# NAVAL POSTGRADUATE SCHOOL

**MONTEREY, CALIFORNIA**

# THESIS

**MANPOWER EVALUATION USING MODELING AND SIMULATION FOR AN UNDERWAY CANADIAN SURFACE COMBAT SHIP**

by

Tommy Poirier

September 2020

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<tr><td colspan="4">REPORT DOCUMENTATION PAGE</td><td colspan="2">Form Approved OMB No. 0704-0188</td></tr>
<tr><td colspan="6">Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.</td></tr>
<tr><td colspan="2">1. AGENCY USE ONLY<br>(Leave blank)</td><td>2. REPORT DATE<br>September 2020</td><td colspan="3">3. REPORT TYPE AND DATES COVERED<br>Master's thesis</td></tr>
<tr><td colspan="4">4. TITLE AND SUBTITLE<br>MANPOWER EVALUATION USING MODELING AND SIMULATION FOR AN UNDERWAY CANADIAN SURFACE COMBAT SHIP</td><td colspan="2" rowspan="2">5. FUNDING NUMBERS</td></tr>
<tr><td colspan="4">6. AUTHOR(S) Tommy Poirier</td></tr>
<tr><td colspan="4">7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>Naval Postgraduate School<br>Monterey, CA 93943-5000</td><td colspan="2">8. PERFORMING ORGANIZATION REPORT NUMBER</td></tr>
<tr><td colspan="4">9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br>N/A</td><td colspan="2">10. SPONSORING / MONITORING AGENCY REPORT NUMBER</td></tr>
<tr><td colspan="6">11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.</td></tr>
<tr><td colspan="4">12a. DISTRIBUTION / AVAILABILITY STATEMENT<br>Approved for public release. Distribution is unlimited.</td><td colspan="2">12b. DISTRIBUTION CODE<br>A</td></tr>
<tr><td colspan="6">13. ABSTRACT (maximum 200 words)<br>We used discrete event modeling/simulation to assess the current manning plan (N=217 sailors) of the Halifax-class frigate in terms of sailor workload, sleep, and task completion. This thesis described the two models developed with the IMPRINT Pro Forces module. The baseline model included planned activities and expected unplanned events. The second (“augmented”) model included all activities and events of the first model plus a number of rarely occurring unplanned events (e.g., fires, floods). Both models assumed a 10-day underway. Results showed that time spent on planned activities, including maintenance, was reduced across all departments in order to support unplanned events, resulting in increased time on duty and reduction in sleep. Specifically, 59% of the sailors in the baseline model averaged between 13 and 15 daily duty hours, whereas 6.5% of the sailors slept on average less than seven hours per day. With the introduction of operationally relevant unplanned events in the augmented model, the percentage of sleep-deprived sailors increased to 35% (a five-fold increase). Watchstanders, starboard particularly, were the most burdened among the crew. Of note, two of the high-priority unplanned events, rescue stations and boarding stations, saw occasional delays and interruptions. Current ship acquisition programs of the Royal Canadian Navy should consider discrete event modeling/simulation to aid decisions regarding manpower determination.</td></tr>
<tr><td colspan="5" rowspan="2">14. SUBJECT TERMS<br>manpower, combat ship, crew determination, modeling and simulation, IMPRINT Pro, Halifax-class, Royal Canadian Navy, ship manning</td><td>15. NUMBER OF PAGES<br>99</td></tr>
<tr><td>16. PRICE CODE</td></tr>
<tr><td>17. SECURITY CLASSIFICATION OF REPORT<br>Unclassified</td><td colspan="2">18. SECURITY CLASSIFICATION OF THIS PAGE<br>Unclassified</td><td colspan="2">19. SECURITY CLASSIFICATION OF ABSTRACT<br>Unclassified</td><td>20. LIMITATION OF ABSTRACT<br>UU</td></tr>
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NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
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**MANPOWER EVALUATION USING MODELING AND SIMULATION FOR AN UNDERWAY CANADIAN SURFACE COMBAT SHIP**

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Submitted in partial fulfillment of the
requirements for the degree of

**MASTER OF SCIENCE IN HUMAN SYSTEMS INTEGRATION**

from the

**NAVAL POSTGRADUATE SCHOOL**
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# ABSTRACT

We used discrete event modeling/simulation to assess the current manning plan (N=217 sailors) of the Halifax-class frigate in terms of sailor workload, sleep, and task completion. This thesis described the two models developed with the IMPRINT Pro Forces module. The baseline model included planned activities and expected unplanned events. The second ("augmented") model included all activities and events of the first model plus a number of rarely occurring unplanned events (e.g., fires, floods). Both models assumed a 10-day underway. Results showed that time spent on planned activities, including maintenance, was reduced across all departments in order to support unplanned events, resulting in increased time on duty and reduction in sleep. Specifically, 59% of the sailors in the baseline model averaged between 13 and 15 daily duty hours, whereas 6.5% of the sailors slept on average less than seven hours per day. With the introduction of operationally relevant unplanned events in the augmented model, the percentage of sleep-deprived sailors increased to 35% (a five-fold increase). Watchstanders, starboard particularly, were the most burdened among the crew. Of note, two of the high-priority unplanned events, rescue stations and boarding stations, saw occasional delays and interruptions. Current ship acquisition programs of the Royal Canadian Navy should consider discrete event modeling/simulation to aid decisions regarding manpower determination.

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ARL | Army Research Laboratory |
| BAE | British Aerospace |
| CSC | Canadian Surface Combatant |
| CCDC | Combat Capabilities Development Command |
| CSE | Combat Systems Engineering |
| CSV | Comma Separated Values |
| CO | Commanding Officer |
| CISN | Communications, Information Systems and Networks |
| CM | Corrective Maintenance |
| DC | Damage Control |
| DRDC | Defence Research and Development Canada |
| DOD | Department of Defense |
| DND | Department of National Defence |
| DON | Department of the Navy |
| GAO | Government Accountability Office |
| HFX | Halifax |
| HRED | Human Research & Engineering Directorate |
| HSI | Human Systems Integration |
| IMPRINT | Improved Performance Research Integration Tool |
| ISMAT | Integrated Simulation Manning Analysis Tool |
| IQR | Inter Quartile Range |
| LCS | Littoral Combat Ship |
| MANPRINT | Manpower and Personnel Integration |
| MSE | Maritime Systems Engineering |
| MTBF | Mean Time Between Failures |
| MTTR | Mean Time To Repair |

| | |
|---|---|
| MOS | Military Occupation Specialty |
| NPS | Naval Postgraduate School |
| NAF | Navy Availability Factor |
| NAVMAC | Navy Manpower & Material Analysis Center |
| NSWW | Navy Standard Workweek |
| NATO | North Atlantic Treaty Organization |
| OPNAVINST | Office of the Chief of Naval Operations Instruction |
| POE | Projected Operational Environment |
| PVT | Psychomotor Vigilance Test |
| RSN | Random Seed Number |
| RAS | Replenishment At Sea |
| ROC | Required Operational Capability |
| RCN | Royal Canadian Navy |
| SSO | Ship's Standing Orders |
| SCORE | Simulation for Crew Optimization and Risk Evaluation |
| SD | Standard Deviation |
| SE | Standard Error |
| SOR | Statement Of Requirements |
| SOW | Statement Of Work |
| SME | Subject Matter Expert |
| SCN | Suprachiasmatic Nucleus |
| US | United States |
| USN | United States Navy |
| UAV | Unmanned Aerial Vehicle |
| WSB | Watch and Station Bill |

# EXECUTIVE SUMMARY

The acquisition of navy ships requires much care be taken while conducting manpower determinations given that this element remains one of the main cost drivers of a platform's lifecycle. The Royal Canadian Navy (RCN) is currently acquiring a number of new ships, including a Canadian Surface Combatant ship that is to replace the legacy Halifax-class frigates. One of the goals during this specific acquisition process is to drastically reduce the size of the crew aboard these combat ships. Yet, no tool or methodology is currently used formally within the RCN to predict workload and sleep outcomes for sailors based on intended ship manning levels.

Based on the aforementioned background, we used discrete event modeling/simulation to assess the current manning plan of the Halifax-class frigate in terms of sailor workload, sleep, and task completion. We built two models using the Improved Performance Research Integration Tool (IMPRINT) Pro Forces module. Both models included the entire crew (N=217 sailors). The operational scenario was based on a notional 10-day patrolling mission at sea. The first ("baseline") model covered all daily planned activities (watch, eating, maintenance, personal time, departmental work, and sleep) as well as expected, but randomly scheduled, unplanned events (i.e., drills, evolutions, and corrective maintenance). Compared to the approximately fixed schedule of the planned activities, these types of unplanned events are expected to occur; but, they are random in terms of their start time and duration. The baseline model is considered a base case outcome for this notional scenario, considering that no mishaps, incidents, or adversarial interactions take place. To serve as a validation of this baseline, the average time on duty and sleep durations of sailors per department was compared to data collected at sea for an equivalent crew and ship. The second ("augmented") model builds upon the baseline by adding rarely occurring unplanned events such as floods, fires, man overboard rescue, ship boarding, and other randomized events to simulate a more operationally realistic mission with higher tempo compared to the baseline notional mission. In both cases, the inputs needed for the models such as crew composition, sailor jobs, and roles as well as duration ranges and frequencies for various tasks were based on

existing Halifax-class frigate operational studies and associated Watch and Station Bill. Information from subject matter experts was used to ensure realism in the models' parameters.

The overall goal of the study was to answer a set of questions regarding performance and readiness of the crew and, consequently, the ship. First, can the current crew of 217 aboard a Halifax-class combat ship satisfactorily complete the majority of all planned and unplanned events while on a notional mission of ten days at sea? Which job positions, military occupation specialty, schedules, and departments are expected to experience the heaviest workloads and, consequently, its sailors reduced sleep? And finally, what is the impact on crew workloads, sleep, and task failures when mishaps and incidents are included in the model?

Based partly on existing studies, three hypotheses were formulated with respect to the two IMPRINT Pro models. A general hypothesis was that some individual sailors, departments, or schedules would experience increased working hours and, consequently, would sleep less. Furthermore, it was expected that watchstanders, in particular, would be more heavily impacted by increased workloads and decreased sleep compared to departmental workers. Regarding unplanned events and planned activities, it was hypothesized that we would observe an increase in task completion failures, delays, and task interruptions.

The baseline model was validated successfully against existing data, showing no significant difference for average sleep per department or ship-wide. In terms of workload, 59% of the sailors in the baseline model had between 13 and 15 duty hours per day. Despite the favorable ship average daily sleep of 7.6 hours, the baseline model did have 13 watchstanding sailors who averaged less than 7 hours of sleep per day. Activities and events also showed a small percentage of failures, delays, and interruptions for some of the lower priority events, including a 5% ship-wide reduction in total planned maintenance hours.

A paired comparison of all metrics between the baseline and augmented models gave credence to the study hypotheses. Specifically, 76 (35%) sailors in the augmented model were now considered sleep deprived (a five-fold increase compared to the baseline model), 38 of which were starboard watchstanders. All these sailors had a mean reduction of daily sleep of at least 30 minutes compared to the baseline model. In terms of time on duty, 60 sailors (28%) saw an increase of 30 minutes or more of average daily time on duty. Among those who saw an increase, 62% were on departmental schedules and the most impacted were the executive department, logistics, and deck. With the exception of a finding of 8% to 25% failure to start for helicopter flights, no other increase in event failures occurred in the augmented model. On the other hand, delays and interruptions increased significantly for approximately half of all events. Planned maintenance across the ship saw an additional decrease of 7% in total maintenance hours, with the Combat Systems Engineering department seeing the most impact with a 10.7% decrease in planned maintenance.

The baseline IMPRINT Pro model shows that even under normal operating conditions, sleep deprivation is evident and activity completion issues begin to emerge. The inclusion of mishaps and incidents in the augmented model caused 28% of the crew to suffer an increase in time on duty and 35% of sailors to become sleep deprived. These findings suggest that the current size and composition of a Halifax-class crew does not allow for sufficient spare capacity to complete the majority of this scenario’s tasks, despite the reduction in sleep time of many sailors.

It is suggested that the RCN and Canadian Surface Combatant program office adapt this modeling and simulation tool to determine the projected crew size in relevant mission scenarios. This will allow for the prediction of sailor workload and sleep outcomes, including the effects of modifying crew size and composition. This approach would be valuable in support of manning determination for any ship, existing or upcoming.

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## ACKNOWLEDGMENTS

I wish to express great thanks to my advisors, Dr. Panagiotis Matsangas and Dr. Lawrence Shattuck, whose knowledge, guidance, and occasional tough love made this research work possible. Gratitude also to Mr. Mike O'Neil for the early help and insights into the naval operations world. This team came together nicely and provided the support I needed. Thank you for making this thesis process as rewarding as it was challenging.

I would also like to give a special thanks to Mr. Steve Upton from the SEED (Simulation Experiments & Efficient Designs) Center for the critical and timely support. Mr. Upton's wizardry in coding made the extraction and processing of massive amounts of data inconceivably effective. I would be remiss if I did not thank the group of experienced sailors, from Canada, the U.S., and Australia, who helped greatly expand my knowledge and comprehension of operations aboard a ship. Their inputs have greatly increased the quality of the models created for this thesis.

Last, but not least, I must express my most heartfelt thanks to my wife, Annie Bouchard, as well as our daughters, Abby and "production baby" Alex. Without their love and support, all of this would simply have been impossible. In these difficult times, they have endured as much as I have with the long hours of hard work.

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# I. INTRODUCTION

In the current state of global uncertainty, North Atlantic Treaty Organization (NATO) naval ships face a rapidly expanding variety of threats and must conduct various types of operations in response to these threats. Against this backdrop, both the United States Navy (USN) and the Royal Canadian Navy (RCN) are moving forward with major ship acquisitions, but these acquisitions present significant design challenges of their own, given the generalized philosophy of doing more with less (Canadian Naval Review, 2017). Budgetary constraints not only limit the scope and capabilities of a system but also impact the personnel who will be operating and supporting said system. Considering that operations and support costs for a surface ship account for approximately 70% of total ownership cost and that 50% of those funds are disbursed on manpower (Spindel et al., 2000), we then conclude that personnel costs account for roughly 30% of a ship's lifecycle. Ship service life extends up to 50 years in some cases, such as with the Arleigh-Burke class and amphibious assault ships (Larter, 2018); so, it is not surprising that reducing manning is one of the key cost-saving objectives when acquiring new vessels. This leads to the navy and Program Managers imposing a maximum crew size as a requirement of a new ship design, with an implied objective of achieving a minimum / optimal crew size while maintaining targeted capabilities and operational readiness.

Given the highly complex system-of-systems nature of naval ships, crew size cannot be considered in a vacuum. When acquisitions personnel perform manpower determinations, a number of complex interacting factors must be taken into account. The exact outcomes of these interactions are difficult to predict. The qualifications of personnel, training needs, sleep/work cycles, shiftwork, operational conditions, mission types, and automation levels of the ship are some of the factors that will affect sailor workload.

A number of tools and methods have been developed to model and simulate these complex interactions in the military setting. A few studies (Hollins & Leszczynski, 2014; Shattuck & Matsangas, 2015) have shown promising ship crew modeling results in predicting workload and operational effectiveness as a function of manpower, but the use of these more evolved tools in ship manning modeling is still in its early days.

