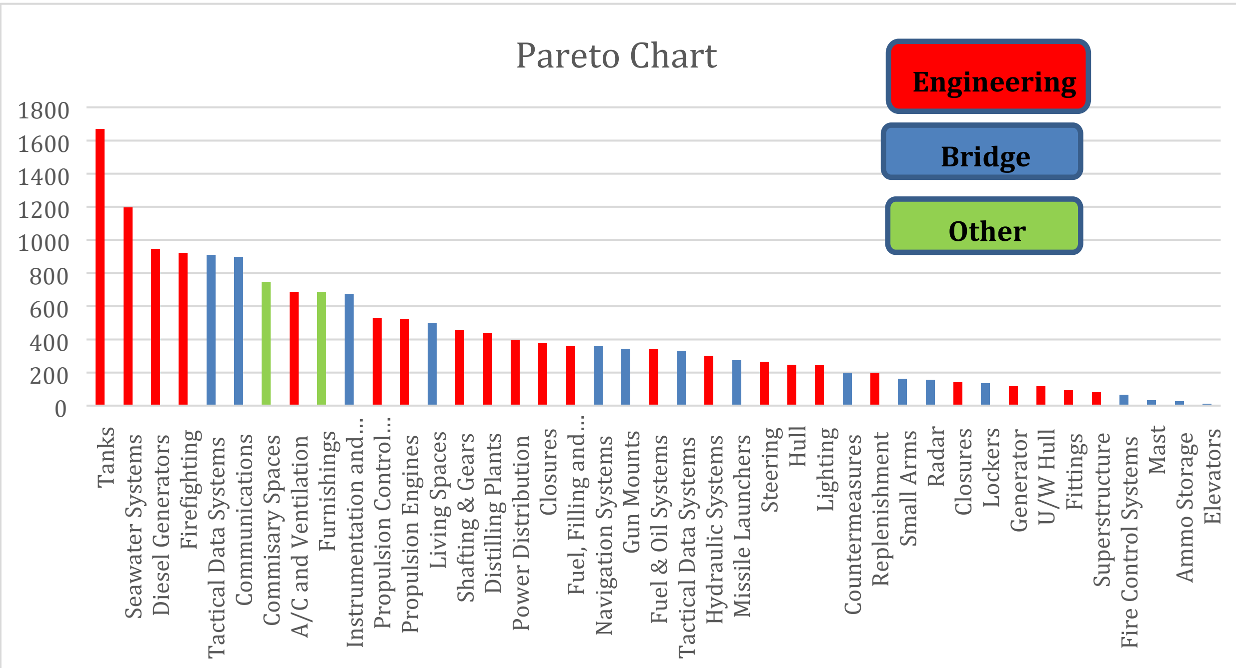


Figure 25. Pareto Chart of LCS Failure Data (6-yr summary)

In order to determine the best subset to focus the analysis, the results of the first Pareto chart were weighted using a "Mission Impact" scale of 1 to 3 (1 being lowest, 3 highest) to focus on the discrepancies with the highest potential impact of failure to mission. The decision for rating a system 1 to 3 was based on operator experience and the known mission failures mentioned earlier in the paper. This generated a slightly different Pareto chart in Figure 26.

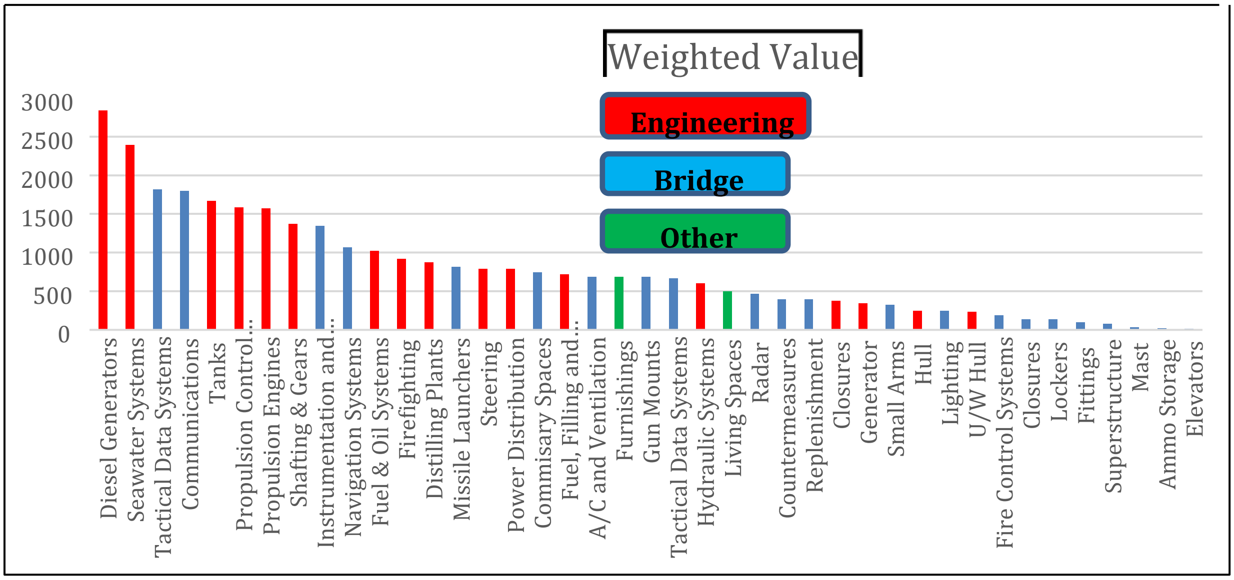


Figure 26. Weighted Pareto Chart (accounting for mission impact)

Based on this information, a selection of individual jobs was selected for modeling from the HSC components listed in the top 50% of the Pareto Analysis. This was also the criteria for selecting Operating and Planned Maintenance Procedures for modeling in the next steps. Delimitation. In researching the documentation for maintenance and operations, as well as the causes of the most significant failures, it was found that engineering procedures were generally more accessible and presented a more robust case for modeling. For these reasons, further analysis was limited to engineering procedures for corrective maintenance, planned maintenance, and operations.

2. Engineering Operating Sequence Procedures: These are formal procedures used to define operation of the Engineering Plant. These are generally 1-2 pages long and provide step by step directions to be, followed by the operators. For the engineering operators in question there are a total of 63 EOSS procedures that fall into two

categories: Routine and Emergency Procedures. Based on the known incidents of failure and the record of failure data contained in the maintenance records of LCS-1, the following procedures were selected for risk analysis (the full matrix is included as appendix E):

EOSS Nr.	**Component**	**Title**
CAEPA	Electric Plant	Alignment Procedures
FSST	Service and Storage Tanks	Stripping water and contaminants
FOMT	Fuel Oil Transfer Pump	Align for Remote Operations
FOAS	Fuel Oil Service System	Align for Operation
CPTM	Gas Turbine Brake	Operation, motoring
CPDME	Main Propulsion Diesel	Starting/Operating/Stopping
CLOP	Lube Oil Pumps	Starting/Stopping
CFOP	Fuel Oil Pumps	Starting/Stopping
BGTM	B Fire GTM	B Fire
CASF	Electric Plant	Bus Tie Parallel
CASSDG	Cool Air	Failure
CASG	Gas Turbine Generator	Fire
CSFG	Diesel	Fire
CED	Educator	Operation, motoring
CFD	Fuel	Sample Detector
CFOSS	Boats	Fuel
CFP	Fire Pump	Operation, motoring
CFMPO	EDG	Console Operation
CHAA	CHT	Alarm
MLOL	Main Lube Oil	Pump Operation
CPTM	Console	Operation
CPWS	Potable Water	Operation, motoring
CFSRT	Fuel System	Refuel Helicopter
EPOP	Electric Plant	Operation, motoring

Table 13. Initial selection of Critical Operational Procedures

EOSS Nr.	**Component**	**Title**
EPT	Power Turbine	Vibration
FOAS	Fuel Oil System	Align
GTES	Gas Turbine	Start
HBDG	Hot Bearing	Casualty Response
FPM	Fire Pump	Operation, motoring

Table 13. Initial selection of Critical Operational Procedures (continued)

3. Planned Maintenance Procedures: These are formal procedures that are used to conduct routine maintenance on engineering equipment. They are categorized by system in a document called a Maintenance Index Page (MIP) and then by individual Maintenance Requirements Cards (MRC). The work centers that perform maintenance on engineering equipment are machinists (EA Division) and electricians (EE Divisions). There is a total of 76 MIPs in the EA division PMS schedule, and a total of 875 individual MRC's. Based on the weighted Pareto analysis above, the following MIP's were selected for risk/impact analysis:

MIP	MRC	Nomenclature
2331	4M-5	Diesel Engine Governor Lube
	4-M6	Inspect LO Pump
	9M-1	Engine Test
	M-1R	LO Sample
	M-6	Inspect Air Filter
	R-3D	LO Viscosity Test
	W-1R	Inspect Loop Seal
2341	8M-1	Power Turbine LO Sample
	A-9	Inspect LO Cooler
2342	A-1	GT Oil Sample
	W=2R	Test GT LO Flash Point
2418	M-1R	Clean Air Filter
	M-2	Replace Air Filter
	R-34M	Test Air Flow
	R-33D	Reduction Gear Pilot Light
2531	R-4D	Stern Seal Leakage
	R2-W	Flash Point Test
2471	R-10W	Drain Water from Filter
256		Seawater Cooling

Table 14. Initial Selection of Planned Maintenance Procedures

The full risk matrix is included as Appendix D. From the above procedures, a select few were used as a representative sample for modeling using the risk analysis method outlined in the next step.

4.5 IMPRINT MANPOWER MODEL VERIFICATION

In order to evaluate the integrated system using IMPRINT, an integrated Risk Analysis must be performed in the various procedures to select a defensible subset for analysis. Risk analysis consists of determining the combination of “likelihood” and “severity” of a particular event in order to determine its impact. Table 15 represents a standard risk analysis chart and shows the resulting risk values in a generic fashion. Table 16 is that three-dimension risk analysis tailored to LCS Procedure Analysis Protocol. Table 17 specifies the risk definitions applied to each level.

0 – 5 = Low Risk 6 – 10 = Moderate Risk 11 – 15 = High Risk 16 – 25 = extremely high unacceptable risk		Severity of the potential injury/damage				
		Insignificant damage to Property, Equipment or Minor Injury 1	Non-Reportable Injury, minor loss of Process or slight damage to Property 2	Reportable Injury moderate loss of Process or limited damage to Property 3	Major Injury, Single Fatality critical loss of Process/damage to Property 4	Multiple Fatalities Catastrophic Loss of Business 5
Likelihood of the hazard happening	Almost Certain 5	5	10	15	20	25
	Will probably occur 4	4	8	12	16	20
	Possible occur 3	3	6	9	12	15
	Remote possibility 2	2	4	6	8	10
	Extremely Unlikely 1	1	2	3	4	5

Table 15. Standard Risk Analysis Table

In order to define risk in more precise terms to support this analysis, a 3-Dimensional Risk Matrix was developed by normalizing the Navy vernacular (For example, the Navy assigns 4 levels of “impact” and of “likelihood” in their maintenance and casualty documentation. The next step consists of combining the criteria from the above table into a single table that accounts for all three factors: Frequency, Impact, and Degree of Automation. Breakpoints for Red, Yellow and Green were correlated to the standard risk matrix (for example, the highest value is a 4x4x4=64). The results are shown in Table 18.

	H-M Integration	1	2	3	4
Frequency	Automation Impact				
1	1	1	2	3	4
2	1	2	4	6	8
3	1	3	6	9	12
4	1	4	8	12	16
1	2	2	4	6	8
2	2	4	8	12	16
3	2	6	12	18	24
4	2	8	16	24	32
1	3	3	6	9	12
2	3	6	12	18	24
3	3	9	18	27	36
4	3	12	24	36	48
1	4	4	8	12	16
2	4	8	16	24	32
3	4	12	24	36	48
4	4	16	32	48	64

Table 16. 3-D Risk Table (tailored to LCS Procedure Analysis Protocol)

IMPRINT Task Risk Matrix

Criteria	Low	Med-low	Med-high	High
Value	1	2	3	4
Frequency of Occurrence	Greater than Quarterly	Quarterly	Monthly	Weekly or Daily
Impact on Mission	Minor Impact to secondary mission (Priority 4)	Major Impact to Secondary Mission (Priority 3)	Minor Impact to Primary Mission or Loss of Secondary Mission (Priority 2)	Loss of Primary Mission (Priority 1)
Degree of Human-Machine Integration	Fully manual or completely automated (3 SD from equal levels) <10% or >90% Automated	2 SD from equal levels 75-90% or 10-25% Automated	1 SD from equal levels 60-75% or 25-40% Automated	Equal level of Manual and Automated Functions 50% +/- 10% Automated

Table 17. Tailored Task Risk Matrix Definitions

Final Selection of Procedures: Due to the extensive detail required for IMPRINT modeling and the focus of this "proof of concept", this analyst selected 3 procedures from each category (Corrective Maintenance, Planned Maintenance, and Operating Procedures) to build a complete workflow model and program IMPRINT. These three were selected based on the following criteria:

a. Related to a high impact documented failure

b. A risk factor of Yellow or Red

c. A mix of levels of automation from mainly human/mechanical to highly automated

Table 18 represents the results of this analysis for the Operating Procedures as an example of how this process was applied.