## A. CANADIAN PATROL FRIGATE BACKGROUND

According to the Government of Canada (2016), the Halifax-class multi-role patrol frigates constitute the backbone of the RCN (Figure 1). These 4770-tonne, 134-meter ships were designed for combat, helicopter-carrying and are capable of supporting a crew of 225 personnel (217 without air detachment). This class of frigate is capable of reaching 30 knots and cover 17600 kilometers while carrying torpedoes, anti-ship missiles, a 57-millimeter naval gun, and a close-in weapon system for defensive purposes. In 2016, the final delivery of a $4.3 billion modernization program took place in order to significantly upgrade the ships' capabilities as they reached the middle of their expected service life. The list of upgrades includes a number of components, such as a new Combat Management System, new radar suite, internal communications system, missile system, electronic warfare systems, and a new Integrated Platform Management System offering better damage control. These implementations allow the patrol frigates to shift their original role of anti-submarine and anti-surface warfare in the open ocean to being effective in the littoral near-shore environment. One frigate in particular, HMCS *Montréal*, has been dubbed X-ship, and has the specific mission of supporting various experimentations, studies, and trials for the advancement of warship deployment, crewing, and sustainment. Among the more elaborate trials in which X-ship was involved was the validation of a crew of 217 by Defense Research & Development Canada (DRDC). Defense scientists used a tool called the Simulation for Crew Optimization and Risk Evaluation (SCORE) to build a notional crew that was to be compared to a real-world scenario at sea while the crew conducted their regular shipboard routines aboard X-ship (Public Services and Procurement, Government of Canada, 2016).

SCORE is more akin to an advanced scheduling tool and is deterministic in its output. In contrast, the Improved Performance Research Integration Tool (IMPRINT) Pro, a tool developed initially by the U.S. Army, contains a module that can model a crew and run discrete event simulations containing stochastic elements. This tool has been used successfully in recent years specifically toward modeling USN ship crews.

Figure 1. Halifax-class multi-role patrol frigate, HMCS *Fredericton.* Source: Royal Canadian Navy (2018).

## B. CANADIAN SURFACE COMBATANT BACKGROUND

"Strong, Secure, Engaged," Canada's defense policy, has committed approximately $60 billion to acquire 15 Canadian Surface Combatant (CSC) ships with start of construction planned for early 2020 (Defence, 2013). These ships are intended to be a major component of surface combat power and will fulfill a number of roles such as counter-piracy, counterterrorism, interdiction, embargo operations, humanitarian aid, search and rescue, and law and sovereignty enforcement. The CSC, as part of the National Shipbuilding Strategy, will effectively replace both the Iroquois-class destroyers and the Halifax-class multi-role patrol frigates with this single class of ship. This platform's versatility will operate on the open ocean as well as in coastal environments for up to a number of months with a limited logistic footprint. The CSC project is the most complex Canadian shipbuilding initiative since World War II (Defence, 2013). The contract was awarded to BAE Systems' Royal Navy type 26 Global Combat Ship design alongside Lockheed Martin Canada to further evolve the Canadian-specific design.

Lockheed Martin is also contributing to this new ship by including their current Combat Management System that is in use on the Halifax-class frigates (Canada's Combat Ship team, n.d.). The main characteristics of the CSC are: 6900 tonnes displacement, 150 meters length, accommodation for 208 crew, top speed of 26 knots, range in excess of 7000 nautical miles, and a flight deck capable of landing a Chinook helicopter. It will also be an especially flexible platform due to a very high level of modularity in its design (BAE Systems, n.d.) Although the definition phase is nearly finalized to shift towards the implementation phase in 2020, manpower determination is still very much in draft form. A maximum crew size has been determined but no finalized watch bills have been confirmed, nor any optimal crew size / composition analysis completed.

## C. STUDY OBJECTIVES

This current effort using IMPRINT Pro was put forth in order to answer the following research questions:

- Can the current crew of 217 aboard a Halifax-class combat ship satisfactorily complete the majority of all planned and unplanned events while on a notional mission of ten days at sea?
- Which job positions, military occupation specialty (MOS), schedules, and departments are expected to experience the heaviest workloads and, consequently, its sailors reduced sleep?
- What is the predicted severity of impact on crew workloads, sleep, and task failures when mishaps and incidents are included in the model?

# II. LITERATURE REVIEW

## A. WORKLOAD IMPLICATIONS

One of the main metrics of concern for the navy in determining the minimum or optimal crew size for any given ship is the expected workload of every individual sailor on board. Wickens and Tsang (2015) have described workload as the relationship between the resources required to carry out a task and the resources available to the personnel carrying out said task. The nature of those resources varies, they claimed, depending on the task; but, one of the most common and universal resources is certainly time. In any situation where a task requires more time than is available, the workload can be qualified as being excessive, either for the individual or for the team. Since reducing manpower levels is a key objective for ships currently going through the acquisition process, it is expected that overall workloads will increase unless mitigations are put in place. There are a number of approaches that make it possible to accomplish the same amount of work with a decreased number of hands available. Sailors that have more experience, better training, or who are more qualified may complete tasks more efficiently compared to others. Crew members who are less fatigued are also more likely to successfully complete a task in a shorter amount of time. But these personnel level considerations only support task completion efficiency; they do not reduce the overall ship workload that consists of all concurrently ongoing tasks.

By implementing advanced technologies, ship designers are aiming to greatly increase automation levels of various systems to reduce sailor workloads by removing specific sailor tasks entirely. Such an effort has been an integral part of the design of the Littoral Combat Ship (LCS) as well as the Zumwalt-class destroyer for the USN, but workloads have been observed as impossible to sustain while following the ambitious reductions in crew size initially hoped for (Fredenburg, 2016). Accomplishing mission tasks as needed was not achievable with the reduced crew. Operating on an underway ship, the mission must go on, which means sailors must sacrifice non-productive time (which accounts for eating, sleeping, and personal time) in their daily schedule to complete essential tasks. As workloads increase, individual crew members may sacrifice sleep hours in order to complete tasks that cannot be postponed. Workloads have a direct link with crew sleep/fatigue, which in turn has an effect on ship readiness, safety as well as operational effectiveness.

## B. MANPOWER DETERMINATION

The USN has a detailed and well- established procedure in place to formulate manpower requirements for all classes of ships. The roles and responsibilities of manpower formulation are captured in a Chief of Naval Operations instruction (OPNAVINST) titled *Manual of Navy Total Force Manpower Policies and Procedures*. The Naval Manpower Analysis Center (NAVMAC) is the organization responsible for determining the type and level of personnel needed to support the required ship capabilities and ensure mission effectiveness (Department of Navy (DON), 2015). Given that for fiscal year 2019, personnel costs were nearly $50 billion, which is equivalent to total Operations & Maintenance (O&M) costs (DON, 2019), it is not surprising that Department of Defense (DOD) policy still enforces employing the lowest number of sailors that allow for mission completion (Government Accountability Office (GAO), 2003).

There are a handful of key documents that are produced as part of the determination process of Fleet manpower requirements for the USN. The Required Operational Capability (ROC) indicates a desired level of readiness in accordance with specific readiness conditions. The Projected Operational Environment (POE) describes the possible operating environments in which a specific ship is expected to operate (DON, 2015). The two documents provide the foundation for all manpower requirements for a class of ship using this process of manpower determination. The measurable levels of crew workload that result from the ROC/POE are then used by NAVMAC to align with the Navy Standard Workweek (NSWW) guidelines in order to calculate the minimum number of sailors needed to complete daily tasks and missions. Lastly, the results of this analysis are captured and published in a Ship Manpower Document.

The RCN employs a much less formal process to estimate manpower requirements of a ship entering the first acquisition phases. Initial steps of manpower determination are based on the ship's Statement of Requirements (SOR) as well as the Statement of Work (SOW), which contains highly detailed characteristics to be included in the ship's design (Lamb et al., 2018). From these documents, Subject Matter Experts (SME) will make comparisons to existing and legacy RCN ships that have similar capabilities, as well as leverage their knowledge and experience to estimate crew size and composition. A suggested watch and station bill (WSB) is also produced following this analysis. The WSB contains the job positions, ranks, and MOS as well as the specific roles and responsibilities of each sailor aboard the ship for a given mission.

## C. NAVY AVAILABILITY FACTOR / NAVY STANDARD WORK WEEK

Previously known as the Navy Standard Workweek or NSWW, the Navy Availability Factor (NAF) provides guidelines for the USN that cover the "total average hours per week that are available per person to accomplish the required workload (including watches) of the various Navy units" (DON, 2015). The document also states that it should be used to calculate peacetime and mobilization manpower requirements and that resulting requirements must be in line with the minimum manpower resources needed to fulfill the missions. The ship's ROC/POE guides NAVMAC in determining positions, shipboard watch requirements and workloads, as well as the required sailor specialties and experience levels that are then aligned with the NAF to complete the minimum manpower determination. The NAF breaks down the weekly hours, as shown in Table 1.

Table 1. Afloat (operational)—military personnel. Adapted from DON (2015).

| | | |
|---|---|---|
| NAF (NOTE 4) | | 81.00 |
| Productive Availability Factor | | 67.00 |
| Analysis of Duty Hours | | |
| Non-Productive Availability Factor: | | 14.00 |
| Training (NOTE 2) | (8.00) | |
| Service diversion (NOTE 3) | (6.00) | |
| Total Hours Available for Productive Availability Factor (NOTE 1) | | 67.00 |

These numbers, which are based on a 168-hour week (NOTE 4) and a NAF of 81 hours, indicate that a sailor is to be considered non-available for 87 of those 168 hours. Specifically for watchstanders, 56 hours are allocated to watch stations, which translates to 11 hours available for additional work (totaling 67 hours) (NOTE 1). There are five weekly hours for scheduled events such as drills, and the remaining three hours are intended for individual training such as skills and qualifications (NOTE 2). What is referenced as "service diversions" are activities such as administrative tasks, quarters, inspections, sick calls, and administrative requirements (NOTE 3). Basic USN manpower assumptions by the leadership are that the NAF are to be used as guidelines for sustained personnel utilization and the proper NAF table will be used for the corresponding personnel type. The term "afloat" implies "a unit steaming in condition III (wartime and deployed cruising readiness) on a three-section watch basis" (DON, 2015). It is important to understand the nuance that these numbers are intended for sustained work, but they in no way align with possible personnel endurance limits.

Once again, the RCN does not have a formal document similar to the one used by the USN that guides what should constitute a standard workweek for a sailor aboard a surface ship. In fact, studies that have been conducted for the RCN have used the USN workweek as a standard for sailor time breakdown at sea. The knowledge and experience of SMEs, along with analysis of previous operations on existing ships, serve as a basis to establish individual work/rest cycles. That being said, some guidance can be found in the

Ship's Standing Orders (SSO) in the daily sea routine schedules (Royal Canadian Navy, 2014). With a wakeup call at 07:00, 30 minutes are planned per meal and the pipe down (end of day) sounds at 21:30. Although personal time is certainly taken into consideration and expected in the schedules, there is no official requirement or guidance documented.

## D. HUMAN PERFORMANCE

There are a number of publications that have explored the relationships between workloads, performance, and fatigue in a number of work environments and conditions. Many researchers have concluded that high workloads and fatigue, due to lack of sleep or otherwise, contribute to a decrement in performance (Hockey et al., 2003). They have put efforts into predicting the occurrence of decreased performance in complex tasks. A reduction in performance can be cognitive and physical in nature; both of which may increase the time needed to complete tasks or increase the rate of worker errors. Fatigue is caused by varying factors, and it affects systems of the human body in different ways.

### 1. Shiftwork and Circadian Rhythms

While underway, the nature of military ships implies that operations are ongoing 24 hours a day, seven days a week. Specifically, watch stations must be manned continuously for every minute of every day. Obviously, not a single crew member can sustain work without rest or sleep, which means shiftwork is always an important factor in naval operations. The *Cambridge Dictionary* (2020) describes shiftwork as "a system in which different groups of workers work somewhere at different times of the day and night." Many industries today rely on shiftwork where at least two teams/sections rotate shifts to cover necessary duties around the clock. Shiftwork does bring a number of side effects to humans that can be difficult to mitigate and tend to worsen over the long term. All life essential activities such as sleeping and eating are shifted from the usual sun-up to sundown schedule and this affects the body's physiology. Examples of adverse health effects are cardiovascular issues and gastrointestinal disorders, as well as mental health impacts (Harrington, 1990). One significant aggravating factor for navy personnel is that some of the watchstanding systems can be constantly shifting from day to day (such as with a five-and-dime watch schedule). This means that some crew members are essentially in a constant state of "jet-lag," since meal and sleep times are shifted nine hours from the preceding day. As seen in Table 2, the cycle repeats every three days and results in vastly different sleep and meal opportunities within a given section. Specifically, Table 2 shows an example of a "five and dime" watch schedule where all sailors on this rotation of three sections will be five hours on watch followed by ten hours off.

Table 2. Three-section, 5 hours on-duty /10 hours off, Watch Schedule

| Time | Day 1 | Day 2 | Day 3 |
|---|---|---|---|
| 0700-1200 | 1 | 3 | 2 |
| 1200-1700 | 2 | 1 | 3 |
| 1700-2200 | 3 | 2 | 1 |
| 2200-0200 | 1 | 3 | 2 |
| 0200-0700 | 2 | 1 | 3 |

Physiological disturbances caused by maintaining wakefulness at night occur when the body is subjected to a non-circadian (24-hour) schedule. In simple terms, humans are not built to sleep during the day and work during the night. The area of the brain responsible for the regulation of human circadian rhythm is in the hypothalamus, more precisely the suprachiasmatic nucleus (SCN) (Sack et al., 2007). The SCN regulates sleep and alertness by secreting hormones such as melatonin and cortisol, both of which synchronize the body to a cycle of approximately 24 hours. This system is influenced greatly by environmental signals of the solar light/dark cycle (Sack et al., 2007), and this influence will in turn affect sleep quality and quantity for crew members. Over time, the end result is an accumulated lack of sleep that is difficult to overcome, especially under high workload conditions.

### 2. Lack of Sleep

Although difficulties with the quantity and quality of sleep an individual may experience are not always linked to circadian issues, the outcomes of lack of sleep must be considered from a manning perspective. Akerstedt (1990) has observed that accident rates increase, especially at night, where operators are experiencing sleepiness and other circadian effects such as hormone releases and digestive disruption. Some studies have even demonstrated that, following a waking state in excess of 17 hours, human performance can decrease significantly to the point of being equivalent to a blood alcohol concentration considered “legally drunk” in Canada (Dawson & Reid, 1997). This impairment applies both to cognitive capacities as well as motor skills. Shattuck and Matsangas (2015) have conducted an impressive amount of work studying sleep of real sailors operating in various conditions. They have demonstrated that crew members who exhibit poor sleep hygiene, such as sections on 5/10 non-circadian watch, performed significantly poorer on the Psychomotor Vigilance Test (PVT) (Shattuck et al., 2015). They have also shown that levels of sleep deprivation differ as a function of the type of watch schedule the sailors are maintaining. A combination of manpower, workloads, training, schedules, and task automations all contribute in some way to the quantity or quality of sleep each crew member aboard receives.