EOSS Nr.	Component	Title	Frequency	Impact	Degree of Automation	Risk Value
CAEPA	Electric Plant	Alignment Procedures	2	3	4	24
FSST	Service and Storage Tanks	Stripping water and contaminants	4	2	3	24
FOMT	Fuel Oil Transfer Pump	– Align for Remote Operations	3	2	4	24
FOAS	Fuel Oil Service System	Align for Operation	2	3	2	12
CPTM	Gas Turbine Brake	Operation, motoring	2	1	1	2
CPDME	Main Propulsion Diesel	Starting/Operating /Stopping	2	4	1	8
CLOP	Lube Oil Pumps	Starting/Stopping	4	3	3	36
CFOP	Fuel Oil Pumps	Starting/Stopping	4	3	2	24
BGTM	B Fire GTM	B Fire	1	3	1	3
CASF	Electric Plant	Bus Tie Parallel	4	1	4	16
CASSDG	Cool Air	Failure	2	1	2	4
CASG	Gas Turbine Generator	Fire	1	4	3	12
CSFG	Diesel	Fire	1	4	4	16
CED	Eductor	Operation, motoring	3	1	1	3
CFD	Fuel	Sample Detector	1	4	3	12
CFOSS	Boats	Fuel	2	2	2	8
CFP	Fire Pump	Operation, motoring	4	3	1	12
CFMPO	EDG	Console Operation	4	3	3	36
CHAA	CHT	Alarm	1	1	2	2
MLOL	Main Lube Oil	Pump Operation	3	1	4	12
CPTM	Console	Operartion	1	2	2	4
CPWS	Potable Water	Operation, motoring	2	2	1	4
CFSRT	Fuel System	Refuel Helo	4	3	3	36
EPOP	Electric Plant	Operation, motoring	4	4	1	16
EPT	Power Turbinqe	Vibration	2	2	3	12
FOAS	Fuel Oil System	Aligm	4	2	3	24
GTES	Gas Turbine	Start	3	3	3	27
HBDG	Hot Bearing	Casualty Response	3	1	3	9
FPM	Fire Pump	Operation, motoring	4	2	1	8

Table 18. Critical Operating Procedures

Failure Mode and Effects Analysis: Once the tasks have been selected for modeling based on the risk of mission failure as described above, the next process to be applied is the Failure Mode and Effects Analysis. The basic steps of this are defined below:

a. Define the system

b. Define ground rules and assumptions

c. Construct system block diagrams

d. Identify failure modes

e. Analyze failure effects and causes

f. Feed results back into design process

In order to accomplish this, a total of 9 tasks were selected, 3 from each area (corrective maintenance, planned maintenance, and operational procedures). A standard tool for the above analysis is called the Out of Control Action Plan, or in this case the IMPRINT Action Plan, which was a plan adapted and built for each procedure to be analyzed using the critical failure modes to capture design changes that may be required. An example Critical Failure Analysis for one of the selected procedures is shown in Figure 27.

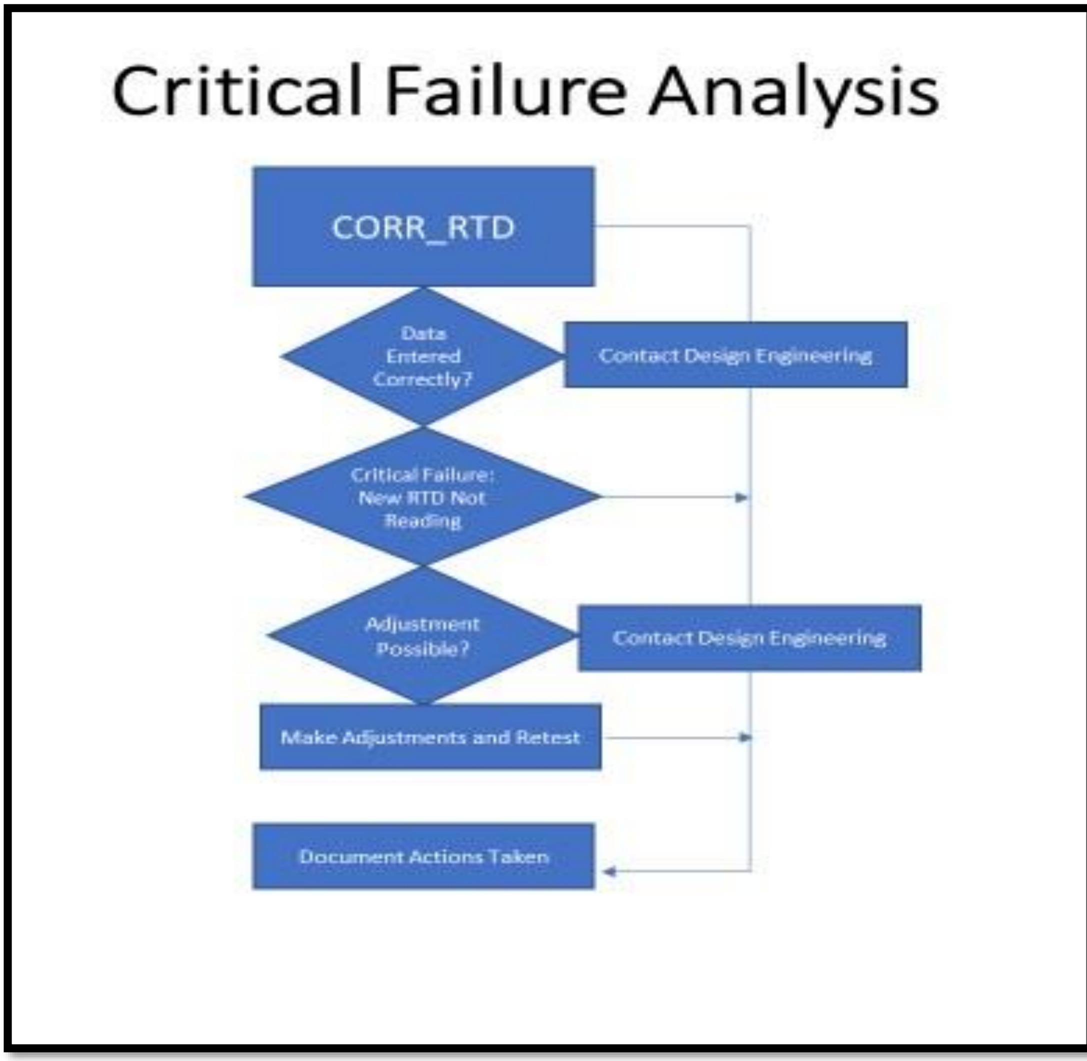


Figure 27. Modified Action Table for LCS Analysis (entry into IMPRINT)

Using the Task Analysis Worksheets, each task is broken into its discrete subtask elements and critical failure modes are identified. Once these have been identified, the cause and effects noted, and results can be programmed back into the model. Model runs can then be compared to determine if risk of failure changed due to these updates, resulting in possible improvements. The below form was developed to capture the critical failure modes of the key steps in each procedure, and one example is presented in Table 19 (the remainder are included in Appendix H):

Ranking	SEV Severity	OCC Frequency	DET Detectability	SEV Severity	OCC Frequency	DET Detectability
	Qualitative Condition			Quantitative Condition		
1	Minor	Remote	Very High	Inconvenience, Cosmetic Damage, Mission Delay	Once in ship's lifetime	100%
2	Very Low	Very Low				
3	Low	Low	High			<75%
4	Moderate	Moderately Likely	Moderate	Minor Mission Degradation or Minor Equipment Damage	Once per deployment Cycle (3 year)	
5						<50%
6						
7	High	Highly Likely	Low	Severe Injury, major Equipment Damage Loss of secondary Mission	Once per Deployment (6 months)	<10%
8						
9	Extreme	Very Likely	Very Low	Death or Loss of Primary Mission	Monthly or higher	<1%
10						

Procedure: EOS_Start Diesel__Date:__10 Feb_Analyst:__JPC___

Process Step	Potential Failure Mode	Potential Failure Effect	SEV	Potential Cause	OCC	Current Process Controls	DET	RPN	Action Recommended	SEV (Revised)	OCC (Revised)	DET (Revised)	RPN (Revised)
Press "Yes" to start Diesel	Fails to start	Unable to provide electric power	9	Failure of automated signal	3	None	4	108	Install "Fail to start" signal	9	3	1	27
Press "Yes" to start Diesel	Fails to start	Unable to provide electric power	9	Mechanical Failure of Diesel	4	None	4	144	Install "Fail to start" signal	9	4	1	36

Table 19. Failure Mode Analysis Key and Example.

Workload: IMPRINT captures the workload for each operator compared to a user selected "threshold", in this case set at 60% of the individual's capacity. This is the default condition for

IMPRINT, and corresponds to other research showing that this is the point at which a skilled operator becomes “task saturated” and has to either prioritize or shed tasks in order to accomplish the mission (Columbi et al, pg. 454). A report is then generated that shows the actual workload over the course of the mission against this threshold. The below graph is an example of a single run of the IMPRINT scenario with the graphs of the workload vs. time of the two Engineering operators (RCO and EPT) as they execute the watch duties. By setting thresholds in workload and comparing the results of multiple runs, the changes in workload can be visualized and the effects of changing a single parameter (for example, hours without sleep) can be seen. In the figure below, for example, the effects of an alarm at time 21:36 can be seen as a short spike in workload; in this case the total capacity is not exceeded, but the effects are clear.

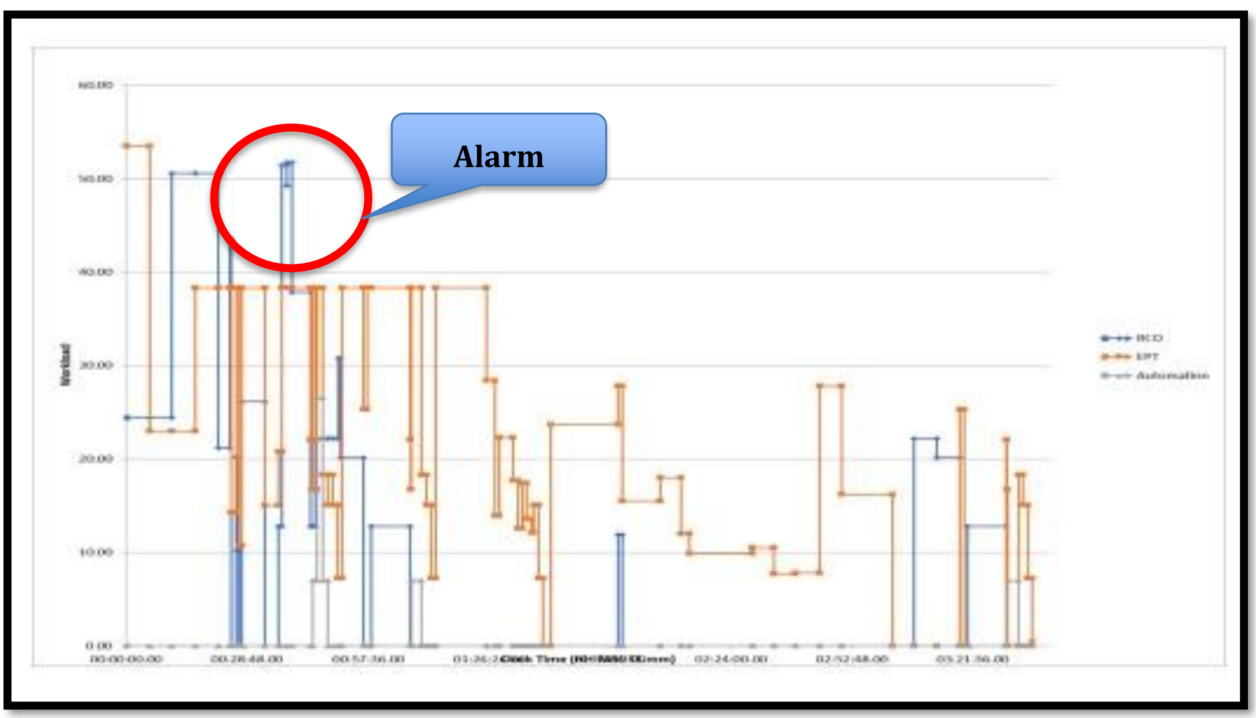


Figure 28. IMPRINT Workload Graph of Engineering Operators (EPT/RCO/Automation)

The above graph would be extremely useful in comparing workloads of operators under a variety of conditions, and to demonstrate the effects of unplanned events that may distract from the task at hand (i.e., the alarm circled in the diagram above) or more encompassing events like a casualty response to a fire or flooding, which could consume the entire watch team for a significant portion of the watch period. IMPRINT can also capture instances and specific tasks where workload exceeds the threshold and may result in a task failure and, if that task is linked to accomplishment of the mission, a complete abortion of the mission. Such an analysis would show what parts of a particular procedure would contain the highest risk of failure in a modeling scenario and allow for consideration of changes to the manpower level, the procedure, or the time allotted for the procedures. One consideration in constructing the watch period for this model was that there was a set of operating procedures, a planned maintenance procedure, and a corrective maintenance procedure scheduled for the 3-hour period, resulting in a high concentration of workload at period when operators (mainly the EPT) were trying to multi-task. IMPRINT also has a simulation function to capture the cognitive aspects of various tasks and model how they interfere with one another – for example the sound of an alarm interfering with concentration while attempting to follow a procedure or give a verbal order. An example of this is shown below. This sample shows the potential of IMPRINT workload functionality to model a fairly complex work period using detailed procedures to focus on the areas of highest risk and assist planners in making risk decisions.