## E. WATCHSTANDING ON SHIPS

Watchstanding is an essential manning requirement for any underway surface ship. The main concept is that sailors on watch must be capable of maintaining vigilance and professionalism in order to ensure safety and operational effectiveness of the ship. An underway ship has various ongoing watch duties such as monitoring equipment on the bridge or providing weapon support for force protection, all of which are taking place 24 hours a day. There are numerous possible ways of configuring ship watch rotations both in the civilian and military worlds. The principal metric is the number of daily sections, which may vary from two to four depending on manpower levels. Although it may seem preferable to employ a higher number of sections to reduce the duration of all watch rotations, the decision is mostly supported by the number of qualified personnel onboard that can occupy the stations.

Even though it is one of the most common watch schedules, the three-section 5/10 (five hours on watch, ten hours off) has been shown problematic with regards to sleep and fatigue. Research has shown promising results with the use of 3/9 and 6/18 rotations exhibiting markedly better sleep hygiene and PVT performance (Shattuck et al., 2015).

## F. SCORE

The Simulation for Crew Optimization and Risk Evaluation is a tool developed by DRDC Toronto that was intended for use by the Future Fleet team of the Directorate of Naval Personnel and Training (D Nav P&T) and the Assistant Deputy Minister (Materiel) Project Management Offices to evaluate potential crewing options (Lamb et al., 2018). Traditionally, crew modeling using SCORE has been based on guidelines, policies, procedures, orders, and subject matter expertise along with a number of assumptions regarding how work will be conducted on the ships. A ship's SCORE model consists of: (1) a crew manifest of all of the people aboard with their ranks, qualifications, and occupations; (2) lists of all activities the ship is expected to perform, a priority level of each activity, and the roles required to perform each of those activities; (3) an assignment matrix of which crew members will perform each of the activity roles (watch and station bill); and (4) a scenario of when the ship will perform each activity. The output of a SCORE crew validation includes the following: (1) usage rates of individual crew members (average daily hours on duty); (2) the amount of time crew members perform the activities scheduled in the scenario; (3) the number of crew members performing each activity; (4) the number and duration of roles of activities that are not performed in a scenario because higher priority level activities have superseded them; (5) the number and duration of conflicts that occur when crew members are assigned to two roles of the same priority level at the same time; and (6) the number of off-duty periods (breaks) and the duration of the shortest and longest break for each crew member per scenario day (Lamb et al., 2018). The software has been constantly updated as work was being conducted on existing and future ships for the RCN. The main limitation of the tool is that it is deterministic and has no stochastic implementation according to a 2018 report by Lamb et al.

## G. IMPRINT PRO FORCES

The Improved Performance Research Integration Tool (IMPRINT) Pro is a human performance modeling tool that was developed by the U.S. Army Research Laboratory, Human Research & Engineering Directorate (ARL-HRED) to support Manpower and Personnel Integration (MANPRINT) as well as Human Systems Integration (HSI) (Alion, 2018). Alion's user guide explains further that IMPRINT's engine is based on Micro Saint Sharp, which is a discrete event task network modeling language, both of which have been produced by Alion Science and Technology (after they acquired Micro Analysis and Design). Discrete event simulation can be described as a method of simulating the behavior and performance of a real-life process, facility, or system (Allen et al., 2015). This method allows someone to model the system as a series of "events" that logically occur over time with the assumption that the system does not change between events (Allen et al., 2015). In other words, events are simulated chronologically, and these events have effects on the system as a whole. IMPRINT was initially conceived and used by the U.S. Army to simulate workloads in order to estimate manpower requirements and human performance. The latest pro version of the tool has been put to use by all DOD services thanks to its expanded capabilities (U.S. Army, CCDC Data and Analysis Center, 2019) IMPRINT pro is composed of four different modules that can be used independently or in conjunction. These modules are: the Mission, Equipment, Warfighter, and Forces modules. These modules contain different levels of data that cover tasks, equipment, qualifications, manning, schedules, etc. IMPRINT Pro allows for the creation three different types of models (operations, maintenance, and forces). The operations model is used to develop a network of tasks that is built into an operator's workload. Task completions over a given time frame can predict mission success rates. The maintenance model allows someone to generate predictions of maintenance outcomes by modeling manpower and readiness alongside scenarios, systems, and repair tasks. The forces model takes the analysis one step further by providing predictions of multilevel manpower requirements for a crew composed of diverse positions and roles. The end result is a manpower prediction that takes into account routine and unplanned events that must be completed by the unit (Alion, 2018).

Since its initial release, different versions of IMPRINT have been used in a wide variety of applications. Successful studies and research initiatives using IMPRINT have been conducted on subjects such as performance effects of clothing, equipment, and aircrew life support equipment on Army aviators (Salvi, 2001), stressor effects on performance of users in a moving vehicle (Wojciechowski, 2007), crew workload levels in unmanned aerial vehicle operations (Hunn & Heuckeroth, 2006), tank crew individual workload levels (Mitchell, 2009), and even hospital staff mental workload (Maxheimer, 2016). Modeling efforts using IMPRINT Pro for Navy ship and crew assessments are a recent application and have shown promising results. An initial report developed a methodology and concept model using IMPRINT Pro Forces for planned and unplanned events aboard the LCS using current manning levels (Shattuck & Matsangas, 2015). The second phase of the project helped further develop the IMPRINT software and present a proof of concept by modeling the outcomes of three different crew sizes for an underway LCS (Hollins & Leszczynski, 2014). Lastly, the final part of the three-phase project built upon the previous efforts to refine the LCS IMPRINT Pro Forces model and assess variations in crew and types of unplanned events (Meredith, 2016). Although it has been suggested, using this modeling methodology for ships that have not yet been built has not been done to the author's knowledge.

Furthermore, a number of plug-ins are available to include additional metrics in an analysis. Examples of such plug-ins are combat damage, sleep and fatigue, and sea state, among others. These plug-ins have not been included in the context of this study.

## H. OTHER MANPOWER/WORKLOAD MODELING TOOLS

Other modeling and simulation efforts have taken place, focusing on existing navy ships. Modeling with the Arena simulation package based on the Arleigh-Burke class destroyer used work backlog of tasks and sailor utilization rates to generate manpower requirements as an alternative to the currently established process (Carlton, 2012). It is suggested by Carlton (2012) that the method described in this thesis could be applied to manpower determination for ship classes yet to be built.

A thesis from Virginia Polytechnic Institute and State University used a manning task network analysis tool (ISMAT, Integrated Simulation Manning Analysis Tool, Micro Analysis and Design) to determine optimal crew size while taking into account equipment, maintenance practices and automation levels. The model was based on the documentation and available data for a CG-47 class ship (Scofield, 2006). The methodology is complex and labor intensive and demands deep knowledge of the software being used. A more recent effort using ISMAT for manpower determination of a small guided missile destroyer was also published (Velez, 2014).

Ultimately, the software that was selected for this thesis was IMPRINT Pro (Forces module) for a few key reasons. In-house students and faculty members at the Naval Postgraduate School (NPS) were knowledgeable and experienced with the tool, which made guidance and assistance readily available. A number of guides, tutorials, and aids were readily available as was a recent copy of the software itself. IMPRINT Pro is a more modern software package with an interface that is more user friendly and has a lesser learning curve compared to Arena or ISMAT. Lastly, a three-phase project from NPS on the LCS (Shattuck & Matsangas, 2015), producing two theses, used IMPRINT Pro to model the ship's crew. These theses were leveraged in conducting this study.

## I. TASK ANALYSIS

In order to build a model and run simulations of any workforce operations, some level of analysis is necessary to adequately understand and realistically include task characteristics within the modeling software's parameters. Task parameters may include the sequence of manipulations performed, the tools used, the duration of all parts of the task, and even the worker's thought process during execution. Numerous tools, techniques, and methods exist today to enable various levels of task analyses within the different types of work environments we may encounter. Kirwan and Ainsworth (1992) have created an extensive list of task analysis techniques that can be used, depending on resources availability, time commitment, and level of fidelity needed. Some types of analyses are also not suitable for certain types of work, which is one reason for the wide variety of techniques presented by these authors. As a simple example, observing workers, be it in person or on video, while they sit at a workstation screen pressing buttons does not convey any information on thought process or provide insight as to why they are using a given sequence. On the other hand, techniques such as walkthroughs and talkthroughs give workers the opportunity to explain their reasoning to the observer in much greater detail. The authors included “computer modeling and simulation” as one of the listed techniques by which worker activities are represented by running a number of simulations, which allows observers to estimate cycle times and error likelihoods. Although there is no mention of it in Kirwan and Ainsworth’s publication, when modeling a real-world workforce, some form of job assessment or task analysis is needed in order to build a realistic simulation. Ideally, an investigator would physically be on location at the workplace to collect data by using techniques such as activity sampling, observations, and discussions with operators, while possibly conducting interviews or administering questionnaires. Limitations of resources or time constraints often limit this type of approach. This thesis work was accomplished by using previously existing data collected by researchers aboard underway ships, and no traditional technique or method of task analysis was used in building the models. Due to the type of higher organizational level modeling that the IMPRINT Pro Forces module creates, there are no details of manipulations or of precisely what a worker is doing when undertaking a task. Data needed for a forces model include job positions, roles, daily schedules, and total durations for time spent by the whole team assigned to a task. For this reason, all model inputs were extracted from existing documents, such as the ship’s standing orders (Royal Canadian Navy, 2014), the Watch and Station Bill, and sailor activity tracking reports (Exercise SPARTAN WARRIOR 16). In order to further refine model inputs and confirm the level of realism, interviews were conducted with RCN SMEs to review the data, given that this opportunity would have otherwise taken place during an onboard ship task analysis.

The NAF and equivalent RCN approach are intended to maintain sailor workloads at a manageable level. Sleep deprivation is a serious concern considering the negative health and performance impacts on workers, which are aggravated by shift work and watchstanding. A series of tools have been developed over the years in an effort to assess risks related to worker workload and rest. Data on workload and sleep hours aboard Canadian combat ships are available in the literature and can be used as inputs in a model. Initial hypotheses for the outputs of an IMPRINT Pro model of a Halifax-class crew are that some sailors, departments, and schedules will experience sleep deprivation and increased working hours. It is also hypothesized that watchstanders will be more severely impacted than departmental workers across the simulations. Lastly, a third hypothesis is that some activities and events will experience failures, delays, and interruptions. There are numerous steps needed in order to build an IMPRINT model, all of which are detailed in the following chapter.

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# III. METHODOLOGY

## A. METHODOLOGY OVERVIEW

The overall goal of this thesis is to inform ship acquisition decision makers within the Royal Canadian Navy and Department of National Defense (DND) about a tool that gives insights into manpower considerations aboard an underway Canadian combat ship. Specifically, the IMPRINT models generated provide estimates and predictions of various job positions, MOS, and departments resulting from various types of operational activities. In order to attain this objective, three different ship crew models were created to reflect varying scenarios and levels of events. Initially, a baseline model was built to include only planned activities that take place as normal day-to-day work aboard the ship for a crew of 217 sailors. This model also included unplanned but expected events such as corrective maintenance as well as non-daily activities such as specific drills. The second model included all the planned activities and expected unplanned events from the baseline model with the addition of "mishaps" such as fires, floods, man overboard, and other emergencies. This simulation's output allowed for identification of crew members that experienced high workloads, extended on-duty hours, and reduced sleep hours, and also provided activity failure rates. This chapter covers all the steps and data input details that went into creating these models in the IMPRINT Pro Forces module.

## B. MODEL OBJECTIVE

The models we developed using the IMPRINT Pro Forces module were created in order to answer the following questions: Can the current crew of 217 aboard a Halifax-class combat ship satisfactorily complete all planned and unplanned events while on a notional mission of ten days at sea? Which job positions, MOS, and departments are expected to experience the heaviest workloads and, consequently, its sailors reduced sleep?

## C. SUBJECT MATTER EXPERTS ENGAGEMENTS

Given the model's need for precise and specific data regarding combat ship operations, support from SMEs was crucial to ensure model inputs were realistic and operationally valid. RCN members who possess current or prior operational experience at sea were contacted via email, phone, and online teleconference to comment on IMPRINT Pro Forces inputs and parameters. Interviews and discussions took place regarding sailor schedules (per department and watch status) as well as regarding task and event parameters (frequency, duration, number of sailors involved, and qualifications needed). This was necessary to ensure that all inputs and conditions did not go against the way real operations on an underway ship take place.

## D. APPARATUS

The following section lists and describes all software and equipment that were used while building the models as well as during the processing and analysis of the data.

### 1. IMPRINT Pro Forces Module

The modeling software used was IMPRINT Pro version 4.6.54.0, specifically the Forces module, to include the whole crew of 217 sailors. This module includes sub-sections for activities (both planned and unplanned), jobs or positions, schedules, a task prioritization matrix (Activities Trump Matrix), and job roles or qualifications.

### 2. Datasets

For the purpose of building spreadsheets prior to data input into IMPRINT Pro, Microsoft Excel 2016 version 16.0.4939.1000, 64-bit was used to organize, sort, and edit all relevant information for the two models being designed. Because numerous runs of the model were needed and because outputs of IMPRINT Pro are compatible with Excel, the latter was also used to compile and further analyze the spreadsheets generated by each model. To overcome the limitations of the maximum number of rows (1,048,576) in Excel and perform statistical calculations on large datasets, JMP Pro 15 version 15.1.0 was used for the final analysis.

### 3. Hardware

An Acer Spin 7 personal laptop running Windows 10 was used to design and build all spreadsheets and ship crew and scenario data inputs. The laptop was also used as the communication hub for emails and teleconferences with thesis advisors and participant SMEs. A second stand-alone and off-network Dell Latitude laptop was used to house the IMPRINT Pro software and input all data points that were saved into an ".imprint" proprietary format file. Lastly, a more powerful desktop computer was intended to be used to run 1,000 iterations of each of the ship models created.

## E. MODEL DEVELOPMENT

This section provides an overview of the two models being developed for this study as well as a description of the inputs used as parameters for both models. Lastly, a detailed description of all the steps needed to build an IMPRINT Pro Forces model is provided in sequence.

### 1. IMPRINT Models Overview

We developed two models. The first (baseline) model included all daily planned activities (eat, sleep, train, work, etc.), as well as expected/regularly occurring unplanned events such as drills and flight stations. This represented a "best case" scenario where everything went essentially according to plan. The model included data for 217 crew members of a Halifax-class Canadian combat ship for a period of ten days underway.

The second model was built upon the first by including rarely occurring unplanned events, e.g., floods, fires, man overboard, and evolutions (rather than drills). This was used as a representation of a challenging series of events that would demand more work and manpower to successfully accomplish. As in the basic model, the second model included data for 217 crew members of a Halifax-class Canadian combat ship for a period of ten days underway.

These two models were directly compared to assess the impacts of added events and mishaps on the metrics of interest. Focus was aimed at observing shifts or continued trends for planned maintenance hours, time on duty, sleep, and unplanned event failures, delays, or interruptions. This was done by observing sailors individually and grouped by department or schedule (departmental and watch/non-watch)

### 2. Model Inputs

The data used to generate the models was extracted from one main source and later supplemented by SME comments and inputs. The bulk of the Halifax-class ship and crew information was taken directly from the Watch and Station Bill (WSB) that was finalized following the completion of the X-ship SCORE study by DRDC Toronto (Lamb et al., 2018). These researchers made corrections to a pre-study WSB in order to reflect the true composition and characteristics of the crew onboard. This WSB included all 217 crew members, their job, rank, MOS, section of the ship, type of schedule, and roles/responsibilities/qualifications according to ship evolutions, tasks, and events. This detailed spreadsheet was in line with the ship's flex for this exercise at sea, meaning it included all the tasks, drills, and evolutions that were planned for the 10-day underway duration.