Interfaces	Resources						
	Auditory	Cognitive	Fine Motor	Gross Motor	Speech	Tactile	Visual
Bridge Console	☑	☑	☐	☐	☑	☑	☑
CrewStation	☑	☑	☑	☐	☐	☐	☑
Diesel Control Panel	☑	☐	☑	☐	☐	☐	☑
LO Pump Controller	☑	☐	☑	☐	☐	☐	☑
SW Pump Controller	☐	☐	☐	☐	☐	☐	☐

Table 20. Resource Interface Cognitive Interferences.

Fatigue: IMPRINT can also model the fatigue of the operator as a Performance Shaping Factor (PSF) that can be toggled between choices of “Sleepless Hours” from 0-24, 25-48, and so on. In this example, the Watch Period mission was executed with the default setting of 0-24 Sleepless Hours. The initial run shows a task failure rate of only 4 failures, as shown in Table 21.

Analysis Name: LCS Operations Watch Model.v.12
Mission: Watch Period
Initial RNS: 1
Date: 12-Mar-19

	Function		Task		Time of Failure	
Run	ID	Name	ID	Name	(HH:MM:SS.mm)	Consequence of Failure
1	1	Watch Turnover (EPT)	1_1	Tour Plant	00:05:19.87	No effect
1	5	EOS 2 Start LO Pump	5_2	Verify lube oil sump level	00:23:39.00	No effect
1	5	EOS 2 Start LO Pump	5_4	Order EPT to align Sea Water cooling to CG/SG lube oil coolers	00:24:23.65	No effect
1	4	EOS 1 Start Diesel	4_1	Verify Combining Gear LO Temp >90F	00:30:03.75	No effect

Table 21. IMPRINT Task Failure Report (PSF “Sleepless Hours” set at 0-24)

After the above mission run, the “Sleepless Hours” for both operators was changed to “25 to 48” and the mission run again. Table 22 demonstrates these results.

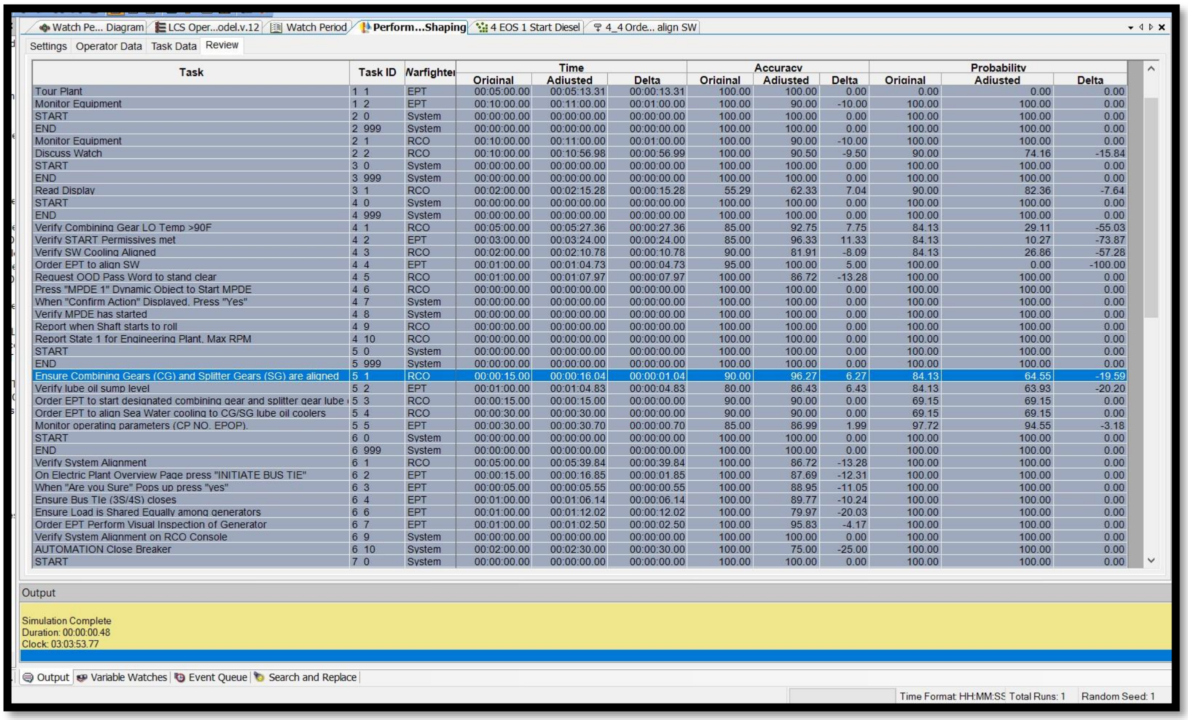
IMPRINT Operations Model Report
Task Failure

Analysis Name: LCS Operations Watch Model.v.12
Mission: Watch Period
Initial RNS: 1
Date: 12-Mar-19

	Function		Task		Time of Failure	
Run	ID	Name	ID	Name	(HH:MM:SS.mm)	Consequence of Failure
1	1	Watch Turnover (EPT)	1_1	Tour Plant	00:05:34.07	No effect
1	1	Watch Turnover (EPT)	1_2	Monitor Equipment	00:16:34.07	No effect
1	5	EOS 2 Start LO Pump	5_4	Order EPT to align Sea Water cooling to CG/SG lube oil coolers	00:26:57.17	No effect
1	4	EOS 1 Start Diesel	4_1	Verify Combining Gear LO Temp >90F	00:33:05.57	No effect
1	4	EOS 1 Start Diesel	4_2	Verify START Permissives met	00:36:10.41	No effect
1	4	EOS 1 Start Diesel	4_3	Verify SW Cooling Aligned	00:38:21.19	No effect
1	4	EOS 1 Start Diesel	4_5	Request OOD Pass Word to stand clear	00:39:29.15	No effect
1	11	PMS 1 Check LO Viscosity	11_2	Open vent screw and remove cap	01:16:21.70	No effect
1	11	PMS 1 Check LO Viscosity	11_6	Enter Viscosity Data	01:22:50.87	No effect
1	8	EOS 2 Start LO Pump1	8_1	Start Designated Pumps (EPT)	02:37:50.14	No effect
1	7	EOS 1 Start Diesel1	7_2	Order EPT to align Seawater	03:04:50.14	No effect

Table 22. IMPRINT Task Failure Report (PSF "Sleepless Hours" set at 25-48 hrs.)

When the "sleepless hours" is set to "25-48" a total of 11 failures occur, a 275 percent increase. While some of these can be attributed to the variability in the IMRINT model, this data clearly demonstrates that the error rate increases dramatically when hours without sleep is increased, and that IMPRINT is capable of modeling this effect. In practice, this result can be further deconstructed to show the actual impact of fatigue on each task associated with each mission as seen in the screen capture below in Table 23.



Task	Task ID	Warfighter	Time Original	Time Adjusted	Time Delta	Accuracy Original	Accuracy Adjusted	Accuracy Delta	Probability Original	Probability Adjusted	Probability Delta
Tour Plant	1 1	EPT	00:05:00.00	00:05:13.31	00:00:13.31	100.00	100.00	0.00	0.00	0.00	0.00
Monitor Equipment	1 2	EPT	00:10:00.00	00:11:00.00	00:01:00.00	100.00	90.00	-10.00	100.00	100.00	0.00
START	2 0	System	00:00:00.00	00:00:00.00	00:00:00.00	100.00	100.00	0.00	100.00	100.00	0.00
END	2 999	System	00:00:00.00	00:00:00.00	00:00:00.00	100.00	100.00	0.00	100.00	100.00	0.00
Monitor Equipment	2 1	RCO	00:10:00.00	00:11:00.00	00:01:00.00	100.00	90.00	-10.00	100.00	100.00	0.00
Discuss Watch	2 2	RCO	00:10:00.00	00:10:56.98	00:00:56.99	100.00	90.50	-9.50	90.00	74.16	-15.84
START	3 0	System	00:00:00.00	00:00:00.00	00:00:00.00	100.00	100.00	0.00	100.00	100.00	0.00
END	3 999	System	00:00:00.00	00:00:00.00	00:00:00.00	100.00	100.00	0.00	100.00	100.00	0.00
Read Display	3 1	RCO	00:02:00.00	00:02:15.28	00:00:15.28	55.29	62.33	7.04	90.00	82.36	-7.64
START	4 0	System	00:00:00.00	00:00:00.00	00:00:00.00	100.00	100.00	0.00	100.00	100.00	0.00
END	4 999	System	00:00:00.00	00:00:00.00	00:00:00.00	100.00	100.00	0.00	100.00	100.00	0.00
Verify Combining Gear LO Temp >90F	4 1	RCO	00:05:00.00	00:05:27.36	00:00:27.36	85.00	92.75	7.75	84.13	29.11	-55.03
Verify START Permissives met	4 2	EPT	00:03:00.00	00:03:24.00	00:00:24.00	85.00	96.33	11.33	84.13	10.27	-73.87
Verify SW Cooling Aligned	4 3	RCO	00:02:00.00	00:02:10.78	00:00:10.78	90.00	81.91	-8.09	84.13	26.86	-57.28
Order EPT to align SW	4 4	EPT	00:01:00.00	00:01:04.73	00:00:04.73	95.00	100.00	5.00	100.00	0.00	-100.00
Request OOD Pass Word to stand clear	4 5	RCO	00:01:00.00	00:01:07.97	00:00:07.97	100.00	86.72	-13.28	100.00	100.00	0.00
Press "MPDE 1" Dynamic Object to Start MPDE	4 6	RCO	00:00:00.00	00:00:00.00	00:00:00.00	100.00	100.00	0.00	100.00	100.00	0.00
When "Confirm Action" Displayed, Press "Yes"	4 7	System	00:00:00.00	00:00:00.00	00:00:00.00	100.00	100.00	0.00	100.00	100.00	0.00
Verify MPDE has started	4 8	System	00:00:00.00	00:00:00.00	00:00:00.00	100.00	100.00	0.00	100.00	100.00	0.00
Report when Shaft starts to roll	4 9	RCO	00:00:00.00	00:00:00.00	00:00:00.00	100.00	100.00	0.00	100.00	100.00	0.00
Report State 1 for Engineering Plant, Max RPM	4 10	RCO	00:00:00.00	00:00:00.00	00:00:00.00	100.00	100.00	0.00	100.00	100.00	0.00
START	5 0	System	00:00:00.00	00:00:00.00	00:00:00.00	100.00	100.00	0.00	100.00	100.00	0.00
END	5 999	System	00:00:00.00	00:00:00.00	00:00:00.00	100.00	100.00	0.00	100.00	100.00	0.00
Ensure Combining Gears (CG) and Splitter Gears (SG) are aligned	5 1	RCO	00:00:15.00	00:00:16.04	00:00:01.04	90.00	96.27	6.27	84.13	64.55	-19.59
Verify lube oil sump level	5 2	EPT	00:01:00.00	00:01:04.83	00:00:04.83	80.00	86.43	6.43	84.13	63.93	-20.20
Order EPT to start designated combining gear and splitter gear lube	5 3	RCO	00:00:15.00	00:00:15.00	00:00:00.00	90.00	90.00	0.00	69.15	69.15	0.00
Order EPT to align Sea Water cooling to CG/SG lube oil coolers	5 4	RCO	00:00:30.00	00:00:30.00	00:00:00.00	90.00	90.00	0.00	69.15	69.15	0.00
Monitor operating parameters (CP NO. EPOP).	5 5	EPT	00:00:30.00	00:00:30.70	00:00:00.70	85.00	86.99	1.99	97.72	94.55	-3.18
START	6 0	System	00:00:00.00	00:00:00.00	00:00:00.00	100.00	100.00	0.00	100.00	100.00	0.00
END	6 999	System	00:00:00.00	00:00:00.00	00:00:00.00	100.00	100.00	0.00	100.00	100.00	0.00
Verify System Alignment	6 1	RCO	00:05:00.00	00:05:39.84	00:00:39.84	100.00	86.72	-13.28	100.00	100.00	0.00
On Electric Plant Overview Page press "INITIATE BUS TIE"	6 2	EPT	00:00:15.00	00:00:16.85	00:00:01.85	100.00	87.69	-12.31	100.00	100.00	0.00
When "Are you Sure" Pops up press "yes"	6 3	EPT	00:00:05.00	00:00:05.55	00:00:00.55	100.00	88.95	-11.05	100.00	100.00	0.00
Ensure Bus TIe (3S/4S) closes	6 4	EPT	00:01:00.00	00:01:06.14	00:00:06.14	100.00	89.77	-10.24	100.00	100.00	0.00
Ensure Load is Shared Equally among generators	6 6	EPT	00:01:00.00	00:01:12.02	00:00:12.02	100.00	79.97	-20.03	100.00	100.00	0.00
Order EPT Perform Visual Inspection of Generator	6 7	EPT	00:01:00.00	00:01:02.50	00:00:02.50	100.00	95.83	-4.17	100.00	100.00	0.00
Verify System Alignment on RCO Console	6 9	System	00:00:00.00	00:00:00.00	00:00:00.00	100.00	100.00	0.00	100.00	100.00	0.00
AUTOMATION Close Breaker	6 10	System	00:02:00.00	00:02:30.00	00:00:30.00	100.00	75.00	-25.00	100.00	100.00	0.00
START	7 0	System	00:00:00.00	00:00:00.00	00:00:00.00	100.00	100.00	0.00	100.00	100.00	0.00