A snapshot of the final post-study WSB for the Halifax-class ship during the 2016 X-ship exercise is shown in Figure 2. This document indicates whether personnel are on one of the watch schedules, the position they occupy, department, MOS, and rank and lists the roles in columns that correspond to ship evolutions or levels of readiness. Sailor roles will shift as a function of the situation or activity taking place.

| | B | C | D | E | F | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Watch | Position | Department | MOSID | Rank | 2nd Degree of Readiness | | OOW | | | After Section Base Team |
| 2 | | | | | | Port | Stbd | Blue | Red | White | |
| 3 | NOT SET | A/MSEO | MSE | MS ENG | Lt(N) | Departmental: A/MSEO | Departmental: A/MSEO | | | | DC COMMS ASB |
| 4 | NOT SET | ACCTS SUPR | Logistics | SUP TECH | PO1 | Departmental: Supply Tech PO1 | Departmental: Supply Tech PO1 | | | | |
| 5 | STARBOARD | ACOUSITC OP | Combat | SONAR OP | LS | | ACOUSTIC OP (MON SPS) | | | | FIREFIGHTER ASB |
| 6 | PORT | ACOUSTIC JR SUPR | Combat | SONAR OP | MS | ACOUSTIC JR SUPR (MON TASSUP) | | | | | |
| 7 | STARBOARD | ACOUSTIC JR SUPR | Combat | SONAR OP | MS | | ACOUSTIC JR SUPR (MON TASSUP) | | | | |
| 8 | PORT | ACOUSTIC OP | Combat | SONAR OP | LS | ACOUSTIC OP (MON SPS) | | | | | |
| 9 | STARBOARD | ARMAMENT MAINTAINER | CSE | W ENG TECH | MS | | MS W Eng (Armament) | | | | |
| 10 | STARBOARD | ARRO | Combat | NCI OP | LS | | TRACK SUP | | | | FIREFIGHTER ASB |
| 11 | STARBOARD | ARRO | Combat | NCI OP | LS | | ARRO | | | | Firefighter 7 ASB |
| 12 | PORT | ASPO | Combat | NCI OP | AB | ASPO | | | | | Firefighter 8 ASB |
| 13 | STARBOARD | ASPO | Combat | NCI OP | LS | | ASPO | | | | FIREFIGHTER ASB |
| 14 | PORT | ASSISTANT IS ADMINISTRATOR | Combat | NAV COMM | MS | CISN Sup | | | | | |
| 15 | NOT SET | ASSISTANT IS ADMINISTRATOR | Combat | NAV COMM | MS | Departmental: IS ADMINISTRATOR | Departmental: IS ADMINISTRATOR | | | | |
| 16 | STARBOARD | ASST CBM | Deck | BOSN | PO1 | | POOW | | | | |
| 17 | NOT SET | ASST CSE OFFR | CSE | NCS ENG | SLt | Departmental: A/CSE O | Departmental: A/CSE O | | | | |
| 18 | PORT | ASWO | Combat | MARS | Lt(N) | ASWD | | | | | |
| 19 | PORT | AWWD | Combat | NES OP | PO1 | SWC | | | | | |
| 20 | STARBOARD | AWWO/SWC | Combat | MARS | Lt(N) | | SWC | | | | |
| 21 | PORT | BOSN MATE | Deck | BOSN | AB | Bosnmate | | | | | |
| 22 | NOT SET | BOSN MATE | Deck | BOSN | LS | Departmental: MESSMAN | Departmental: MESSMAN | | | | |
| 23 | NOT SET | BUFFER | Logistics | COOK | MS | Day: Cook 2 MS | Day: Cook 2 MS | | | | |
| 24 | NOT SET | BWK | Combat | MARS | SLt | | | | 2OOW | | |
| 25 | NOT SET | BWK | Combat | MARS | SLt | | | | | 2OOW | |
| 26 | NOT SET | BWK | Combat | MARS | SLt | | | 2OOW | | | |
| 27 | PORT | C4I JNR SUPR | Combat | NCI OP | MS | C4I MGR | | | | | |
| 28 | STARBOARD | C4I JNR SUPR | Combat | NCI OP | MS | | C4I Mgr | | | | |
| 29 | PORT | C4I TRACKER | Combat | NCI OP | OS | C4I TRACKER | | | | | |
| 30 | STARBOARD | C4I TRACKER | Combat | NCI OP | AB | | C4I TRACKER | | | | |
| 31 | NOT SET | CHIEF BOSN MATE | Deck | BOSN | CPO2 | Departmental: CBM | Departmental: CBM | | | | |
| 32 | NOT SET | CHIEF ENGINEER | MSE | MAR ENG | CPO2 | Departmental: C Eng | Departmental: C Eng | | | | |
| 33 | NOT SET | CISN MANAGER | Combat | NAV COMM | PO1 | Departmental: Nav Comm PO1 | Departmental: Nav Comm PO1 | | | | |
| 34 | PORT | CISN OPERATOR | Combat | NAV COMM | LS | CCR | | | | | |
| 35 | PORT | CISN OPERATOR | Combat | NAV COMM | LS | CCR | | | | | |
| 36 | STARBOARD | CISN OPERATOR | Combat | NAV COMM | LS | | CCR | | | | |
| 37 | PORT | CISN SUPERVISOR | Combat | NAV COMM | PO2 | CISN Admin / Watch supr | | | | | |
| 38 | STARBOARD | CISN SUPERVISOR | Combat | NAV COMM | PO2 | | CISN Admin / Watch supr | | | | |

Figure 2. Snapshot of X-ship, Halifax-class WSB

Inputs to the IMPRINT Pro models required deep knowledge of underway shipboard activities, which were not all extractable from WSB alone. RCN SMEs were interviewed, and discussions took place to better frame the planned activities and unplanned events to include duration and timing of each occurrence. The information, once compiled, was submitted to Halifax-class from the RCN.

### 3. IMPRINT Pro Forces Model Design

The IMPRINT PRO Forces model for the Halifax-class was created by following the process determined by Meredith (2016), which consists of: (1) defining unit of interest, (2) developing a list of jobs, (3) assigning roles to jobs, (4) developing the list of planned activities, (5) developing the list of unplanned events, (6) setting the Activities Trump Matrix, (7) defining the schedules for the jobs and planned activities, and (8) defining the parameters for the unplanned events.

(1) Defining the force unit, the entire crew of 217 of the X-ship Halifax-class Canadian combat ship was based entirely on the previously mentioned WSB for Model 1 and Model 2.

(2) Defining the list of jobs was accomplished by extracting the "position" column, which is equivalent to a billet title, from the WSB. The list had duplicates of jobs and jobs that were further specified to one section of the ship, all of which were included to add up to 217 individual sailors. A number was added to job duplicates, for example, boatswain mate 2, but assignments to ship sections were removed. Jobs included covered both enlisted members and Officer positions.

(3) In the WSB each position (or job) has associated roles that correspond to degrees of readiness, evolutions, response teams, etc. Each position has a variety of roles and each role can be filled by more than one specific position/sailor. This allows the IMPRINT Pro software to determine which roles and responsibilities each individual job position must cover for all tasks and events aboard the ship, be they planned or unplanned. Figure 3 lists a small portion of all possible job roles in the models. In the IMPRINT Pro Forces module, the list of job roles appears on a horizontal axis next to the list of 217 jobs. This allows for check marking all roles that correspond to each of those jobs since a specific role can be found in many different jobs. If a task or event in the model demands a minimum number of sailors who have a specified set of roles, the software will select from the pool the individuals who have those roles checked next to their job name. An excerpt from the standalone job list is shown in Figure 4.

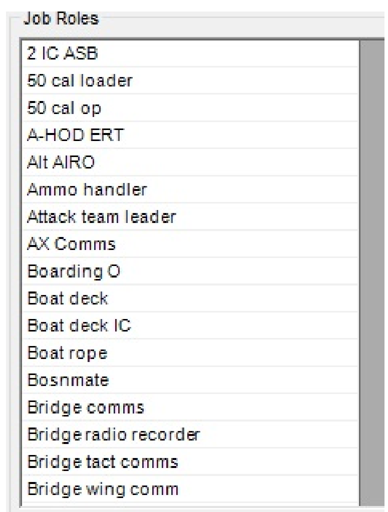



Figure 3. Snapshot of job roles list


Figure 4. Snapshot of Halifax-class job list

(4) Planned activities are created to simulate events that will take place during the ten days underway. These activities will happen daily at different times, with start and end times, but not all activities will take place for everyone onboard the ship depending on their job and position. These are more standard events such as watch-standing, training, eating, and sleeping as shown in Figure 4. This can be considered the business as usual, daily routine, where no mishaps or unexpected situations occur. These tasks are listed individually under the Activities tab of IMPRINT Pro and they are used to build all the model's schedules. A small calendar icon, as seen in Figure 5, indicates which activities are planned.

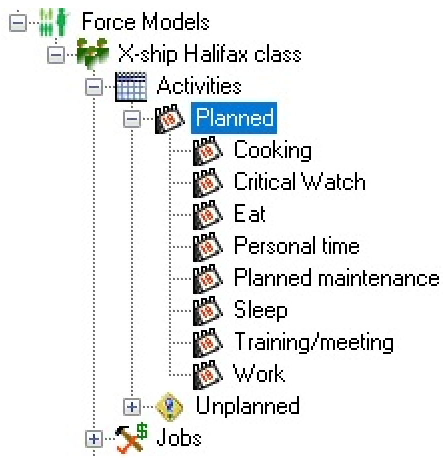



Figure 5. Planned activities

Two parameters are included for each of the planned activities. A “sleep activity” toggle must be set to either true or false, and this sets a special flag on any given activity. The purpose of this function is to tell the IMPRINT Pro software that only the simulated sailors who have had the most sleep shall interrupt this specific activity to go handle any unplanned event that occurs, given that they have the proper job role/qualifications to do so. This setting was set to “True” only for the “Sleep” planned activity, meaning that among the qualified sailors who were asleep at the time an unplanned event took place, the most rested would respond first (Alion, 2018). Setting any other planned activity as sleep would create an unrealistic situation where only the most rested crew members would drop work or eating, for example, to respond to an unplanned event. Lastly, a priority ranking number must be set in order to fit the planned activity in the Activities Trump Matrix (see step 6).

(5) Unplanned events are listed using the events scripted in the X-ship flex document from the 2016 study (Lamb et al., 2018) and augmented with additional issues such as corrective maintenance and mishaps that must be addressed by the crew. The full list of these events is shown in Figure 6. Although the term “unplanned” is used, there are in fact two types of events present in this list. Some activities, such as drills, are in fact planned, but they are not on a strict schedule, nor do they occur daily. For example, some drills may take place twice a week but not on a specific day and not within a certain time-

of-day window. This allows the ability to add variability and some randomness to the models, even if the activity was technically planned on the ship's schedule. Other events, such as a fire or flood, are truly random and unexpected, as would be the case while underway on a real ship. These specifics, such as frequency of occurrence, are developed in step 8 of the process.

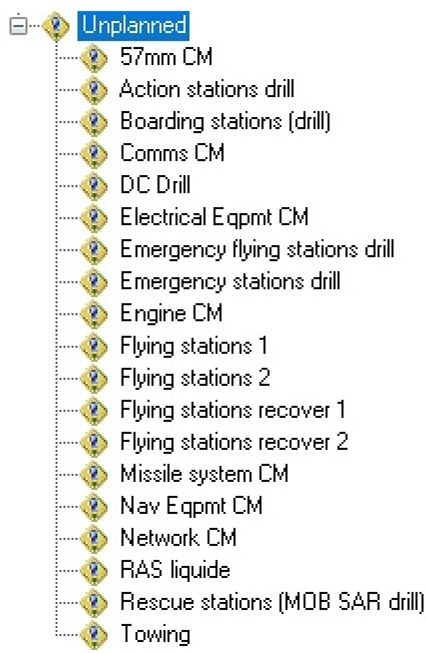



Figure 6. Unplanned events and activities

(6) The Activities Trump Matrix is generated in order to include priorities for all events both planned and unplanned. This is needed to address simultaneity of tasks where the software must be told which tasks must be completed first. This ensures that simulated sailors take care of a fire before conducting maintenance, as would be the case in the real world. The list in Figure 7 includes all planned and unplanned events with their corresponding priority rankings.

| Priority | Name | Type |
|---|---|---|
| 1 | Critical Watch | Planned |
| 4 | Electrical Eqpmt CM | Unplanned |
| 5 | Network CM | Unplanned |
| 6 | Comms CM | Unplanned |
| 8 | 57mm CM | Unplanned |
| 9 | Missile system CM | Unplanned |
| 10 | Engine CM | Unplanned |
| 11 | Nav Eqpmt CM | Unplanned |
| 19 | RAS liquide | Unplanned |
| 20 | Flying stations 2 | Unplanned |
| 30 | Flying stations 1 | Unplanned |
| 40 | Flying stations recover 1 | Unplanned |
| 50 | Flying stations recover 2 | Unplanned |
| 120 | Towing | Unplanned |
| 160 | Boarding stations (drill) | Unplanned |
| 162 | Action stations drill | Unplanned |
| 164 | DC Drill | Unplanned |
| 170 | Rescue stations (MOB SAR drill) | Unplanned |
| 190 | Emergency stations drill | Unplanned |
| 200 | Emergency flying stations drill | Unplanned |
| 220 | Eat | Planned |
| 230 | Planned maintenance | Planned |
| 240 | Cooking | Planned |
| 250 | Work | Planned |
| 260 | Training/meeting | Planned |
| 270 | Sleep | Planned |
| 280 | Personal time | Planned |

Figure 7. Activities Trump Matrix

All crew members are occupying one of the planned activities listed here at any given point in time around the clock. Unplanned events that occur will then pull away the necessary workers from other activities, planned or unplanned, having a higher number (i.e., lower priority) to fill the positions. Workers will return to their regular planned schedule once the unplanned event is completed or canceled. These numbers may be set directly in the matrix or within the parameters of each planned and unplanned event, where values remain identical in both places, no matter which one is modified.

(7) The schedules mentioned at step 4 must be built for each watch section, departmental day worker, and for more specific jobs such as cooks. Individual planned activities such as eating, sleeping and working that were created previously must be inserted into these schedules. Figure 8 shows the list of all schedules included in the

models. Figure 9 presents an example of a watchstander schedule. All schedules last 24 hours total and are repeated unchanged for each day of simulation.