Simulation Complete
Duration: 00:00:00.48
Clock: 03:03:53.77

Table 23. IMPRINT Task Summary showing effects of changing Sleepless Hours PSF

The above table shows the effects of fatigue in several areas. Specifically, a large number of tasks (as in the blue highlighted task) show an increased time to complete them, a reduced accuracy, and a decreased probability of success. An expanded table shows an example of these specifics (Table 24).

Task 5.1 Attribute/ Sleepless Hours	0-24 hrs.	25-48 hrs.	Delta
Time (hr./mm/ss)	00:15:00	00:16:04	+01:04
Accuracy (%)	96.27	90	-6.27
Probability of Success (%)	84.13	64.55	-19.59

Table 24. Detail of effects on time, accuracy, and probability of success

An additional possibility in IMPRINT is to run multiple iterations of a mission and capture the results in terms of mission success. The following graphs show the increase in mission failures when sleepless hours are increased from "0-24" to "25-48". A two-sample p-test was conducted in Minitab 18® for statistical difference Ho: p (25-48; 41/150 = 0.273) – p (0-24; 34/150 = 0.227) equal 0 versus Ha: not equal 0. The Minitab output reported no statistical difference with p-value = 0.351. and 95% confidence interval (-0.0512, 0.1445). This lack of statistical difference is most likely an artifact of IMPRINT's lack of categorical resolution of sleepless hours 0-24 and sleepless hours 25-48. Studies over the last 50 years have demonstrated that the relationship between fatigue and hours sleep deprivation is asymptotically increasing one. Benitez, et al. (2009) modeled the effect of sleep deprivation on performance over the range of zero to 72 hours. They found that relative reaction time increased over the range of zero to 20-hours, approximately leveled (with caffeine) or slightly declined (with no caffeine) up to about 40-hours deprivation, increased between 41 and 48-hours deprivation, leveled or slightly declined between 49 and 65-hours, and increased up to 72 hours. Given the noise in their data and averaging over 0 to 24 hours and 25 to 48 hours, as in IMPRINT's categorical ranges, there should be no statistical difference in the observed p-values. The results are summarized below:

Test and CI for Two Proportions

```
Sample   X    N  Sample p
1       41  150  0.273333
2       34  150  0.226667


Difference = p (1) - p (2)
Estimate for difference:  0.0466667
95% CI for difference:  (-0.0511892, 0.144522)
Test for difference = 0 (vs ≠ 0):  Z = 0.93  P-Value = 0.351
```

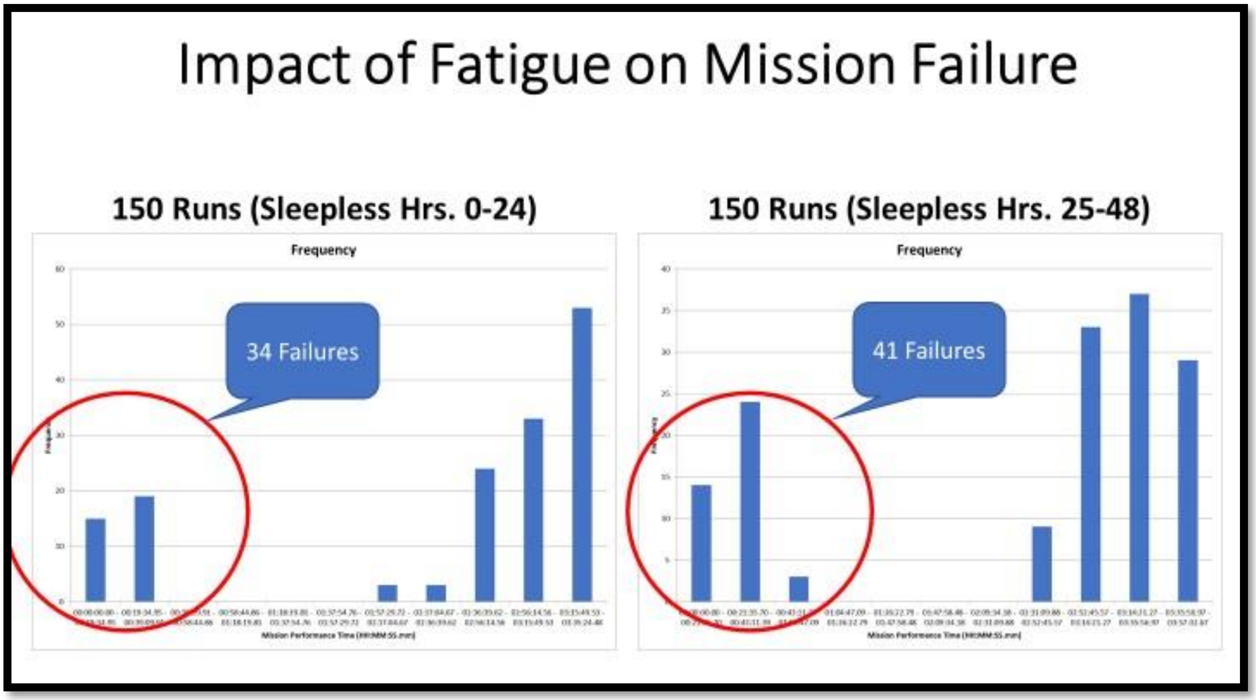


Figure 29. Graph of mission failure comparison for multiple runs (n=150) with aborted missions on the left of each graph and successful missions on the right.

This selection of reports is the basis for the discussions and conclusions in the next chapter and is intended merely to demonstrate the range of information available from the IMPRINT model and the potential to model a wide variety of missions, functions and tasks.

Automation-Human Interface: IMPRINT is primarily designed as a human operator model, and as such the algorithms for automation are designed to operate in an optimal manner – that is, success is automatically 100 per cent and workload capacity is assumed to be infinite (IMPRINT User's Guide). In working with the designer, however, it is possible to create a simulation for the automation by assigning the system as another operator and capturing its workload and failure rate.

Looking again at the workload diagram from above, the circle captures the "system" tasks and workload where it occurs in the model. This is shown in Figure 30.

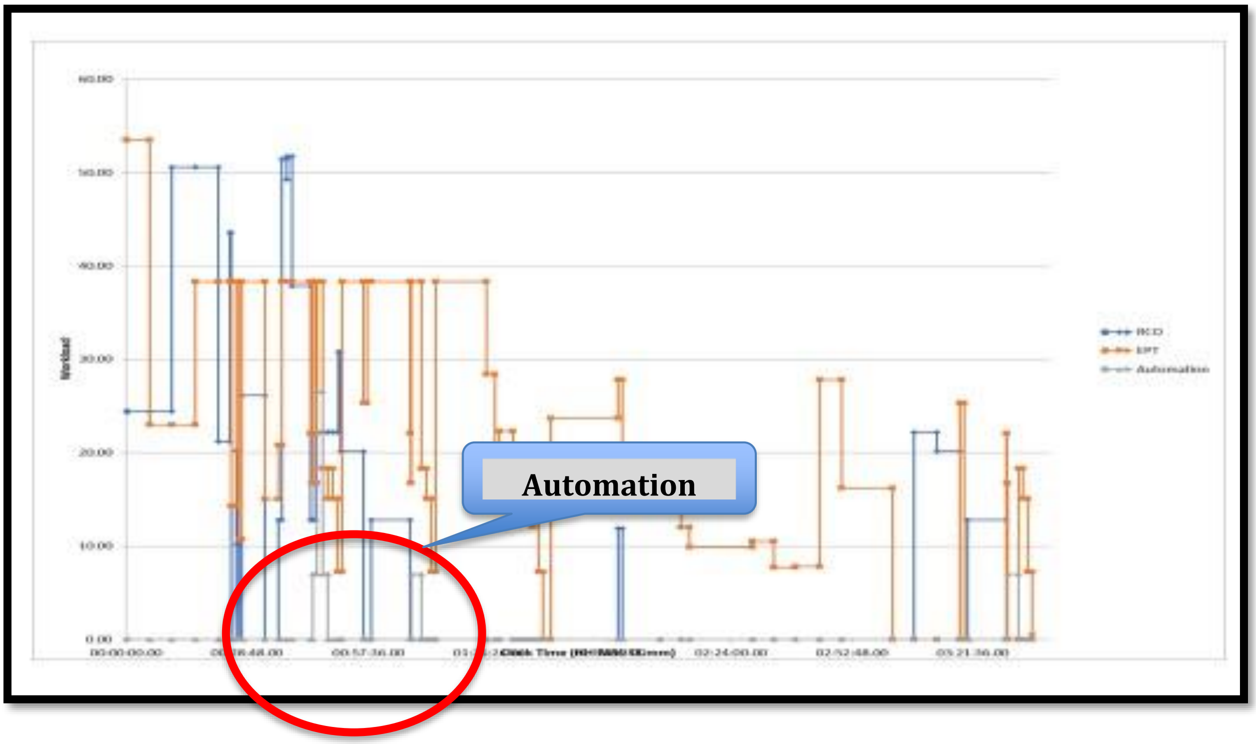


Figure 30. IMPRINT Workload Graph showing Automation (simulated).

While the actual programming of this feature would require access to the automation functionality and is beyond the scope of this project, this process could be coded into IMPRINT and could eventually be used to better capture a more realistic simulation of automation, especially once detailed failure data was available, perhaps in a future research project. This feature would be especially helpful as ships become more and more automated.

CHAPTER 5

DISCUSSION

5.1 OVERVIEW OF FINDINGS.

The project started with a hypothesis that the LCS Crew modeling could be improved by using the IMPRINT program, which had been used extensively in Army applications and to some extent in analysis of the LCS crew, could be improved using data derived from crew surveys and an examination of the actual procedures (watch, operations, and maintenance) used by crew members, to modify the Operations Module of IMPRINT. The majority of the studies conducted in the past used the Force Model feature of IMPRINT; in this more global force level manpower study, "workload" is just simple engagement with high level activities. In a detailed human performance study using the IMPRINT Operations Model used in this project, workload is the mental capacity being utilized to perform more definitive tasks. The detailed human performance models allow the analyst to consider outcomes such as mission times, mission completion, and errors and their consequences as metrics. The LCS Crew survey was intended to identify the strengths and weaknesses in manning model of the LCS automation-human operational environment. It was important to use statistical analysis to validate the design and response coherence of the survey itself. Consistency analysis confirmed that the results of the survey were coherent. Multivariate analysis confirmed that the four dimensions sampled were independent, and LCS personnel responses support that they are relevant to the design of automation-human performance. Demographics were statistically homogeneous and independent of the survey questions. This observation makes sense given that most individuals stand the same watch rotation and perform similar maintenance duties and other tasks, whether supervisory in nature or not, for about the same amount of time each day.

The four dimensions of fatigue, maintenance tasking, watch tasking, and automation-human integration are important for consideration in refining the LCS manning model to be incorporated and tested in an IMPRINT model in the next phase of this research. Specifically, a majority of those surveyed feel that fatigue, overtasking (watch and maintenance), and the degree of automation inherent in the current manning model for LCS present significant challenges. This leads to the conclusion that these areas merit further cognitive/physical task workflow analysis toward refinements to the existing LCS manning model. Additionally, an examination of specific areas of the automation-human system integration may be appropriate. One of the most significant findings of this survey came from the joint analysis of the MJCA demographics and response biplots. Joint analysis suggests that the design of and training for the LCS automation-human operational environment assumes a standard Navy personnel profile and does not account for natural differences in human capabilities.

Based on the survey results, we performed cognitive/physical task workflow analysis of bridge and engineering tasks, as well as examining past failures, and built an initial IMPRINT crew manning model that accounts for the four survey dimensions in the next stage of research. It is worth noting that this survey was conducted only for the LCS class of ships; this does not imply that these challenges are unique to LCS; perhaps an expansion to other classes of ship is worthy of an expanded follow-on survey. References listed below were utilized in developing the survey but are not indexed in the text; they are provided to allow the reader to focus any design of the research.

The workflow analysis structure performed in this paper does seem to support the viability of this approach to model crew activity. While this study focused on a small sample (about 20% of the sum total of procedures in each area) that were chosen based on risk analysis, the process proved to be relatively straightforward and repeatable to expand the study to model the entire spectrum of maintenance and operations for the engineering team, and then transpose this process onto the bridge and other teams for a more complete analysis that is beyond the scope of this project.

The combination of the lessons from the LCS IMPRINT survey, which validated that operators perceive challenges with automation, overtasking, and fatigue as valid concerns in accomplishing assigned missions and the workflow analysis performed in support of this article form the foundation for a contribution to the body of work related to crew modeling in the future using IMPRINT. Specifically, the impact of human-automation integration and fatigue on workload completion and on risk to mission success are not captured under current manpower models, which treat each human equally without regard to human factors or limitations of the automated portion of the machine-human interface, an ever-increasing trend in ship design.

5.2 RESEARCH IMPLICATIONS

Other Solutions Found. In exploring the IMPRINT software, it does seem to have the basic building blocks necessary to model a broad range of missions, and other areas of exploration into the primary mission areas (i.e., Mine Warfare) would be possible applications since these "mission packages" come with a discrete team of individuals tailored to the mission.

Additional Problems Identified: Initially, the project required a steep learning curve to build an Operations model in IMPRINT, since previous research was focused on the Crew Model, which focuses on a broader perspective and does not “drill down” to the task level. In attempting to translate Navy procedures into IMPRINT models, a few challenges were identified:

a. Lack of detail in procedures. The majority of Navy procedures are simply a set of steps, with limited explanation of the reasoning behind the procedures and, in areas of automation, no detail in what the automated system is actually doing. This made failure analysis challenging, as the analyst has to rely on experience to understand the system responses.

b. Lack of a Navy Tailored version of IMPRINT. The baseline IMPRINT scenarios and crew models are based on an Army schematic, and while many of the attributes carry over and tailoring was possible for a Navy scenario, having the baseline already implemented in IMPRINT would have saved a great deal of programming time as the process developed.

c. Lack of definition of the Human-Automation interface. The procedures do identify which steps require interaction with the automated systems and the expected responses, but there is no delineation that clarifies the role of automation, leaving it up to the analysist to decide as to the degree of automation. In this case, the author has a good deal of experience with Navy ships and automated systems, so educated estimates were possible.

d. Fatigue Modeling in IMPRINT. The Navy’s primary modeling tool for the effects of fatigue is the FAST tool, which provides a detailed output in terms of “effectiveness” at certain tasks based on the sleep amounts and daily schedule that is input. Unfortunately, the IMPRINT model, while it does have a fatigue element in the human-factors module, is limited in fidelity (a pull-down menu for "hours without sleep": 024 hrs., 24-48, etc.) is useful but does not capture the Navy model of a rotating or fixed watch schedule.

Recommendations for Future Performance Improvement: If the Navy wanted to use IMPRINT as a tool for modeling the entire crew of a ship at the Operations Model, a few changes would greatly facilitate this effort, specifically.

a. FAST Model integration. Many of the crew surveyed perceived fatigue as an impediment to mission accomplishment. A way to integrate the output of the FAST model directly into IMPRINT would allow for much more fidelity in determining the effects of manning and watch rotation changes on the level of risk to mission resulting from these changes. This could be accomplished in the "Performance Shaping" module of IMPRINT. There is an add-on that can be implemented but it was not used in this particular analysis, and it could be tailored for future detailed studies using actual crew fatigue data.

b. Navy Crew Tailoring. While demographics was considered as part of the LCS crew survey, there is a possibility that it could factor more heavily into future more detailed analysis. To facilitate future modeling efforts, the detailed specialties (Navy Enlisted Classifications) could be pre-loaded into IMPRINT and a watch assignment matrix based on ship's manning documents could be programmed in as a baseline for future analysis and updated to reflect current doctrine and requirements, as well as better reflect the limitations of experience and training and their effect on performance.

There are versions of this in existence that could be tailored to match ship manpower profiles.

c. Increased visibility of the Human-Automation Interface. As automation increases in Navy ships, the procedures could be improved by providing more detail on the actual degree of automation and the failure modes/expected responses to assist operators at various levels of training in utilizing the procedures. The current LCS pipeline is over 18 months long and could be perhaps shortened if the procedures and automation were more comprehensive and transparent.

d. For more complex and detailed modeling, one recommendation would be to assign the task to a small team consisting of a Navy Subject Matter Expert, an IMPRINT expert, and a researcher with extensive experience in workload modeling. This would dramatically increase the speed of building the model and improve the accuracy and validity at several stages, including the risk analysis and time-motion analysis. Observation of some of the tasks to validate times and effects would also be an improvement that was beyond the scope of this initial proof of concept.

5.3 RESEARCH LIMITATIONS

There were two limitations to the risk analysis process: (1) the risk analysis of the procedures would have benefitted from a "colleague interrater reliability" exercise, subjecting the decision process to multiple subject matter experts to refine the solution, and (2) the risk analysis was not subjected to review by actual Naval personnel; these are mitigated by the fact that the purpose of the risk assessments was not to provide direct feedback about specific procedures but merely to serve as a means to support the proof of concept. These two steps would be a recommended improvement for future research and would add rigor to an analysis that would be used to support decision making.

There were two limitations related to changes in the LCS crews since the survey was completed: (1) the LCS crew manning policies have changed since the completion of the initial survey, including increased manning, modified crew composition, and the implementation of circadian watch rotations; these were not accounted for in this analysis but would be worthy of note and comparison in a future survey. (2) In the interim, the size of the respondent pool has increased. These changes would need to be accounted for in any future survey and are mitigated by the fact that the survey was not the main effort of this project but was merely intended to inform the IMPRINT modeling process scenario failure modes, and thus a less robust sample size was deemed acceptable in this context.

To truly capture the interactions between crew members and teams, a similar study would be necessary including all three watch teams on the bridge and in engineering. Limited access to detailed procedures for the bridge and the varied nature of bridge operations and maintenance (compared to the fairly narrow scope of engineering operations) would require a broader application of this analysis. This "proof of concept" was able to show that, with minor modifications, the IMPRINT program can be used to model more complex aspects of the Sailor workload using existing documentation and task structure of differing levels of tasking (or overtasking), automation, and fatigue and the resulting changes in risk of failure in discrete teams. As demonstrated in the IMPRINT modeling runs, as each of these factors is increased, the risk of mission failure increases. While this was only a limited study, it lays the foundation for a more robust model. This model can provide feedback for both the number of operators (for example, adding a fourth watch section to reduce fatigue) or improving the explanation of failure modes in procedures with a high level of automation so that operators can gain a better understanding of what the automation is or is not doing. By examining a small subset of the crew, focused on areas where previous mission failures can be associated to either overtasking, understaffing, lack of understanding of automated features, or fatigue, designers can achieve a better prediction of the impact of manpower decisions. This work can be a foundation upon which a model of the entire crew can be built using a modified version of IMPRINT.

CHAPTER 6
CONCLUSIONS

6.1 PRIMARY CONTRIBUTIONS OF THIS STUDY

The primary contribution of this analysis is a "Proof of Concept" that demonstrates a viable method of applying a Time-Motion Risk Integration process to model Human-Automation workflow as a tool for operational risk analysis. Other contributions are as follows:

a. The LCS Crew Survey showed that fatigue, workload, and the human-automation interface are perceived by experienced crew members as factors that impact the ability of the crew to operate and maintain the ship. This is an important data point that could be used as a starting point for future surveys or analyses without the need to validate the veracity of the survey, which was confirmed herein by robust statistical analysis.

b. The detailed workflow analysis process for Navy procedures could be implemented as developed here to dramatically expand the number of procedures available for a future use of IMPRINT. Since the "proof of concept" demonstrated that IMPRINT has the capability to model the workload of a small watch team using the Naval Allowance Factor (formerly Navy Standard Work Week) and crew model, this model could be used to build a more complete "library" of operating and maintenance procedures that could be used in an expanded model.

c. The analysis provided a template for developing an improved cognitive element to Navy procedures, which could be implemented as way of accounting for the effectiveness and risks inherent in the design of the Human-Automation interface, vice assuming that all automated functions are fully reliable. Since this capability is not currently part of the IMPRINT model, it was simulated by assigning “Automation” as if it were a human; this could be programmed into a future version of IMPRINT to accomplish the same thing on a repeatable basis.

d. The analysis showed the effect of fatigue on effectiveness during a representative watch period, with a mix of operating, corrective, planned maintenance, and emergency procedures executed over a finite time at varying fatigue levels. This demonstrates that it is possible to apply the Navy Allowance Factor template in IMPRINT to determine the increase risk from fatigue resulting from manpower decisions that affect the number of personnel available to stand watch, as well as the effects of a circadian vice noncircadian rotation, if FAST (Fatigue Avoidance Scheduling Tool) and other fatigue refinements were made to the IMPRINT program to allow a more detailed modeling of human fatigue.

e. The analysis showed that IMPRINT Operations Model is capable of modeling the workload of individual operators and conducting a fairly robust failure mode analysis of critical procedures. With some refinement, this process could be used to model and analyze current operational and maintenance procedures, proposed procedures, and provide risk analysis for manpower decisions for LCS and future ship classes.

6.2 WIDENING THE SCOPE

This analysis was limited to the Engineering watch team as a proof of concept, although one member of the team actually stands watch on the bridge. The next logical step would be to model all 3 or 4 entire watch teams on the Bridge and Engineering, since this is where the primary mission failures in the program have occurred. Operations modeling of multiple watch teams could allow more robust analysis of team workload, work sharing, and interactive dynamics of unplanned operations (such as Flight Operations or emergencies). This would be the next logical progression now that the building blocks and process map has been established for turning standard Navy maintenance and operations procedures into IMPRINT missions, functions, and tasks in this project.

6.3 SUGGESTIONS FOR FUTURE RESEARCH

The following suggestions would allow researchers to expand on the work described in this analysis:

a. Building a larger model. If further study proves these contributions to be valid, one recommendation would be to build an Operations Model of the three main watch areas of the LCS (or future ship design) that could in place and readily available as a baseline to feed more informed risk analysis into the way the Navy models shipboard manpower. This could result in better manning decisions that lead to increased crew safety and decreased mission impacting mechanical failures when operating these ships at sea.

b. Conduct an actual at-sea validation by observing real individuals performing operating and maintenance procedures to capture times, record the frequency of errors, and measure other factors such as fatigue and workload to validate the model results. These could then be entered into the notional model to give a more realistic set of parameters and facilitate better analysis of the possible outcomes when running the model.

c. Build an "Automation" function for IMPRINT that could capture the steps of procedures that are assumed to be perfectly executed by the system and look for areas where actual failure modes, causes, and mitigations can be inserted back into Navy procedures. This would create a more realistic expectation on the part of operators and could reduce errors associated with the automation-human interface.

d. Consider the use of the results of this modeling process as a basis to make recommendations to the manning program during the acquisition process to include the impact of fatigue, workload thresholds, and automation on operational risk.