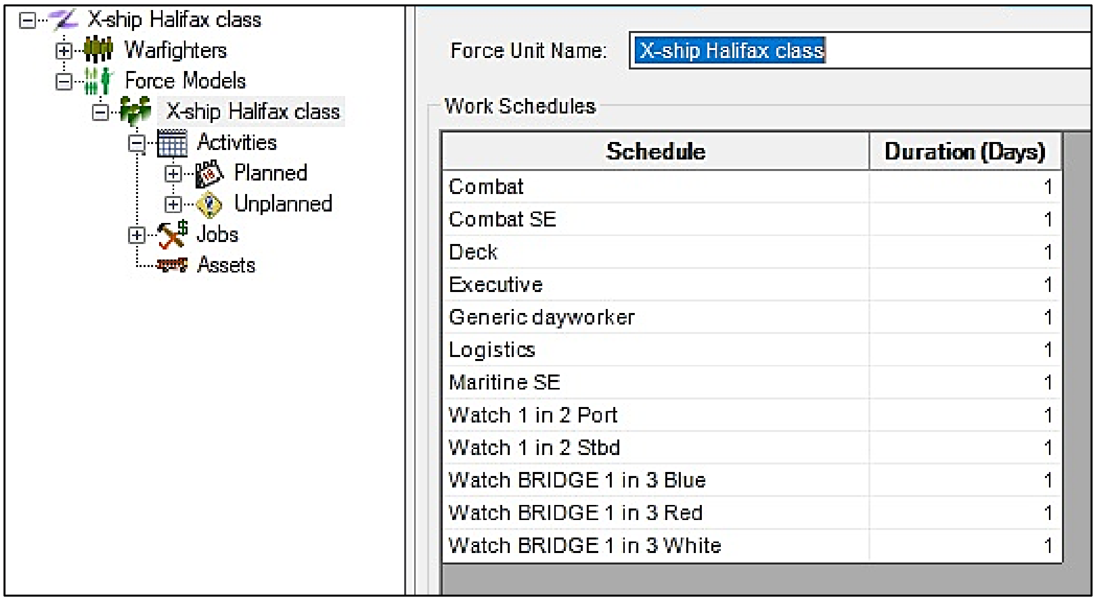
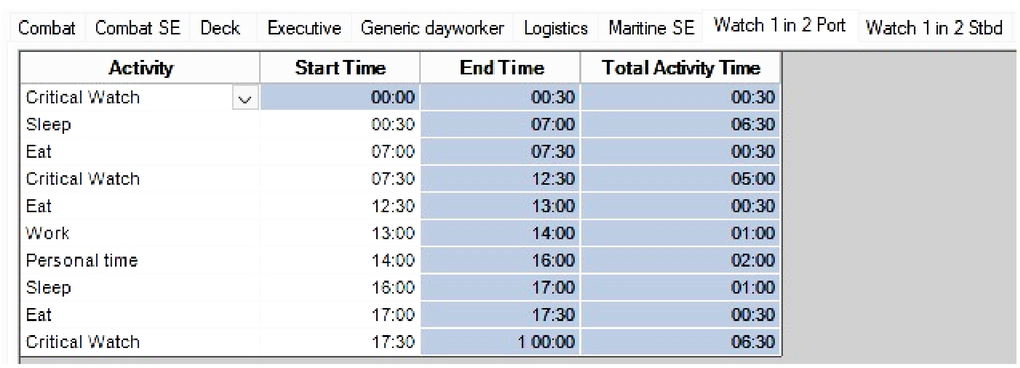



Figure 8. Snapshot of Halifax-class schedules




| Activity | Start Time | End Time | Total Activity Time |
|---|---|---|---|
| Critical Watch | 00:00 | 00:30 | 00:30 |
| Sleep | 00:30 | 07:00 | 06:30 |
| Eat | 07:00 | 07:30 | 00:30 |
| Critical Watch | 07:30 | 12:30 | 05:00 |
| Eat | 12:30 | 13:00 | 00:30 |
| Work | 13:00 | 14:00 | 01:00 |
| Personal time | 14:00 | 16:00 | 02:00 |
| Sleep | 16:00 | 17:00 | 01:00 |
| Eat | 17:00 | 17:30 | 00:30 |
| Critical Watch | 17:30 | 1 00:00 | 06:30 |

Figure 9. Watch 1 in 2 Port, daily schedule

These schedules were created based on 30-minute meals, three times a day, with at least one hour for personal time, and the watch rotation hours specified in the X-ship study (Lamb et al., 2018). All schedules, including departmental dayworker schedules, were presented to SMEs to ensure they were logical and plausible during real ship operations.

(8) Each unplanned event has a series of parameters that must be determined in order to ensure that the simulation includes them realistically. The IMPRINT Pro user guide (Alion, 2018) contains descriptions of all the parameters contained in this section. This includes the following categories:

1. Sleep Activity

This function is identical to the sleep activity toggle found in the planned activities covered in step 4. This ensures that IMPRINT Pro considers the crew members who are the most recently rested respond to unplanned events. This could apply to unplanned or somewhat random sleep such as naps when an opportunity arises. This aspect has not been modeled for this thesis.

2. Interrupt Strategy

An activity is flagged in one of three ways in this section; Resume, Restart or Abort. Selecting "Resume" implies that the activity will stop and restart where it left off once the crew resources become available once again. For example, if this task were to take 35 minutes to complete and was interrupted after 15 minutes, an additional 20 minutes would be needed to render the activity completed. In the same line of reasoning, "Restart" indicates that the activity cannot be "paused" and will take the full 35 minutes to complete once the sailors become available to return on this job. Activities with an "Abort" strategy are canceled altogether and considered to have missed their window of opportunity. Drills can fall into this category where they will only be completed on a subsequent day, if they can proceed uninterrupted.

3. Job Roles

This table contains the full list of job roles found in the model and can be considered somewhat analogous to a list of sailor qualifications. All unplanned events have a set of necessary roles (both in type and quantity) in order to complete the task. Two columns are used to distinguish the required job roles from the desired job roles. In other words, the former represents the minimum set of roles needed to complete the activity, while the later equates to the ideal or optimum number of roles when crew availability is not an issue at that point in time. This allows for some flexibility in manning any of the unplanned events, as is often the case aboard a real ship.

4. Adding Crew Members

Depending on the task and situation, adding crew members to an activity may reduce the time needed to complete the task. This parameter allows for inclusion of an effect on time when the "desired" number of sailors is present. Two options are possible: Either decrease time to completion proportionally to the number of additional members or decrease time by a specific percentage for each additional member. A final option allows for inclusion of a cut-off point "Maximum # of crewmembers" beyond which the move to add sailors gives no time reduction advantage. These options are displayed as "has no effect," "reduces Time Proportionally," and "reduces Time Somewhat." Given that determining the potential effects of additional crew is quite complex in the absence of real-world data, and that this may skew model outputs, it was decided to exclude this aspect from the models as a simplifying assumption.

5. Start

This property dictates the day and time when the activity will or can start. A fixed start time can be entered or one of many possible distributions such as log, normal, or discrete uniform may be used. Each distribution demands a range input such as a mean and standard deviation or a minimum/maximum value. Distributions allow for some level of randomness in start time while still controlling when the activity can or cannot debut.

6. Duration

This category is identical to the previous but applies to how long an unplanned event will last. Once again, this duration can be a fixed number that does not fluctuate, or randomness of how long an event lasts may be induced by using various distributions.

7. Cancel

A cancellation can be added to an activity to ensure that IMPRINT Pro does not continue indefinitely to try to pull the resources needed. If all crewmembers are not available at the start of the unplanned event, the software will check availability again at

15-minute intervals. The number entered as the cancellation time is in fact an interval originating at start time after which the activity will be flagged as “failed.” For example, setting cancel as 30 minutes would mean that IMPRINT Pro would check twice (at +15 and +30 minutes) for crew availability and then abort if the required roles are not reached.

8. Repeat

A check box allows the model builder to decide whether the activity will repeat or occur only once. If repeat is selected, this parameter gives the option of using a fixed interval since an activity’s last start time or using distributions to include randomness, as was the case for “start” and “duration” mentioned previously. For example, an activity can be set to repeat at the same hour every two days, or it can use a distribution that would repeat anywhere between two and four days.

9. Stop Repeat

For activities that were set as repeating, the software gives the ability to set a day and time beyond which the event will not occur. For example, the CO could decide that no drills would take place on the last day underway, which means that stop repeat would be set to 24 hours prior to the end time of the simulation. The following screen capture shows the interface that is displayed when an unplanned event is selected in IMPRINT Pro. All parameters are entered in this window and the tabs at the bottom toggle between the different time-based inputs that are either fixed or distribution based. Figure 10 shows the interface within IMPRINT Pro that contains all inputs for the unplanned events explained previously.

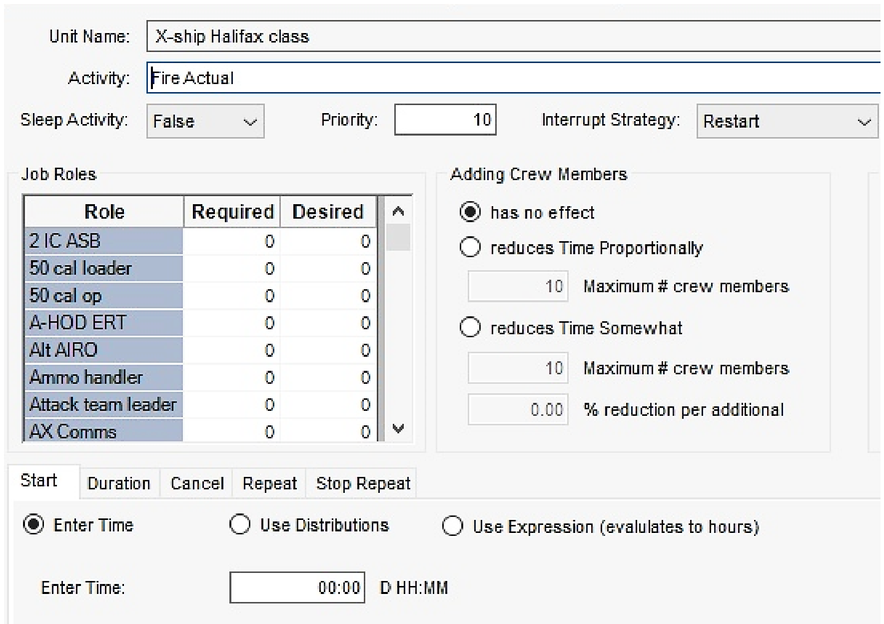



Figure 10. Parameters of an unplanned event

Table 3 shows the details of all the parameters that were set for all unplanned activities included in the baseline model. These inputs were prepared in Excel spreadsheets and reviewed by RCN SMEs prior to adding them directly into the IMPRINT model file.

## Table 3. Parameters of unplanned events

| Priority | Name | Interupt | Start | | Duration | | | Cancel | Repeat Interval | Data Source |
|---|---|---|---|---|---|---|---|---|---|---|
| 8 | 57mm CM | Resume | Discrete Uniform | | Triangular | | | 24 hrs | Exponential | Meredth, 2016 |
| | | | Min | Max | Mode | Min | Max | | 7 days | |
| | | | 0 | 20 days | 1 hr | 30 min | 4 hrs | | | |
| 162 | Action stations DRILL | abort | Fixed | | Triangular | | | 1 hr | Fixed | Lamb et al. 2018 |
| | | | day 5, 10:00 | | Mode | Min | Max | | 5 days | |
| | | | | | 1 hr | 55 min | 1hr20 | | | |
| 160 | Boarding stations DRILL | abort | Fixed | | Triangular | | | 1 hr | Fixed | Lamb et al. 2018 |
| | | | day 2, 13:00 | | Mode | Min | Max | | 2 days | |
| | | | | | 3 hrs | 1hr45 | 4hr20 | | | |
| 6 | Comms CM | Resume | Discrete Uniform | | Triangular | | | 24 hrs | Exponential | Meredth, 2016 |
| | | | Min | Max | Mode | Min | Max | | 3 days | |
| | | | 0 | 3 days | 15 min | 10 min | 2 hrs | | | |
| 164 | DC Drill | abort | Fixed | | Triangular | | | 1 hr | Fixed | Meredth, 2016 |
| | | | day 3, 10:00 | | Mode | Min | Max | | Every 5 days | |
| | | | | | 1h30 | 1h25 | 2 hrs | | | |
| 4 | Electrical Eqpmt CM | Resume | Discrete Uniform | | Triangular | | | 24 hrs | Exponential | Meredth, 2016 |
| | | | Min | Max | Mode | Min | Max | | 1 day | |
| | | | 0 | 1 day | 30 min | 15 min | 2 hrs | | | |
| 200 | Emergency flying stations DRILL | abort | Fixed | | Triangular | | | 1 hr | Fixed | Lamb et al. 2018 |
| | | | 1st day, 10:00 | | Mode | Min | Max | | 5 days | |
| | | | | | 30 min | 25 min | 35 min | | | |
| 190 | Emergency stations DRILL | abort | Fixed | | Triangular | | | 1 hr | Fixed | Lamb et al. 2018 |
| | | | day 2, 10:00 | | Mode | Min | Max | | 5 days | |
| | | | | | 1 hr | 55 min | 1hr15 | | | |
| 35 | Engine CM | Resume | Discrete Uniform | | Triangular | | | 24 hrs | Exponential | Meredth, 2016 |
| | | | Min | Max | Mode | Min | Max | | 7 days | |
| | | | 0 | 7 days | 1 hr | 30 min | 24 hrs | | | |
| 30 | Flying stations 1 | Abort | Fixed | | Triangular | | | 1 hr | Fixed | Meredith, 2016 + SME input |
| | | | 9:00 | | Mode | Min | Max | | daily | |
| | | | | | 35 min | 30 min | 45 min | | | |
| 20 | Flying stations 2 | Abort | Fixed | | Triangular | | | 1 hr | Fixed | Meredith, 2016 + SME input |
| | | | 12:30 | | Mode | Min | Max | | daily | |
| | | | | | 35 min | 30 min | 45 min | | | |
| 40 | Flying stations recover 1 | Restart | Triangular | | Triangular | | | 3 hrs | Fixed | Meredith, 2016 + SME input |
| | | | 11:00, 11:30, 12:00 | | Mode | Min | Max | | daily | |
| | | | | | 35 min | 30 min | 45 min | | | |
| 50 | Flying stations recover 2 | Restart | Triangular | | Triangular | | | 3 hrs | Fixed | Meredith, 2016 + SME input |
| | | | 16:00, 16:30, 17:00 | | Mode | Min | Max | | daily | |
| | | | | | 35 min | 30 min | 45 min | | | |
| 9 | Missile system CM | Resume | Discrete Uniform | | Triangular | | | 24hrs | Exponential | Meredth, 2016 |
| | | | Min | Max | Mode | Min | Max | | 7 days | |
| | | | 0 | 20 | 1 hr | 30 min | 4 hrs | | | |
| 11 | Nav Eqpmt CM | Resume | Discrete Uniform | | Triangular | | | 24 hrs | Exponential | Meredth, 2016 |
| | | | Min | Max | Mode | Min | Max | | 2 days | |
| | | | 0 | 2 days | 30 min | 15 min | 2 hrs | | | |
| 5 | Network CM | Resume | Discrete Uniform | | Triangular | | | 24 hrs | Exponential | Meredth, 2016 |
| | | | Min | Max | Mode | Min | Max | | 2 days | |
| | | | 0 | 1 day | 10 min | 5 min | 2 hrs | | | |
| 19 | RAS liquide | Restart | Discrete Uniform | | Triangular | | | 4 hrs | Fixed | Lamb et al. 2018 |
| | | | min | max | Mode | Min | Max | | N/A | |
| | | | day 4 07:30 | day 4 18:00 | 1h20 | 2 hrs | 2h40 | | | |
| 170 | Rescue stations (MOB DRILL) | abort | Fixed | | Triangular | | | 1 hr | Fixed | Lamb et al. 2018 |
| | | | **day 4, 13:00** | | Mode | Min | Max | | 5 days | |
| | | | | | 35 min | 30 min | 40 min | | | |
| 70 | Towing | Resume | Discrete Uniform | | Triangular | | | 2 hrs | Discrete Uni | Lamb et al. 2018 |
| | | | min | max | Mode | Min | Max | | day 5 and day 6 | |
| | | | day 1 | day 5 | 1 hr | 55 min | 3hr30 | | | |

Inputs to the unplanned events parameters comprise a combination of data from Meredith's thesis (2016) on LCS manpower and the SCORE validation study (Lamb et al., 2018) of a Halifax-class ship. For all Corrective Maintenance (CM) activities, the time data was extracted from the LCS thesis where the "duration" column effectively represents the mean time to repair (MTTR) of the system. The "repeat" column is analogous to the mean time between failures (MTBF), which represents how often, on average, the system breaks down. The distribution type selected for all CM event repeat intervals was the exponential distribution, since it is widely used and recognized as the way system failures occur (Sherwin & Bossche, 1993.) must include proper reference). Exponential distributions mean that, as time increases, the probability of failure becomes greater. All unplanned events included in the models used a triangular distribution for their durations. The rationale behind this decision was that distributions such as "normal," where an average and a standard deviation are entered, will occasionally present a behavior for which the duration of an activity is unrealistically short. For example, a drill or corrective maintenance task would only last seconds, since values approaching zero can be part of the distribution. To avoid these situations, the use of triangular distributions ensures that one-time duration happens most often (the mode) while a minimum and maximum give realistic limits at both ends of the spectrum. As was discussed with SMEs, activities will occasionally take slightly less time than usual to accomplish, as they can seldom take much longer to complete when problems arise. The use of the triangular distributions allows for the proper behavior of the simulation, which reflects real-world duration variations.