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APPENDIX A

LCS WATCH TEAM COMPOSITION

Condition III					
WATCHSTATION	Section I	Section 2	Section 3	Section I	Section 2
WATCH HOURS	0300-0700	0700-1200	1200-1800	1800-2200	2200-0300
OOD	ACPS	EMO	MPA	ACPS	EMO
JOD	CMC	BMC	QMC	CMC	BMC
ROO	GSE1	ENCS	DCC	GSE1	ENCS
EPT	ENC-1	GSM2	EM1	ENC-1	GSM2
TAO	CHENG	OPS	CSO	CHENG	OPS
FNS	OSC-1	OSC-2	OS1	OSC-1	OSC-2
DSO	ETCS	FC1	FC2	ETCS	FC1
TSC	IT1-1	ET1	IT1-2	IT1-1	ET1
COM	FCC	ET2-1	ET2-2	FCC	ET2-1
ACT	OSC-1	OSC-2	OS1	OSC-1	OSC-2

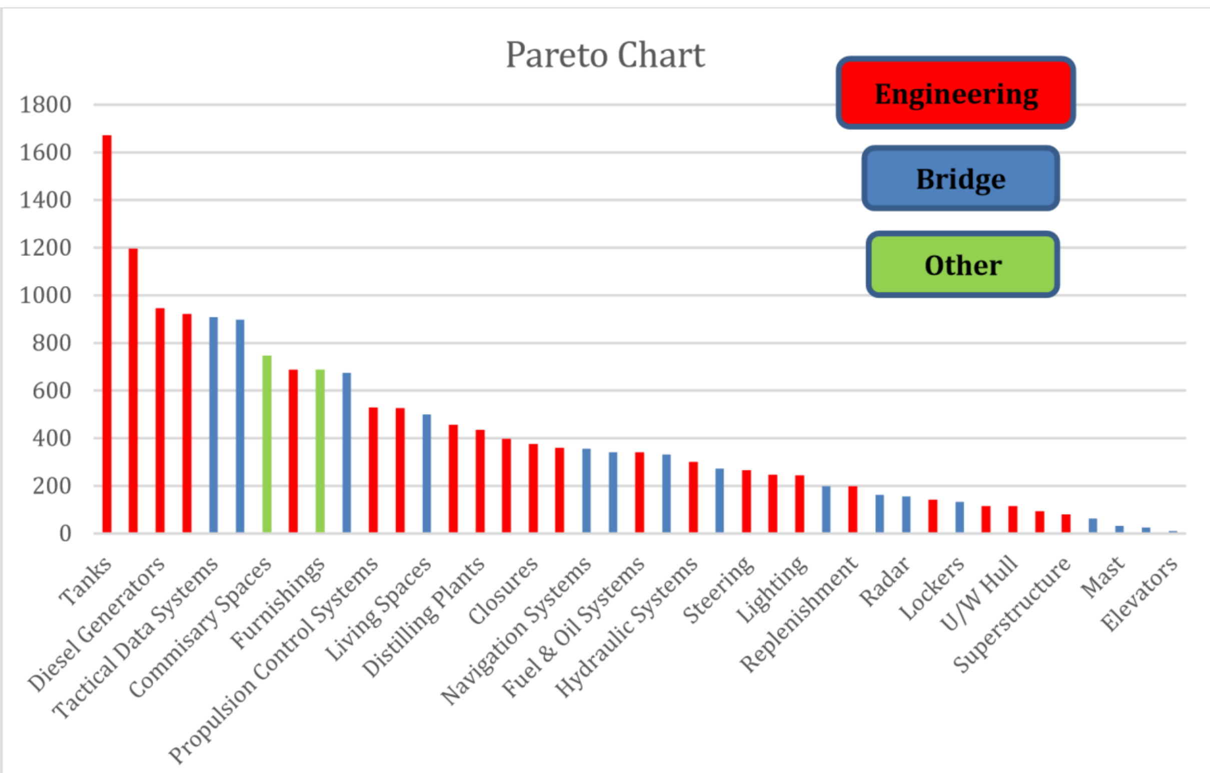
Figure 7. Notional Condition III Five and Dime Watch Rotation with LCS crewmembers

Source: LCS Underway Watch (Condition III) Rotation - Red circle shows Engineer Team. (A LITTORAL COMBAT SHIP MANPOWER ANALYSIS USING THE FLEET RESPONSE TRAINING PLAN, Mckinnya J. Williams-Robinson, Naval Postgraduate School, March 2007, p. 30)

APPENDIX B

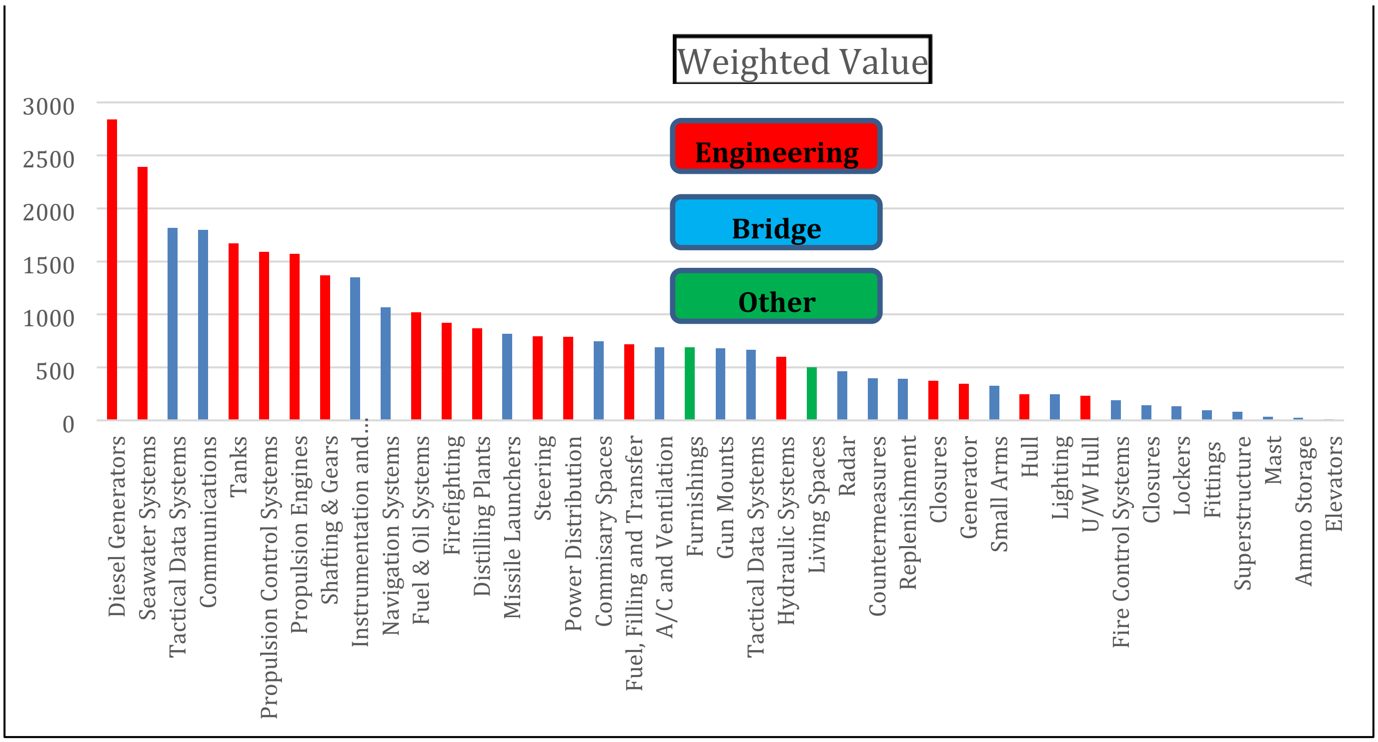
FAILURE MODE PARETO ANALYSIS

A typical LCS ship has approximately 1200 total entries at any given time, and they can be sorted by system to find the systems with the highest number of failures. For this analysis, a 6-year data set was analyzed consisting of 20,245 entries, of which some 10% were "placeholders" for scheduling of inspections, etc. The remaining discrepancies were sorted by Hierarchal Sequence Number (HSC) which separates them into categories by type of equipment (i.e., Diesel Engine, Navigation, etc.). This was then graphed as a Pareto chart, as shown below:



Pareto Chart of LCS Failure Data (6-yr summary)

In order to determine the best subset to focus the analysis, the results of the first Pareto chart were weighted using a "Mission Impact" scale of 1 to 3 (1 being lowest, 3 highest) to focus on the discrepancies with the highest potential impact of failure to mission. The decision for rating a system 1 to 3 was based on operator experience and the known mission failures mentioned earlier in the paper. This generated a slightly different chart:



APPENDIX C

CORRECTIVE MAINTENANCE TABLE

The following maintenance failures were selected based on the fact that they were listed as Priority 1, 2, or 3 maintenance items and that they were associated with equipment that was in the higher end of the Pareto analysis shown in Appendix B. They were then analyzed using the Risk Matrix to determine the most appropriate for modeling:

jcn	priority_code	eswbs_opening	eic nomenclature	csmp_narrative summary	problem_description	Frequency	Impact	Degree of Automation	Risk Value
20126EA 014911	1	23311	ENGINE, DIESEL	MPDE FILTER WARN	DURING OPEN END INSPECTION IT WAS DISCOVERED THAT THE FILTER ASSEMBLY SHOWS SIGNS OF WARE AND METAL SHAVINGS.	1	4	2	8
20126EA 014681	1	31122	GENERATOR SET, 60HZ, DIESEL ENGINE DRIVEN	NR 2 SSDG OOC	NR 2 SSDG OOC DUE TO A FAILED FUEL RECOVERY BLOCK AND ASSOCIATED CONNECTION FITTING. IMPACT: NR 2 SSDG DEGRADED.	2	4	3	24
20126EA 014631	2	23311	ENGINE, DIESEL	NR 1 MPDE JW PUMP OOC	NR 1 MPDE JW PUMP TRIPPED THE CIRCUIT BREAKER. S/F INSPECTION IDENTIFIED PUMP MOTOR OOC DUE TO INTERNAL CORROSION AND DAMAGED WIRING.	2	4	2	16
20126EA 014617	2	31122	GENERATOR SET, 60HZ, DIESEL ENGINE DRIVEN	NR 2 SSDG OOC	NR 2 SSDG VOLTAGE REGULATOR BREAKER TRIPPED WHILE SHIFTING FROM SHIP POWER TO SHORE POWER.. IMPACT: NR 2 SSDG OOC.	2	4	2	16

20126EA 015090	2	31122	GENERATOR SET, 60HZ, DIESEL ENGINE DRIVEN	NR 2 SSDG FUEL OIL LEAK	S/F IDENTIFIED A LEAK ON THE ATTACHED FUEL OIL PUMP. MECHANICAL SEAL AND RETAINING RING REQUIRE REPLACEMENT. IMPACT: REPAIR REQUIRED BEFORE OPERATING NR 2 SSDG.	2	4	1	8
20126EA 014041	2	31123	GENERATOR SET, 60HZ, DIESEL ENGINE DRIVEN	NR 3 SSDG THERMOCOUPLES	S/F IDENTIFIED THAT THERMOCOUPLES ON NR 3 SSDG ARE DEGRADED. IMPACT: MPCMS EXHAUST TEMPERATURES FOR NR 3 SSDG ARE INACCURATE AND DO NOT ALLOW FOR PROPER MONITORING OF NR 3 SSDG.	2	2	4	16
20126EA 013939	3	23311	ENGINE, DIESEL	MPDE PRESS TRANSMITTER ORDER	S/F IDENTIFIED MOATTI FUEL FILTER DIFFERENTIAL PRESSURE TRANSMITTER ON NR 2 MPDE IS FAILING AND WILL EVENTUALLY REQUIRE REPLACEMENT. IMPACT: EVENTUAL FAILURE WILL RESULT IN INABILITY TO MONITOR FUEL OIL FILTER DIFFERENTIAL PRESSURE. LIMITED OPERATIONAL IMPACT.	3	2	3	18

20126EA 013992	3	23311	ENGINE , DIESEL	MPDE CONTROL AIR FILTERS ORDER	S/F REQUIRES ON-HAND SPARES OF MPDE CONTROL AIR FILTER ELEMENTS. ELEMENTS WERE INSTALLED DURING FEBRUARY 2013 AVAILABILITY AND HAVE NOT BEEN UPDATED AS PART OF ON-HAND STOCK, COSAL OR PMS DATABASES. DUE TO LACK OF CURRENT STOCK.	3	2	3	18
20126EA 014222	3	23311	ENGINE , DIESEL	STBD MPDE MOATTI MOTOR OOC	S/F DISCOVERED STBD MPDE MOATTI FUEL FILTER WAS NOT SPINNING. UPON FURTHER INVESTIGATION, S/F FOUND THAT THE HYDRAULIC MOTOR HAD FAILED AND THE SELF-CLEANING FUNCTION OF THE FUEL FILTER WAS COMPLETELY DEGRADED. S/F REQUIRES REPLACEMENT HYDRAULIC MOTOR TO RESTORE STBD MPDE MOATTI FUEL FILTER TO FULL OPERABILITY..	3	2	2	12
20126EA 014789	3	23311	ENGINE , DIESEL	NR 1 MPDE SW PUMP GAUGE LINE	NR 1 MPDE ATTACHED SW PUMP GAUGE LINE FAILED DUE TO SHEARED FITTING.	1	2	1	2
20126EA 015264	3	23311	ENGINE , DIESEL	MISSING GASKETS	MPDES REQUIRE REPLACEMENT OF LEAKY GASKETS.	3	1	1	3

20126EA 015571	3	23311	ENGINE , DIESEL	FAULTY J/W CIRCUIT CARD	CIRCUIT CARD FOR JACKET WATER HIGH TEMP ALARM AND SHUTDOWN IS OOC.	3	2	3	18
20126EA 015590	3	23311	ENGINE , DIESEL	MECH SEAL FAILED NR 1 MPDE	MECHANICAL SEAL FAILED ON NR 1 MPDE JACKET WATER KEEP WARM PUMP.	2	3	1	6
20126EA 014271	3	23312	ENGINE , DIESEL	PORT MPDE OOC	FUEL OIL LEAK ON NR2 MPDE A CHIPPED COUPLING INJECTOR WAS DETERMINED TO BE THE ROOT CAUSE OF THE LEAK AND MUST BE REPLACED BEFORE OPERATING NR2 MPDE. 1 OF 2 MPDE'S OOC.	2	4	1	8
20126EA 015131	3	23312	ENGINE , DIESEL	NR 2 MPDE FUEL LEAK	NR 2 MPDE OOC DUE TO A FUEL LEAK ON THE FUEL PIPE LEADING ASSOCIATED WITH CYLINDER B6 INJECTOR. IMPACT: REPAIR REQUIRED BEFORE OPERATING NR 2 MPDE.	1	4	2	8
20126EA 015138	3	23312	ENGINE , DIESEL	NR 2 MPDE PNEUMAT IC VALVE	NR 2 MPDE P2-P5 VALVE RECEIVING FALSE SIGNAL TO OPEN DUE TO A FAILED PNEUMATIC VALVE. IMPACT: POTENTIAL FOR DECREASED OUTPUT PRESSURE ON THE TURBOCHARGER DUE TO OPEN VALVE.	2	2	3	12
20126EA 015169	3	23312	ENGINE , DIESEL	NR 2 MPDE SW FLAPPER VALVE	VALVE ASSEMBLY PIN HOUSING WAS DEFORMED CAUSING PIN TO BEND AND VALVE TO SEIZE. VALVE ASSEMBLY AND ASSOCIATED COMPONENTS REQUIRE REPLACEMENT.	2	2	2	8

20126EA 015496	3	23312	ENGINE , DIESEL	NR 2 MPDE AIR MOTOR SEIZED	NR 1 MPDE AIR MOTOR BARRING DEVICE IS SEIZED.	2	2	2	8
20126EA 015589	3	23312	ENGINE , DIESEL	MECH SEAL FAILED NR 2 MPDE	MECHANICAL SEAL ON NR 2 MPDE IS GIVING INDICATION OF IMPENDING FAILURE.	2	3	2	12
20126EA 014612	3	23411	PROPU LSION SYSTEM , MAIN GAS TURBIN E, MECHA NICAL DRIVE	NR 1 GTE V-BAND CLAMP	NR 1 GTE V-BAND CLAMP BROKEN. 1 OF 2 V-BAND CLAMPS SECURING THE ANTI-ICING SUPPLY HOSE TO THE ANTI-ICING CONTROL VALVE FAILED. GTE BLEED AIR SYSTEM SUPPLIES THE ANTIICING SUPPLY HOSE VIA THE ANTI-ICING CONTROL VALVE. S/F UNABLE TO MECHANICALLY OR ELECTRICALLY ISOLATE THE ANTIICING CONTROL VALVE. INADVERTENT ALIGNMENT OF THE ANTI-ICING SYSTEM POSSIBLE WITHOUT THE ABILITY TO ISOLATE THE ANTI-ICING CONTROL VALVE. ALIGNMENT OF THE ANTI-ICING SYSTEM COULD CAUSE THE SECONDARY V-BAND CLAMP TO FAIL ON THE ANTI-ICING SUPPLY HOSE. IMPACT: NR 1 GTE OOC UNTIL REPLACEMENT V-BAND CLAMP IS RECEIVED AND INSTALLED.	2	1	2	4

20126EA 013895	3	24111	GEAR ASSEM BLY, MAIN REDUC TION	MRG FILTER REPLACE MENTS	DUE TO WATER INTRUSION IN THE PORT COMBINING AND STBD SPLITTER GEAR DUPLEX FILTERS, S/F MUST REPLACE FILTER ELEMENTS IN BOTH UNITS. IMPACT: FILTER REPLACEMENT REQUIRED TO RETURN REDUCTION GEARS TO OPERATIONAL CONDITION.	1	1	2	2
20126EA 014734	3	24111	GEAR ASSEM BLY, MAIN REDUC TION	GARLOCK 3000	SHIPS FORCE REQUIRES GARLOCK BLUE GUARD 3000 1/8IN THICKNESS TO COMPLETE REPAIRS TO SPLITTER GEAR.	1	1	1	1
20126EA 014792	3	24111	GEAR ASSEM BLY, MAIN REDUC TION	GARLOCK 3000	SHIPS FORCE REQUIRES GARLOCK BLUE GUARD 3000 1/4 IN THICKNESS TO COMPLETE REPAIRS TO SPLITTER GEAR.	1	1	1	1
20126EA 015442	3	24111	GEAR ASSEM BLY, MAIN REDUC TION	VALVES LEAKING	SPLITTER GEAR VALVES RLO-V-105C AND 106C LOCATED ON UNDERSIDE OF GEAR LEAK WHILE OIL IS CIRCULATING AND REQUIRE REPLACEMENT.	2	2	2	8
20126EA 013892	3	24711	PROPU LSION SYSTEM , WATER JET	NR 3 LUBE OIL PP GAUGE OOC	S/F IDENTIFIED DIFFERENTIAL PRESSURE GAGE FOR NR 3 LUBE OIL POWER PACK FILTER ELEMENT IS OOC AND REQUIRES REPLACEMENT. IMPACT: INABILITY TO MONITOR LUBE OIL FILTER DIFFERENTIAL PRESSURE TO DETERMINE FILTER CHANGE OUT	2	2	2	8

					REQUIREMENT.				
20126EA 014250	3	24711	PROPU LSION SYSTEM , WATER JET	PORT STEERABL E WATERJET	WHILE CONDUCTING STEERING CHECKS IN PREPARATION FOR UPCOMING U/W, S/F CYCLED PORT STEERABLE WATERJET 30 DEGREES TO STBD. WHEN ATTEMPTING TO CYCLE PORT STEERABLE WATERJET BACK TO CENTERLINE, THE INDICATOR WOULD NOT MOVE. UPON FURTHER INSPECTION S/F DISCOVERED THAT THE FEED BACK CABLE WAS BROKEN AND THEREFORE NOT ABLE TO SEND	2	2	3	12
					AN INDICATION OF WATERJET MOVEMENT TO THE INDICATOR.				

20126EE 021067	3	25217	LOCAL OPERATING EQUIPMENT, PROPULSION	NR 2 NAVLAN UPS OOC	PMS IDENTIFIED NR 2 NAVLAN UPS OOC. UPS BATTERY REQUIRES REPLACEMENT. IMPACT: LOSS OF 1 OF 2 NAVLAN SERVERS AND LOSS OF REDUNDANCY TO MPCMS UPON LOSS OF SHIPS POWER.	2	2	4	16
20126EE 021155	3	25217	LOCAL OPERATING EQUIPMENT, PROPULSION	MPCMS UPS NR 1 DEGRADED	MPCMS UPS NR 1 DISPLAYING A CHECK INVERTER FAULT. CONTINUED T/S IAW TECH MANUAL INDICATES BATTERIES REQUIRE REPLACEMENT. IMPACT: MPCMS UPS NR 1 DEGRADED UNTIL BATTERIES ARE REPLACED. FOLLOWING A LOSS OF POWER, MPCMS UPS NR 1 IS DESIGNED TO POWER I/O LOOPS 1P, 2P, 5P, AND 5A.	2	2	4	16
20126EE 021156	3	25217	LOCAL OPERATING EQUIPMENT, PROPULSION	MPCMS UPS NR 2 DEGRADED	MPCMS UPS NR 2 BATTERIES SHOW SIGNS OF DEPLETION. IMPACT: MPCMS UPS NR 2 DEGRADED UNTIL BATTERIES ARE REPLACED. FOLLOWING A LOSS OF POWER, MPCMS UPS NR 2 IS DESIGNED TO POWER I/O LOOPS 3P, 4P, 6A, AND 9A.	2	2	4	16

APPENDIX D

PLANNED MAINTENANCE TABLE

The following subset of Planned Maintenance Procedures were selected based on the incidence of failure determined by the Pareto analysis of corrective maintenance, and then analyzed using the Risk Matrix based on frequency, impact and degree of automation:

2331	4M-5	Diesel Engine Governor Lube	1	2	1	2
	4-M6	**Inspect LO Pump**	**1**	**2**	**1**	**2**
	9M-1	Engine Test	1	4	4	16
	M-1R	LO Sample	3	2	1	6
	M-6	Inspect Air Filter	3	2	1	6
	R-3D	**LO Viscosity Test**	**4**	**3**	**3**	**36**
	W-1R	Inspect Loop Seal	4	2	1	8
2341	8M-1	Power Turbine LO Sample	1	2	1	2
	A-9	Inspect LO Cooler	1	3	2	6
2342	A-1	GT Oil Sample	1	3	1	3
	W=2R	Test GT LO Flash Point	4	3	2	24
2418	M-1R	Clean Air Filter	3	2	1	6
	M-2	Replace Air Filter	3	3	1	9
	R-34M	**Test Air Flow**	**3**	**3**	**3**	**27**
	R-33D	Reduction Gear Pilot Light	4	3	3	36
2531	**R-4D**	**Stern Seal Leakage**	**4**	**3**	**2**	**24**
	R2-W	Flash Point Test	3	3	3	27
2471	R-10W	Drain Water from Filter	4	3	2	24
256		Seawater Cooling	4	1	1	4

Table D-1. PMS Procedure Risk Matrix

From the PMS procedures determined to be high risk, the ones chosen for modeling are indicated in BOLD in the table above. To allow for a broad spectrum of risk, one was selected from each category.

APPENDIX E

OPERATING PROCEDURES TABLE

From the Engineering Operating Procedures, a selection was made based on the corrective maintenance Pareto analysis and these were analyzed using the risk matrix. The resulting procedures are shown below:

EOSS Nr.	Component	Title	Frequency	Impact	Degree of Automation	Risk Value
CAEPA	Electric Plant	Alignment Procedures	2	3	4	24
FSST	Service and Storage Tanks	Stripping water and contaminants	4	2	3	24
FOMT	Fuel Oil Transfer Pump	– Align for Remote Operations	3	2	4	24
FOAS	Fuel Oil Service System	Align for Operation	2	3	2	12
CPTM	Gas Turbine Brake	Operation, motoring	2	1	1	2
CPDM E	Main Propulsion Diesel	Starting/Operating/ Stopping	2	4	1	8
CLOP	Lube Oil Pumps	Starting/Stopping	4	3	3	36
CFOP	Fuel Oil Pumps	Starting/Stopping	4	3	2	24
BGTM	B Fire GTM	B Fire	1	3	1	3
CASF	Electric Plant	Bus Tie Parallel	4	1	4	16
CASSD G	Cool Air	Failure	2	1	2	4
CASG	Gas Turbine Generator	Fire	1	4	3	12
CSFG	Diesel	Fire	1	4	4	16
CED	Eductor	Operation, motoring	3	1	1	3
CFD	Fuel	Sample Detector	1	4	3	12

CFOSS	Boats	Fuel	2	2	2	8
CFP	Fire Pump	Operation, motoring	4	3	1	12
CFMPO	EDG	Console Operation	4	3	3	36
CHAA	CHT	Alarm	1	1	2	2
MLOL	Main Lube Oil	Pump Operation	3	1	4	12
CPTM	Console	Operation	1	2	2	4
CPWS	Potable Water	Operation, motoring	2	2	1	4
CFSRT	Fuel System	Refuel Helo	4	3	3	36
EPOP	Electric Plant	Operation, motoring	4	4	1	16
EPT	Power Turbine	Vibration	2	2	3	12
FOAS	Fuel Oil System	Align	4	2	3	24
GTES	Gas Turbine	Start	3	3	3	27
HBDG	Hot Bearing	Casualty Response	3	1	3	9
FPM	Fire Pump	Operation, motoring	4	2	1	8

APPENDIX F

IMPRINT PROTOCOLS

The following notes pertain to the IMPRINT program that was used for this analysis.