#### 4. Running the Models

All models were run for 1,000 replications using the Batch Execution module included with the IMPRINT Pro software package. Due to limited laptop processing power and gradual slowdown of output for large batches, two separate batches of 500 replications were generated per model. The second batch started at seed 501, following the final run seed of the previous batch. This also allowed the simulations to overcome the 999 executions limit of the Batch Execution application packaged with IMPRINT

Pro. Each simulation run uses a random seed number (RSN) that differs from the previous run in order to induce randomness in the stochastic elements of the models. In other words, the RSNs are necessary for parameters such as time to create variations within their respective ranges or distributions. The batch module starts the first simulation run at the RSN entered by the user in the settings section of the execution tab of IMPRINT Pro. The subsequent runs use a different RSN by increasing by increments of one until the entire batch is generated. For each simulation run, IMPRINT creates a folder that contains a file with a proprietary extension (.imprint) that can be accessed through IMPRINT to generate a number of Excel spreadsheets containing the model's data. This can only be done by hand and individually, however, which presents a serious issue when dealing with hundreds of simulations. An extractor application was created using the Scala programing in support for a previous IMPRINT Pro based thesis (Meredith, 2016) to overcome this particular issue. Steve Upton from the Simulation, Experiments, and Efficient Design (SEED) Center at NPS created an updated version of this extractor, which allowed the efficient extraction of various data spreadsheets followed by a compilation of all simulation runs. The application's script created files containing comma-separated values (CSV) and applied further modifications to fix formatting issues and sorting. The last step of the extractor process was to concatenate values across 1,000 simulation runs into a single CSV file per spreadsheet type. In order to analyze each individual sailor's daily sleep and time on duty, as well as the failure rates of unplanned events, further manipulation of those concatenated files was necessary. This was accomplished by using lines of R programing language for statistical computing in order to delete superfluous rows of data, sum totals of remaining rows and sort or group values to obtain the metrics of interest mentioned in this section.

The IMPRINT files created following a simulation run provide data for time durations of all activity types as well the precise status of all unplanned events over the 10-day span of the simulation. The metrics of interest for this study include the percentage of unplanned events (including corrective maintenance) that were delayed, interrupted, or failed, the number of hours spent on preventive maintenance across the ship, as well as time spent sleeping versus time on duty for all individual sailors. "Time on duty" includes all activities, planned and unplanned, with the exception of eating, sleeping, and personal time. The IMPRINT output gives total durations over the course of the 10-day simulation rather than single-day numbers for all activity types. Post-processing of the simulation's raw data allows the user to isolate daily sleep duration per sailor, but this was not possible for unplanned events due to the way the software handles crossing the 24:00 line of any given day. The baseline model's time durations for sleep and time on duty were averaged for each sailor in order to compare them to the daily averages presented in Wang et al.'s (2017) study. The metrics mentioned were also analyzed and compared within the baseline model to assess differences between individual sailors, departments, schedules, and MOSs, as well as between the various unplanned events.

## F. BASELINE MODEL VALIDATION

Even with the best efforts put towards building a model, there is no guarantee that the simulation outputs of this model are realistic representations of real-world outcomes in a similar scenario and mission. An ideal method for validating the numbers obtained through simulation is to collect actual data at sea for all types of activities performed by the whole crew of a Halifax-class ship. This approach was unfeasible in the setting of this thesis, but adequate alternatives were available. Pre-existing studies have been performed underway aboard Halifax-class ships with a full crew of 217 onboard. One such study (Wang et al., 2017) captured time spent across activities, both on and off duty, over a 10-day duration for all ship departments. Although these studies were based on a full-scale exercise at sea that is not entirely analogous to this model's scenario, many of the drills and activities were equivalent as was the high tempo aspect of the daily work accomplished. A comparison of the model's outputs to the results of the study mentioned was performed in order to identify any glaring discrepancies. In addition, a "face" validity check was included in the validation process by sharing model outputs with RCN SMEs, allowing them to identify any results that seemed unrealistic with regards to real-world operations aboard a Halifax-class ship.

These steps were applied to the creation of two similar models of different activity intensities that provided outputs of performance metrics. Specifically, time on duty, sleep hours, and task outcomes (failures, delays, and interruptions) were compared. The detailed values of these metrics are shown and analyzed in the following section.

## G. AUGMENTED MODEL

The second model is designed to start with all parameters included in the baseline model but augmented with a number of actual mishaps and incidents rather than being composed of drills exclusively. An additional modification to the model is the boarding party drills that occurred every two days are now replaced by actual boarding that occurs daily on average (stochastic parameters allow for some days to be skipped and some to have two occurrences). All other baseline model parameters have remained identical. The parameters of the added unplanned events are presented in Table 4. As with the baseline model, parameters include the start time of the first occurrence, the duration, cancellation window, and repeat interval. The priority numbers have also been adjusted to reflect the urgency of these actual unplanned events in contrast to being only drills.

Table 4. Parameters of unplanned events for augmented model

| Priority | Name | Interupt | Start | | Duration (hrs) | | | Cancel | Repeat Interval | Data Source |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Discrete Uniform** | | **Triangular** | | | | Discrete Uniform | |
| **3** | Man overboard | Resume | **Min** | **Max** | **Mode** | **Min** | **Max** | **24 hrs** | 0-3 days | SME discussions + Lamb et al. 2024 |
| | | | 0 | 3 days | 0.5 | 0.75 | 1 | | | |
| | | | **Discrete Uniform** | | **Triangular** | | | | Discrete Uniform | |
| **5** | Helo crash actual | Resume | **Min** | **Max** | **Mode** | **Min** | **Max** | **24 hrs** | N/A | SME discussions + Lamb et al. 2023 |
| | | | 0 | 10 days | 1.5 | 1 | 2 | | | |
| | | | **Discrete Uniform** | | **Triangular** | | | | Discrete Uniform | |
| **7** | Large Fire actual | Resume | **Min** | **Max** | **Mode** | **Min** | **Max** | **24 hrs** | N/A | SME discussions + Lamb et al. 2021 |
| | | | 0 | 5 days | 4 | 3 | 5 | | | |
| | | | **Discrete Uniform** | | **Triangular** | | | | Discrete Uniform | |
| **9** | Flood actual | Resume | **Min** | **Max** | **Mode** | **Min** | **Max** | **24 hrs** | N/A | SME discussions + Lamb et al. 2022 |
| | | | 0 | 10 days | 4 | 3 | 5 | | | |
| | | | **Discrete Uniform** | | **Triangular** | | | | Discrete Uniform | |
| **11** | Action stations actual | Resume | **Min** | **Max** | **Mode** | **Min** | **Max** | **24 hrs** | 0-5 days | SME discussions + Lamb et al. 2020 |
| | | | 0 | 5 days | 1 hr | 55 min | 1hr20 | | | |
| | | | **Discrete Uniform** | | **Triangular** | | | | Discrete Uniform | |
| **13** | HAZMAT actual | Resume | **Min** | **Max** | **Mode** | **Min** | **Max** | **24 hrs** | 0-5 days | SME discussions + Lamb et al. 2018 |
| | | | 0 | 5 days | 2 | 1 | 4 | | | |
| | | | **Discrete Uniform** | | **Triangular** | | | | Discrete Uniform | |
| **20** | Small Fire actual | Resume | **Min** | **Max** | **Mode** | **Min** | **Max** | **24 hrs** | 0-5 days | SME discussions + Lamb et al. 2021 |
| | | | 0 | 10 days | 1 | 0.5 | 1.5 | | | |
| | | | **Discrete Uniform** | | **Triangular** | | | | Discrete Uniform | |
| **25** | Boarding stations | Resume | **Min** | **Max** | **Mode** | **Min** | **Max** | **24 hrs** | 12- 36 hrs | SME discussions + Lamb et al. 2025 |
| | | | 0 | 1 day | 3 | 1.75 | 4.33 | | | |

Results of this second model were compared directly to the baseline analysis by matching the median and Interquartile Range (IQR) values for all metrics for planned activities and unplanned events. This includes the percentages of completion for planned activities within an occupational group and the percentages of failures, delays, and interruptions or unplanned events. The durations of daily sleep and time on duty were submitted to a deeper analysis that allowed for teasing out the operationally significant differences between the two models.

In order to compare the average daily sleep time for each individual sailor between both models, data was paired per random seed number (RSN) from baseline and augmented model for all 217 sailors. The difference was then calculated per RSN to obtain the difference for each 1,000 replications of the models. Analysis showed that all but three sailors slept less in the augmented model compared to the baseline (paired sample Wilcoxon Signed Rank test, all $p<0.05$). A statistically significant difference, however, may not be important in terms of sailor performance or from an operational perspective. For this reason, a threshold was set to only consider sailors for whom the mean sleep reduction brings their median daily sleep duration below seven hours. If their baseline median daily sleep was already less than seven hours, only mean differences of 30 minutes or more are taken into consideration.

A nearly identical approach was used when comparing the average time on duty per individual sailor. Average daily time on duty at the individual sailor level was compared by matching pairs of the same replication RSN between the baseline and augmented models using the same statistical method. To once again address the issue of statistical significance versus the operational significance, a threshold of 30 minutes minimum was used to consider the mean difference for daily time on duty to be meaningful in the model.

# IV. RESULTS

In this chapter, we present the results of the baseline and augmented models following the analysis described in the methodology section. The first step was to use the main metrics that are sleep and time on duty from the baseline model and compare them to existing operational data, both at the individual level and within departments or schedules. The two models were then compared side by side to assess differences in completion of planned activities (watch, maintenance, and work), completion of unplanned events (failures, delays, and interruptions), and sleep durations and time on duty. A matched pairs analysis was conducted on the sleep and time on duty data at the sailor level to calculate mean differences between models. The analysis of these results was designed to shed light on our initial hypotheses regarding sleep, time on duty, and task completion. Specifically, the analysis aimed to confirm that specific sailors and departments have a higher workload and experience sleep deprivation, that watchstanders are more heavily burdened than sailors on other schedules, and that some activities will show increased failures, delays, or interruptions. Even though the baseline model serves as a best-case scenario for the ship's notional mission, some issues regarding sleep and time on duty have been identified in a few areas.

## A. BASELINE MODEL

The output of the baseline model for the 217-crew member Halifax-class ship has shown that some issues do stand out in this particular mission scenario, even when no unexpected events were part of the model's parameters. For each simulation run, IMPRINT Pro generates a table that includes a list of all unplanned events with total occurrences of delays, interruptions, and failures for each type over the 10-day simulation period. These numbers were compiled per simulation run to obtain rates of each status condition as a ratio against the total number of times a given activity was "scheduled" in a semi-randomized matter. These ratios where then compiled over 1,000 simulation runs to calculate median values of those ratios along with IQRs as seen is Table 5.

Failure rates for all activities, save one, have a median value of zero, meaning they were successful in the vast majority of simulation runs. That one exception was the afternoon flying stations (flying stations 2) that could not take place during one of the ten simulation days on average. This is due to conflicts with higher priority activities for some of the flying station's required crew members. Boarding station drills and rescue station drills, although showing a median value 0% failure rate, presented more variability with IQRs of 25% and 50%, respectively. To put this into perspective, boarding station drills failed at a rate between 25% and 28% in 302 of the 1,000 simulation runs. Rescue station drills were scheduled only twice per ten days, which implies that a single failure to complete the activity results in a 50% failure rate for a single simulation run. The relatively low priority of drills compared to other activities increases the likelihood that these types of activities may encounter a delay, interruption, or failure. Out of the 19 activities listed, 13 have a median value of 0% delays while the remaining activities have medians reaching 100% in some cases. This indicates that these activities were delayed at least once for every scheduled occurrence over a single 10-day simulation. A delayed activity may never start and result in failure or it may start later and subsequently succeed, be interrupted, or fail. The values for percentage of interruptions are calculated from only the number of activities that have started. In situations where a delay or interruption takes place, the activity will only count towards a failure if conditions do not allow it to start, restart, or continue the task to completion. Interruptions were seen as occurring frequently for drills given that their priority is quite low in the Activities Trump Matrix list. If any sailor required by the drill is needed elsewhere on a higher priority task and no other qualified sailor is available, the drill will be interrupted in favor of that task.

Table 5. Percentage of tasks that failed to complete, were delayed, and interrupted. Results presented as Median (IQR).

| Unplanned events | Tasks which failed to complete (%) | Delayed tasks (%) | Interrupted tasks (%) |
|---|---|---|---|
| 57mm CM | 0% (0) | 0% (0) | 0% (0) |
| Action stations drill | 0% (0) | 0% (0) | 0% (0) |
| Comms CM | 0% (0) | 0% (0) | 0% (0) |
| Emergency flying stations drill | 0% (0) | 0% (0) | 0% (0) |
| Nav Eqpmt CM | 0% (0) | 0% (0) | 0% (0) |
| Network CM | 0% (0) | 0% (0) | 0% (0) |
| Engine CM | 0% (0) | 0% (0) | 0% (33) |
| Towing | 0% (0) | 0% (0) | 0% (33) |
| Emergency stations drill | 0% (0) | 0% (0) | 0% (50) |
| DC Drill | 0% (0) | 0% (0) | 100% (50) |
| Electrical Eqpmt CM | 0% (0) | 0% (8) | 0% (0) |
| Flying stations 1 | 0% (0) | 0% (11) | 0% (10) |
| RAS liquid | 0% (0) | 0% (50) | 0% (0) |
| Flying stations recover 2 | 0% (0) | 9% (10) | 0% (9) |
| Flying stations recover 1 | 0% (0) | 9% (17) | 9% (17) |
| Missile system CM | 0% (0) | 50% (100) | 0% (0) |
| Boarding stations drill | 0% (25) | 100% (25) | 50% (50) |
| Rescue stations drill | 0% (50) | 100% (0) | 50% (0) |
| Flying stations 2 | 10% (10) | 11% (22) | 0% (11) |

The planned activities were close to their scheduled durations when averaged across respective schedules (either departmental or watchstander) with a few notable exceptions. All three types of watchstanders had their personal time available between 69% and 75%, which represents approximately 30 minutes less than their daily allotted two hours. The Maritime SE department managed to accomplish on average only 90% of the daily planned maintenance while other departments were at, or close to, 100%. Sleep was on average under 90% of the 8-hour initial input for the night cooking crew as well as the starboard watchstanders. There are two departments, Combat SE and Deck, which fell below 90% for completion of daily scheduled work with Deck sailors only completing 82% of their tasks. IQRs were fairly minimal for all other activities as seen in Table 6.

Table 6. Percentage of completed planned activities as per schedule. Results presented as Median (IQR)

| Occupational Group | Watch | Eat | Personal time | Planned maintenance | Sleep | Work |
|---|---|---|---|---|---|---|
| Combat | - | 97.7% (3.3%) | 99.8% (0.5%) | - | 99.4% (0.7%) | 90.6% (7.0%) |
| Combat SE | - | 96.5% (2.7%) | 95.6% (2.0%) | 96.6% (2.6%) | 96.0% (2.1%) | 88.6% (3.1%) |
| Day cooking | - | 98.7% (1.8%) | 100.0% (0%) | 100.0% (0%) | 98.9% (0.2%) | 95.4% (0.8%) |
| Deck | - | 95.3% (4.9%) | 100.0% (0%) | - | 98.8% (0%) | 81.5% (9.6%) |
| Executive | - | 99.6% (1.1%) | 100.0% (0%) | - | 99.6% (0.6%) | 96.9% (4.2%) |
| Logistics (day) | - | 99.8% (0.8%) | 100.0% (0%) | 100.0% (0%) | 99.4% (0.6%) | 90.6% (5.3%) |
| Maritime SE | - | 90.2% (8.7%) | 98.2% (2.8%) | 90.2% (11.2%) | 98.3% (2.3%) | 84.6% (8.5%) |
| Night cooking | - | 100.0% (0%) | 100.0% (0%) | 100.0% (0%) | 87.1% (5.1%) | 100.0% (0%) |
| Watch 1 in 2 Port | 99.8% (0.6%) | 96.8% (7.0%) | 68.8% (9.1%) | - | 97.8% (2.4%) | 92.6% (11.7%) |
| Watch 1 in 2 Stbd | 99.9% (0.5%) | 97.9% (2.9%) | 74.9% (0.5%) | - | 89.4% (3.4%) | 99.9% (0.6%) |
| Watch bridge | 98.9% (1.4%) | 95.3% (7.3%) | 70.2% (10.8%) | - | 99.5% (0.7%) | 92.6% (6.4%) |

Table 7 shows the number of hours of planned maintenance per department if no interruptions take place at any point during the 10-day simulation. This represents the best-case scenario regarding planned maintenance and served as the basis to determine the percentage of completion for the baseline model.

Table 7. Planned maintenance hours per department over ten days

| Department | Daily maintenance hours | Number of sailors on departmental schedule | Total maintenance hours per department |
|---|---|---|---|
| CSE | 2 | 4 | 80 |
| Day Cooking | 2 | 5 | 100 |
| Logistics | 2 | 21 | 420 |
| MSE | 2 | 18 | 360 |
| Night Cooking | 0.5 | 4 | 20 |
| TOTAL | - | - | 1020 |

The ship, across all departments, has 1,020 hours of maintenance scheduled over the course of a 10-day simulation. The resulting distribution of 1,000 simulation runs for total maintenance is shown in Figure 11, while the median values per department are listed in Table 8. The simultaneity of sailor roles and responsibilities combined with the priority levels of other tasks compared to planned maintenance priority results in reduced hours of that type of maintenance. Even at the most favorable simulation outcome, only 973 hours of maintenance occurred compared to the 1,020 hours planned as per the departmental schedules, resulting in a 5.6% loss. The worst culprit was Combat Maritime System Engineering, which managed to complete approximately 96% of all planned maintenance for the majority of simulation runs. IQRs show relatively low variability in median values within a department as well as ship-wide, across all simulations.

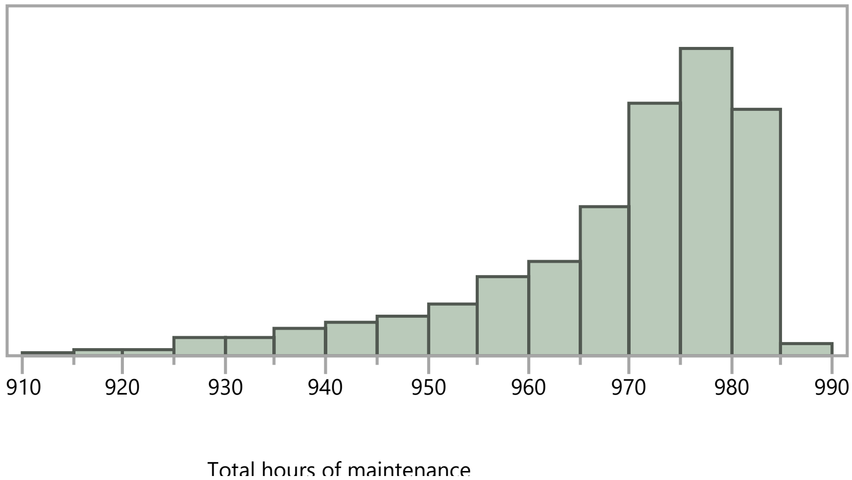



Figure 11. Ship-wide planned maintenance hours distribution (1,000 simulation runs)

Table 8. Completed planned maintenance by department during the 10-day period

| Sailors' departments | Median hrs (IQR) | % hours completed |
|---|---|---|
| Combat SE department | 76.7 (3.07) | 95.9% |
| Maritime SE department | 359 (7.74) | 99.7% |
| Day Cooking schedule | 100 (2.47) | 100% |
| Logistics | 420 (4.50) | 100% |
| Night Cooking schedule | 20.0 (1.66) | 100% |
| Total | 973 (14.5) | 95.4% |

Next, we calculated the median daily sleep for each sailor during the 10-day period of the simulation and the 1,000 runs. We compared the duration of daily sleep with the recommended duration of seven hours (Watson et al., 2015). Among the whole crew, 29 sailors returned no statistical test, given that they had eight hours of sleep at all times for all simulations. As shown in Table 9, 80.2% of sailors had at least seven hours of sleep daily on average while the remaining 6.5% of sailors had less than seven hours of sleep per day. The initially modeled sleep duration for all sailors was eight hours of sleep per day.

Table 9. Sailor distribution by daily sleep duration

| Sleep duration (Median hours/day) | Number of sailors | Sailors by Occupational Group |
|---|---|---|
| 8 | 29 (13.3%) | 1 in Bridge watch<br>5 in Combat Department<br>7 in Logistics<br>6 in MSE<br>10 in Port |
| 8–7 | 174 (80.2%) | 5 in Bridge watch<br>4 in Combat Department<br>4 in CSE<br>6 in Deck<br>6 in the Executive Department<br>22 in Logistics<br>14 in MSE<br>58 in Port<br>53 in Starboard |
| <7 | 14 (6.5%) | 1 in Logistics<br>2 in Port<br>12 in Starboard |

One trend that is clearly evident is that sailors on watch that have a 1-in-2 Starboard schedule are the worst off regarding the amount of sleep they get daily. Twelve (86%) out 14 sailors that had less than seven hours of daily sleep on average were on the Starboard schedule, and none of the Starboard crew members consistently had eight hours of sleep. This can be explained by a majority of “unplanned” events such as drills and evolutions occurring during the day, and if an insufficient number of sailors with the correct roles for the job as required is available, these day-sleeping members will be awakened. For this baseline model, all other schedules and departments experience an adequate seven hours of sleep on average with the exception of a junior CISN operator (Port schedule) and a steward (Night cooking schedule).

Next, we focused on time on duty. Specifically, we calculated the median time on duty for each sailor and classified sailors into four groups. The value of 11.3 hours on average for time on duty was based on an earlier study conducted aboard a Halifax-class ship (Wang et al., 2015). Table 10 below shows the distribution of sailors with regard to time on duty and breaks down the number per department. As shown in this table, the mean time on duty of 12 sailors did not change compared with their initially modeled value of 10.5. The same was evident for 11 sailors who continued working on average 13 hours. This does not imply that these sailors did not partake in any unplanned events or evolutions; but, it does indicate that all unplanned events fell outside of sailor eat, sleep, and personal time scheduled slots. Sailors that experienced less than 11.3 hours of daily time on duty represented 29% of the whole crew and with the exception of 4 Port and 1 Starboard watchstanders, all were departmental day workers. The lowest number of on duty hours was 10.5 with the highest being 11.19 hours within this group. The group of sailors that exceeded the 11.3 hours mark represents the remaining 71% of the crew with a maximum value of 15 hours for a Starboard watch CISN operator. Of the 140 sailors who have a median of at least 13.0 hours of daily time on duty, 136 (97%) were watchstanders. The reference 11.3 ± 2.6 hours is lower, yet overlaps the average across all sailors of 12.7 hours with a standard deviation of 1.4 for the baseline simulated crew. This result is in line with expectations considering that the number of tasks and evolutions included in the baseline model's scenario are higher and the workload more significant than what was scheduled during exercise Trident Fury for the 2015 study.

Table 10. Sailor distribution by daily time on duty (hours per day)

| Time on duty (Median hours/day) | Number of sailors | Sailors by Occupational Group |
|---|---|---|
| 10.5 | 12 | 3 in Combat department<br>6 in Logistics<br>1 in MSE<br>1 in Port |
| 10.5–11.3 | 51 | 1 in Bridge watch<br>3 in Combat department<br>3 in CSE<br>5 in Deck<br>20 in logistics<br>16 in MSE<br>2 in Port<br>1 in Starboard |

| Time on duty (Median hours/day) | Number of sailors | Sailors by Occupational Group |
|---|---|---|
| 11.3–13.0 | 14 | 1 in CSE<br>6 in Executive department<br>4 in Logistics<br>3 in MSE |
| 13.0 | 11 | 1 in Bridge watch<br>1 in Combat<br>9 in Port |
| 13.0–15.0 | 129 | 4 in Bridge watch<br>1 in Combat department<br>1 in Deck<br>57 in Port<br>66 in Starboard |

## B. VALIDATION OF BASELINE MODEL OUTPUT

In order to validate the sleep hours output from the baseline model, data at sea were compiled from an earlier workload and sleep study conducted aboard a Halifax-class ship (Wang et al., 2015). The breakdown of the data is shown in Table 11. With the single exception of the starboard watchstanders of the combat department, which had higher average sleep than the baseline model, all other schedules and departments had a sleep average that fell within one standard deviation (SD) of the reference. The equivalent averages were calculated using the baseline model data grouped by department and by schedule. Of note, the IMPRINT Pro model has a maximum number of hours set to eight hours, which means that there are no instances where a sailor would get more sleep even if a day’s activities would allow for it. This fact also explains in part why, in some cases, sleep hours may have lower averages in the baseline model compared to the real-world data.

Table 11. Daily sleep duration by department and schedule versus reference data from Wang et al. (2015). Results presented as means and (SD).

| Schedule | | Department | | | | | | Avg in schedule |
|---|---|---|---|---|---|---|---|---|
| | | Combat | CSE | Deck | Executive | Logistics | MSE | |
| Non-watch stander | Model output | 7.6 (0.4) | 7.6 (0.3) | 7.6 (0.4) | 7.9 (0.1) | 7.8 (0.4) | 7.6 (0.5) | 7.8 (0.4) |
| | Reference value | 8.4 (1.3) | 8.3 (0.7) | 6.9 (0.6) | - | 8.1 (1.3) | 9.4 (2.5) | - |
| Port | Model output | 7.7 (0.4) | 7.7 (0.4) | 7.8 (0.2) | - | - | 7.6 (0.4) | 7.7 (0.4) |
| | Reference value | 9.2 (1.8) | 7.8 (1.7) | 6.9 (2.1) | - | - | - | - |
| Starboard | Model output | 7.3 (0.4) | 7.5 (0.3) | 7.2 (0.2) | - | - | 7.3 (0.4) | 7.3 (0.4) |
| | Reference value | 9.7 (0.8) | 7.7 (1.7) | 8.3 (2.2) | - | - | - | - |
| Bridge watch | Model output | - | - | - | - | - | - | 7.9 (0.1) |
| | Reference value | - | - | - | - | - | - | - |
| Avg in department | Model output | 7.9 (0.2) | 7.7 (0.3) | 7.7 (0.3) | 7.9 (0.1) | 7.8 (0.4) | 7.7 (0.4) | 7.6 (0.4) |
| | Reference value | 8.9 (1.5) | 7.8 (1.6) | 7.6 (2.2) | - | - | - | 8.3 (1.8) |

The same approach was taken in analyzing the time on duty data for each sailor aboard but with one difference being that the data were used across the whole 10-day duration and divided by ten to obtain a daily average of time on duty. Due to the fact that time spent on unplanned events was included in the “time on duty” metric and how this type of activity is handled by IMPRINT when crossing the 24:00 mark, it was not possible to sort and group these data into daily sets. According to the 2015 work and rest study conducted during exercise Trident Fury by Wang et al. (2015), the average daily time on duty aboard a Halifax-class ship is 11.3 hours with a standard deviation of 2.6 hours. The breakdown of time on duty is presented in Table 12 and was compiled from that study’s time data. The equivalent data from the baseline model are presented alongside as previously done with the sleep data. Due to the relatively small number of participants and the limited 10-day duration of Wang et al.’s study, the standard deviations for time on duty are fairly large and cover a much wider range than seen from the IMPRINT Pro model’s output. Values from the model and collected at sea overlap when taking SD into account for all instances with the exception of Combat Systems Engineering that average significantly lower hours and Deck that averages slightly higher hours in the model for the non-watchstanding sailors.

This real-world data for time on duty and average daily sleep hours, along with the acknowledgment of model output by USN and RCN SMEs serves as validation of baseline outputs regarding the realism of workload and sleep hours for the entire crew.