Version: 4.6.54 dated December 2018

IMPRINT is a modeling program based on C# programming language; knowledge of C# is no required to use the program, but some programming is necessary for more complex scenarios.

IMPRINT has three basic types of models:

- Warfighter – Designed to model large crews at a macro level
- Operations – Designed to model an operational mission (used for this analysis)
- Maintainer – Designed to determine maintenance requirements

For this analysis we used the Operations Model to model the Watch and Work portion of the Naval Allowance Factor (formerly Standard Navy Work Week). Each segment of the NAF was built as a separate "Mission" for analysis. Individual procedures (Planned Maintenance, Corrective Maintenance, Operations) were designated as "Functions" and the steps of these procedures "Tasks".

Once a workflow analysis was performed on the task, using operator experience or known information (for example, the duration of a Planned Maintenance Check is provided on each procedure), the functions were entered in a notional sequence that simulated the normal flow of a watch period.

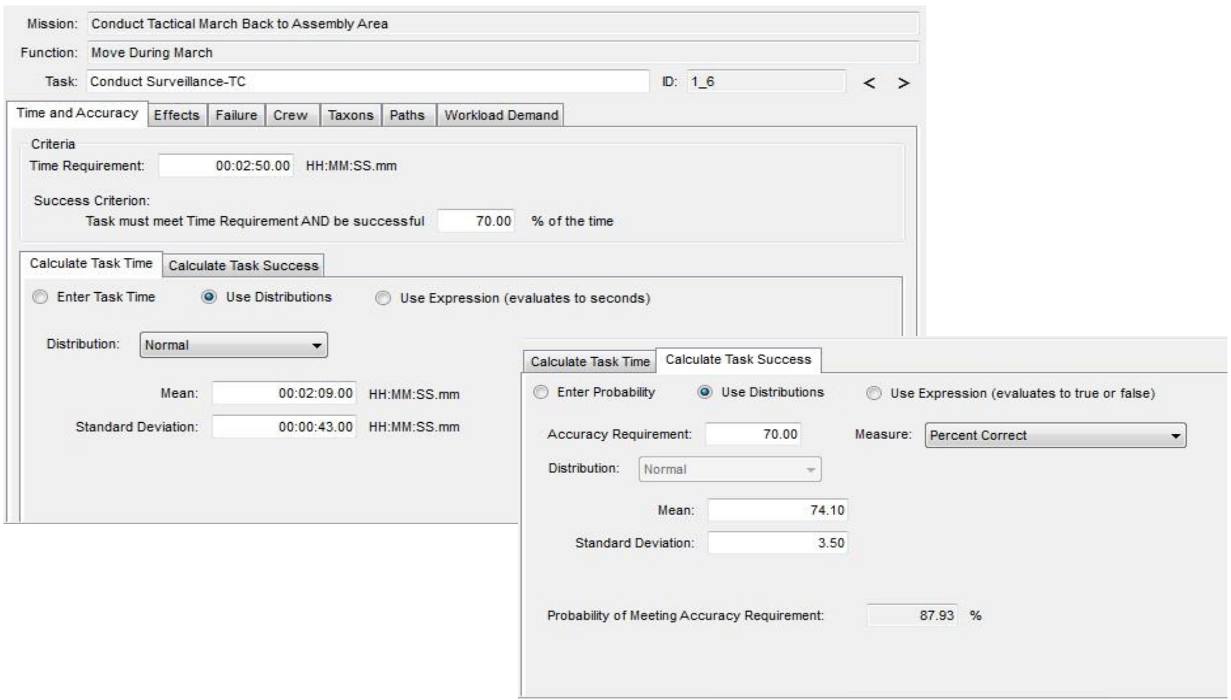


Figure A-1. Time and Accuracy Data Entry Fields

Tasks were then entered in sequence, with the following basic protocols:

The Time Criteria. A value was entered based on the workflow analysis as the expected time required for that particular step. Where possible, this was based on the baseline for similar tasks which is built into IMPRINT, where a variety of tasks are listed along with "standard" times and the research reference that supports it. In cases where this was not available, reasonable estimates were made based on operator experience. These could be refined in future studies, to include observation of these tasks in-situ, where other factors could influence the execution.

Success Criteria. This is for accounting purposes and does not determine success or failure for the mission, however it may yield useful data for future analysis of individual tasks. As a default, the analyst entered 85% for all tasks.

IMPRINT offers three options for entering the expected task time:

- Enter Task Time: A fixed time chosen by the operator (Generally not used)
- Use Expression: A user-entered expression (Generally not used)
- Distribution: A pulldown menu with several options (Used for most tasks) o For most tasks, a normal distribution was chosen, although others are available. This allows for a more realistic simulation for multiple runs to account for performance of procedural tasks by different personnel under variable conditions.
- Mean: A reasonable estimate for the time expected for the operation – may or may not match the time criteria entry
- Standard Deviation: This was generally entered as 20% of the Mean, with a subjective assessment of tasks with a wide range of variability entered as 30% and tasks with little expected variation 10%

The next tab is titled "Calculate Task Success" and is used to enter data that could determine the human error that may be encountered during performance of the task. Here again 85% was entered as the default value for all tasks.

The same rules were applied (Normal Distribution, Mean and Standard Deviation) as in the "Time" section.

This section also has 3 possible criteria to assess accuracy:

- Percent Correct (not used)
- Percent from Desired (not used)

- Number of Errors (Used in this analysis)

Based on the entries here, a “Probability of Success” is calculated and displayed.

The “Effects” tab is used to add conditions (Release Condition, Beginning Effect, Ending Effect) that control the transition to the next task. For the majority of tasks in this analysis, no additional entries were made here, but it is available for detailed tailoring, such as when two tasks have to complete before another one starts. In these cases, basic C# programming language and protocol was used.

The “Failure” tab allows entry of expected failure probability, and the results of this failure (Mission failure, delay, inaccuracy, task repeat or reassignment), represented by percentages that must total 100%. For most tasks, the “No Effect” was chosen, unless the task was a critical one, and a percent failure was entered as appropriate, based on the Failure Analysis for that task (specifically that step in the given procedure).

The “Crew” tab allows the selection of the applicable crew member (in this analysis RCO, EPT and System). Automated tasks were color coded to show those that are performed by automation vice an operator.

The “Taxon” Tab allows operator-entered values for the following: Perceptual, Cognitive, Motor, Communication and allows the opportunity to map these to the workload values added in the following tab.

The “Paths” Tab allows the operator to use single or multiple paths between tasks, including options for multiple outcomes based on a percentage basis.

The “Workload” Tab allows the operator to assign values to each of the taxons based on empirical studies – these are also compared in a matrix to indicate the extent that each one interferes with the others at the various interface workstations. These values may be entered directly or based on pre-selected values from a pull-down menu. For this analysis the values were selected based on the “swim lane” factors determined during the work flow analysis of each procedure. While not exact correlations, the determination was generally straightforward.

The “Performance Shaping” tab has options for noise, heat, cold, vibration, sleep, and MOPP level. These could be used to more closely model individual situations, with the sleep option being the most closely aligned to the dimensions examined in this analysis. These factors can be toggled on and off for comparison between successive executions of the mission. For this analysis, the only PSF implemented was “Sleepless Hours” to model the effects of fatigue.

APPENDIX G

SAMPLE TIME/MOTION ANALYSIS WORKSHEET

OLD DOMINION UNIVERSITY

Time/Motion Operations Analysis

Operation Name: REPLACE RTD Analysis Date: 02 / 04 /2019 Page: 1 of 2

Operation Number: RTD Shift: ________ Operator: ____________

Operation Description: REPLACE REMOTE TEMPERATURE DEVICE (RTD)

Time: ______________

Analysis By: ____________

Physical Element Codes:
PA: Auditory PS: Speech
PC: Cognitive PT: Tactile
PF: Fine Motor PV: Visual
PG: Gross Motor

Cognitive Element Codes:
RN: Realize Need for Decision SA: Select Alternative
GI: Gather Information AC: Act on Decision
MA: Model Alternatives RD: Review Decision
WE: Weigh Evidence DT: Distracted/Inattentive

Automation Element Codes:
AD: Delay AX: Calculate
AS: Display Status
AA: Control Action
AE: Execute Action

Start Time	End Time	PE Code	CE Code	AE Code	Initiating Event	Task Element Description & Effect on System Output Gain	Terminating Event
00	15	PV	WE		Verbal Order	1. Tag out SSDG and the Instrumentation and Control Panel to prevent turning during procedure and to deenergize the RTD.	Tags Hung
15	16	PT	WE	AA	Procedure Step	2. On the Remote-Control Panel at the ECO station, place the associated RTD in "Override" to cancel out the signal	Override
16	25	PG	AD		Procedure Step	3. Remove the installed inoperative Remote Temperature Device (RTD) from the end bearing	Removed
25	30	PF	AD		Procedure Step	4. Disconnect the RTD wiring from the input/output electrical junction box CAUTION: Ensure no dirt or debris falls into the opening while the RTD is removed	RTD Disconnected
30	35	PF	AD		Procedure Step	5. Coat the threads on the new RTD with a light coat of grease and wipe	Threads Coated

APPENDIX H

SAMPLE CRITICAL FAILURE MODE ANALYSIS WORKSHEET

Procedure: EOS_Parallel Bus Tie__Date:_9 Feb__ Analyst:_JPC____

Process Step	Potential Failure Mode	Potential Failure Effect	SEV	Potential Cause	OCC	Current Process Controls	DET	RPN	Action Recommended	Revised SEV	Revised OCC	Revised DET	Revised RPN
Push "Yes" to signal breaker to close	Breaker does not close	Diesel Not available	8	Failed Automation Signal	4	None	6	192	Install "Failed to shut" signal	8	4	1	32
Push "Yes" to signal breaker to close	Breaker does not close	Diesel Not available	8	Mechanical Failure	2	None	6	96	Install "Failed to shut" signal	8	4	1	32

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Procedure: __Test LO Viscosity_Date: 9 Feb_ Analyst:_JPC____

Process Step	Potential Failure Mode	Potential Failure Effect	SEV	Potential Cause	OCC	Current Process Controls	DET	RPN	Action Recommended	Revised SEV	Revised OCC	Revised DET	Revised RPN
Unit Display Prompt to enter density	Fails to prompt	Unable to complete test	6	Automation Failure	2	None	2	24	Backup Power Supply	4	1	2	8
Ball Travel Through sample	Ball sticks	Unable to complete test	4	Mechanical Failure	2	None	2	16	Redesign tube	4	1	2	8

3

VITA

Captain (ret) Cordle is a native of Rome, Georgia and a 1984 graduate of the U.S. Naval Academy with a Bachelor of Science Degree in Ocean Engineering (With Merit), a Master of Science Degree in Strategic Planning from the Naval War College in Newport, Rhode Island, and a Master of Arts Degree in engineering Management from Old Dominion University. Captain Cordle retired after 30 years' service in 2013. His final tour was as Chief of Staff for Commander, Naval Surface Forces Atlantic, where he also served as Force Maintenance and Force Manning Officer. He most recently commanded USS SAN JACINTO (CG 56), completing an INSURV and a Counter-Piracy deployment. He was the 2010 recipient of the U.S. Navy League's Captain John Paul Jones Award for Inspirational Leadership during this tour, the BUMED "Epictetus" Award for Innovative Leadership, and the 2013 Surface Navy Association Literary Award for the "most significant article of the year" for his co-authorship of the article *A Sea Change in Standing Watch,* and again in 2018 for his work in the area of manpower and shipboard watch rotations. He was awarded the U. S. Naval Institute "Author of the Year" award in 2018, and has been published several times in the Naval Engineering Journal.