Table 12. Daily time on duty per department and schedule versus reference data from Wang et al. (2015). Results presented as means and (SD).

| Schedule | | Department | | | | | | Avg in schedule |
|---|---|---|---|---|---|---|---|---|
| | | Combat | CSE | Deck | Executive | Logistics | MSE | |
| Non-watch stander | Model output | 10.6 (0.2) | 11.1 (0.4) | 10.8 (0.2) | 12.3 (0.7) | 10.8 (0.5) | 10.9 (0.4) | 10.9 (0.6) |
| | Reference value | 10.2 (2.2) | 13 (0.9) | 9.2 (1.3) | - | 10.3 (2.3) | 9.5 (2.2) | - |
| Port | Model output | 13.4 (0.4) | 13.3 (0.3) | 13.8 (0.5) | - | - | 13.4 (0.4) | 13.4 (0.4) |
| | Reference value | 12.1 (2.2) | 12.7 (1.3) | 14.6 (2.4) | - | - | - | - |
| Starboard | Model output | 13.9 (0.4) | 13.8 (0.2) | 13.9 (0.3) | - | - | 14.1 (0.4) | 13.9 (0.4) |
| | Reference value | 13 (0.9) | 12.7 (1.9) | 12.9 (1.2) | - | - | - | - |
| Bridge watch | Model output | - | - | - | - | - | - | 13.1 (0.5) |
| | Reference value | - | - | - | - | - | - | - |
| Avg in department | Model output | 13.2 (1.1) | 13.3 (0.9) | 12.8 (1.5) | 12.3 (0.7) | 10.8 (0.5) | 12.7 (1.5) | 12.7 (1.4) |
| | Reference value | 11.4 (2.4) | 12.7 (1.6) | 13.1 (2.7) | - | - | - | 11.3 (2.6) |
| | Reference value | 11.4 (2.4) | 12.7 (1.6) | 13.1 (2.7) | - | - | - | 11.3 (2.6) |

## C. AUGMENTED MODEL

Using the baseline model as the foundation, the augmented model for the full crew of the Halifax-class frigate adds unplanned events and mishaps to the simulation as was described in the methodology section. The percentages of failures, delays, and interruptions for all unplanned events were compiled in two separate tables for this second model. Table 13 includes all the unplanned events that were included in the both models. Results show that Flying station 1 fails an additional 25% of time on average, meaning that even fewer daily flights occur while all other events maintain the same failure ratio as in the baseline model. Electrical, navigation, and missile corrective maintenance have shown a slight increase in delays as well as all flying stations. The most affected event is Replenishment at Sea, which shows a 50% increase in delays compared to the baseline. Engine corrective maintenance and towing are interrupted 33% more often, and surprisingly, the rescue stations drill experiences 50% fewer interruptions than the baseline model.

Table 14 includes all the unplanned events that were added in the augmented model. As expected, given their high priority within the augmented model, none of these events failed, but there were some instances of delays for rescue stations (actual) and boarding stations (actual), as well as interruptions 10% of the time for the latter. The fact that the additional unplanned events did not show any failures, delays, and interruptions is as expected given that these actual events (as compared to drills) are at the top of the priority list. Delays or interruptions for these events will only occur when some of the required sailors are needed for a higher priority event found only within that table. For example, a small fire would get interrupted if a large fire occurs simultaneously and too few sailors were available to handle both fires.

Table 13. Unplanned event status (failed to complete, delayed, interrupted) in both models. Results presented as Median (IQR).

| Unplanned events | Tasks that failed to complete (%) | | | | Delayed tasks (%) | | | | Interrupted tasks (%) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Baseline model | | Augmented model | | Baseline model | | Augmented model | | Baseline model | | Augmented model | |
| Emergency flying stations drill | 0% | (0) | 0% | (0) | 0% | (0) | 0% | (0) | 0% | (0) | 0% | (0) |
| Emergency stations drill | 0% | (0) | 0% | (0) | 0% | (0) | 0% | (0) | 0% | (50) | 0% | (50) |
| Action stations drill | 0% | (0) | 0% | (0) | 0% | (0) | 0% | (0) | 0% | (0) | 0% | (100) |
| DC Drill | 0% | (0) | 0% | (0) | 0% | (0) | 0% | (0) | 100% | (50) | 100% | (50) |
| Comms CM | 0% | (0) | 0% | (0) | 0% | (0) | 0% | (10) | 0% | (0) | 0% | (0) |
| Network CM | 0% | (0) | 0% | (0) | 0% | (0) | 0% | (20) | 0% | (0) | 0% | (0) |
| 57mm CM | 0% | (0) | 0% | (0) | 0% | (0) | 0% | (33) | 0% | (0) | 0% | (25) |
| Engine CM | 0% | (0) | 0% | (0) | 0% | (0) | 0% | (33) | 0% | (33) | 33% | (50) |
| Electrical Eqpmt CM | 0% | (0) | 0% | (0) | 0% | (8) | 7% | (11) | 0% | (0) | 0% | (0) |
| Nav Equipment CM | 0% | (0) | 0% | (0) | 0% | (0) | 14% | (25) | 0% | (0) | 0% | (0) |
| RAS liquid | 0% | (0) | 0% | (0) | 0% | (50) | 50% | (100) | 0% | (0) | 0% | (75) |
| Missile system CM | 0% | (0) | 0% | (0) | 50% | (100) | 63% | (100) | 0% | (0) | 0% | (25) |
| Flying stations recover 1 | 0% | (0) | 0% | (9) | 9% | (17) | 30% | (20) | 9% | (17) | 17% | (16) |
| Towing | 0% | (0) | 0% | (25) | 0% | (0) | 0% | (50) | 0% | (33) | 33% | (50) |
| Rescue stations drill | 0% | (50) | 0% | (100) | 100% | (0) | 100% | (50) | 50% | (0) | 0% | (50) |
| Flying stations recover 2 | 0% | (0) | 8% | (11) | 9% | (10) | 30% | (17) | 0% | (9) | 9% | (11) |
| Flying stations 2 | 10% | (10) | 11% | (25) | 11% | (22) | 20% | (20) | 0% | (11) | 13% | (22) |
| Flying stations 1 | 0% | (0) | 25% | (32) | 0% | (11) | 30% | (20) | 0% | (10) | 0% | (13) |

Table 14. Additional unplanned event status (failed to complete, delayed, interrupted) in the augmented model. Results presented as Median (IQR).

| Unplanned events | Tasks which failed to complete (%) | Delayed tasks (%) | Interrupted tasks (%) |
|---|---|---|---|
| Action stations actual | 0% (0) | 0% (0) | 0% (0) |
| Fire actual large | 0% (0) | 0% (0) | 0% (0) |
| Fire actual small | 0% (0) | 0% (0) | 0% (0) |
| Flood actual | 0% (0) | 0% (0) | 0% (0) |
| Helicopter crash actual | 0% (0) | 0% (0) | 0% (0) |
| Rescue stations actual | 0% (0) | 0% (20) | 0% (0) |
| Boarding stations actual | 0% (0) | 22% (15) | 10% (10) |

Next, we compared the rate of completion of the planned events between the augmented and the baseline models to identify any notable differences. Table 15 shows the differences in the percentage of completed planned events by activity and department. In general, reduced durations are modest when averaging per occupational group. There are reductions, however, in personal time across the board, as well as in planned maintenance and sleep, as shown previously.

Table 15. Percentage of completed planned activities as per daily schedule for both models. Results presented as Median (IQR).

| Occupational group | Watch | | Eat | | Personal time | | Planned maintenance | | Sleep | | Work | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Baseline | Augment. | Baseline | Augment. | Baseline | Augment. | Baseline | Augment. | Baseline | Augment. | Baseline | Augment. |
| **Combat** | - | - | 97.7% (3.3%) | 95.2% (5.7%) | 99.8% (0.5%) | 96.0% (4.7%) | - | - | 99.4% (0.7%) | 95.5% (4.6%) | 90.6% (7.0%) | 90.1% (5.8%) |
| **Combat SE** | - | - | 96.5% (2.7%) | 88.3% (1.5%) | 95.6% (2.0%) | 87.6% (4.0%) | 96.6% (2.6%) | 87.2% (1.2%) | 96.0% (2.1%) | 86.5% (4.5%) | 88.6% (3.1%) | 84.7% (0.7%) |
| **Day cooking** | - | - | 98.7% (1.8%) | 93.6% (1.9%) | 100.0% (0%) | 93.3% (2.5%) | 100.0% (0%) | 92.0% (1.2%) | 98.9% (0.2%) | 92.3% (4.1%) | 95.4% (0.8%) | 80.6% (6.8%) |
| **Deck** | - | - | 95.3% (4.9%) | 83.4% (6.7%) | 100.0% (0%) | 86.6% (3.8%) | - | - | 98.8% (0%) | 85.9% (4.7%) | 81.5% (9.6%) | 82.4% (4.4%) |
| **Executive** | - | - | 99.6% (1.1%) | 84.3% (4.7%) | 100.0% (0%) | 88.6% (4.6%) | - | - | 99.6% (0.6%) | 86.2% (5.2%) | 96.9% (4.2%) | 87.6% (4.9%) |
| **Logistics (day)** | - | - | 99.8% (0.8%) | 92.7% (5.8%) | 100.0% (0%) | 92.4% (5.7%) | 100.0% (0%) | 91.7% (6.1%) | 99.4% (0.6%) | 91.6% (6.2%) | 90.6% (5.3%) | 82.2% (8.4%) |
| **Maritime SE** | - | - | 90.2% (8.7%) | 86.7% (8.0%) | 98.2% (2.8%) | 93.0% (2.3%) | 90.2% (11.2%) | 88.4% (8.4%) | 98.3% (2.3%) | 92.8% (2.7%) | 84.6% (8.5%) | 94.1% (6.6%) |
| **Night cooking** | - | - | 100.0% (0%) | 96.0% (3.5%) | 100.0% (0%) | 91.9% (4.9%) | 100.0% (0%) | 90.1% (8.2%) | 87.1% (5.1%) | 83.2% (6.9%) | 100.0% (0%) | 96.0% (4.4%) |
| **Watch 1 in 2 Port** | 99.8% (0.6%) | 98.0% (1.6%) | 96.8% (7.0%) | 91.4% (7.8%) | 68.8% (9.1%) | 68.5% (6.0%) | - | - | 97.8% (2.4%) | 93.4% (5.0%) | 92.6% (11.7%) | 89.2% (6.6%) |
| **Watch 1 in 2 Stbd** | 99.9% (0.5%) | 98.5% (1.7%) | 97.9% (2.9%) | 92.2% (5.4%) | 74.9% (0.5%) | 71.6% (3.2%) | - | - | 89.4% (3.4%) | 85.7% (4.6%) | 99.9% (0.6%) | 96.0% (4.4%) |
| **Watch bridge** | 98.9% (1.4%) | 97.1% (2.6%) | 95.3% (7.3%) | 92.4% (8.7%) | 70.2% (10.8%) | 68.2% (9.1%) | - | - | 99.5% (0.7%) | 90.6% (7.7%) | 92.6% (6.4%) | 89.2% (6.6%) |

As shown in the previous table, there is an overlap in percentages, when taking IQRs into account, with planned maintenance being a notable exception that deserves closer examination beyond the daily average. The sum of all sailors' planned maintenance during a 10-day simulation is less affected by averaging the data, which may give a clearer picture of the situation. The outcome for completed planned maintenance is of particular interest because it has a direct impact on corrective maintenance in the real world. Figure 12 shows the ship-wide completed planned maintenance distribution in the augmented model. The median value of completed planned maintenance during the 10-day underway was 916.3 (53.8) hours, which is 57 hours (median value) lower than the baseline model. Table 16 shows the breakdown by department of the mean percentage of maintenance that was not completed compared to the baseline model. These data are based on the total sum of maintenance hours accomplished over the entire duration of the 10-day simulation. All departments experienced reduced planned maintenance hours and the standard errors are small enough that the percentages remain above zero. Combat Systems Engineering and Logistics were the most affected, with reductions of hours completed calculated to be 10.66% and 9.67%, respectively.

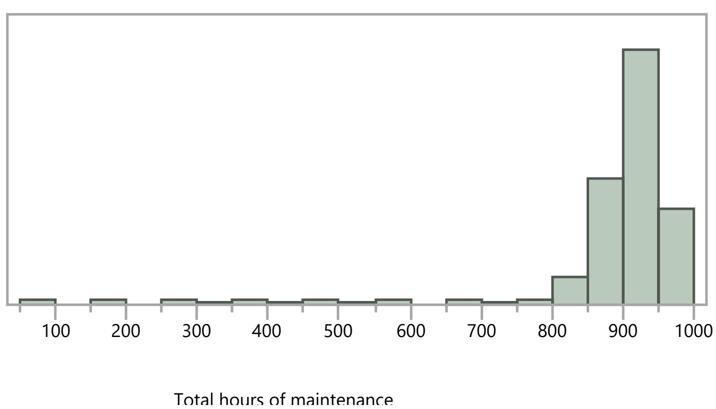



Figure 12. Distribution of ship-wide hours of planned maintenance in the augmented model

Table 16. Mean reduction in percentage of total planned maintenance completed over ten days

| Occupational group | Mean % difference (SE) | Corresponding hours |
|---|---|---|
| Combat SE | 10.66% (0.39%) | 8.53 |
| Day Cooking (logistics) | 8.30% (0.49%) | 8.30 |
| Logistics (day) | 9.67% (1.90%) | 40.63 |
| Maritime SE | 3.78% (1.64%) | 13.59 |
| Night Cooking (logistics) | 7.92% (0.11%) | 1.58 |
| Total | 7.12% (0.34%) | 72.63 |

The next analysis focused on the mean differences in daily sleep at the individual level, with a threshold of at least 30 minutes reduction and a median value of less than seven hours of sleep. This analysis showed that 76 sailors met the aforementioned criteria (details are provided in the Appendix). Within this group, the demographics of schedules and departments are shown in Table 17. Results show that watchstanders are most heavily burdened and sleep deprived, especially the starboard watch.

Table 17. Sailors per schedule and department with less than seven hours median sleep and mean reduction in sleep ≥ 30 minutes

| | Department | | | | | | |
|---|---|---|---|---|---|---|---|
| Schedule | Combat | CSE | Deck | Executive | Logistics | MSE | Total |
| Departmental | 2 | 1 | 5 | 4 | 11 | 1 | 24 |
| Port | 2 | 4 | 3 | - | - | 1 | 10 |
| Starboard | 13 | 13 | 7 | - | - | 5 | 38 |
| Watch Bridge | 3 | - | 1 | - | - | - | 4 |
| Total | 20 | 18 | 16 | 4 | 11 | 7 | 76 |

For the average daily time on duty at the sailor level, a threshold of 30 minutes minimum was used to consider the mean difference for time on duty to be meaningful in the model. The range of mean additional time on duty spread from 30 minutes up to two hours and affected 60 sailors. Unsurprisingly, the Commanding Officer, Deck Officer, Executive Officer, and Coxswain are in the top 15 sailors with highest mean increase in time on duty, given that they are involved in most unplanned events. The breakdown of schedules and departments to which these sailors belong is shown in Table 18. As a percentage of sailors affected within their respective departments, the executive department, logistics, and deck are the most burdened for a total of 27.6% of the crew experiencing an increased daily average time on duty. Unlike what was observed for mean differences in sleep, watchstanders are not specifically impacted by increased time on duty, given that their baselines are already among the highest across the whole crew. A small increase of time on duty can bring a watchstander below the seven hours average daily sleep, given that many of these sailors are close to seven hours at baseline.

Table 18. Sailors by department and schedule, with mean increased time on duty >30 minutes/day

| | Department | | | | | | |
|---|---|---|---|---|---|---|---|
| Schedule | Combat | CSE | Deck | Executive | Logistics | MSE | Total |
| Departmental | 1 | 3 | 5 | 5 | 16 | 7 | 37 |
| Port | 3 | 4 | 1 | - | - | 2 | 10 |
| Starboard | 3 | 4 | 4 | - | - | 0 | 11 |
| Watch Bridge | 2 | - | 0 | - | - | - | 2 |
| Total | 9 | 11 | 10 | 5 | 16 | 9 | 60 |
| Percentage of department | 12.5% | 33.3% | 47.6% | 83.3% | 53.3% | 16.4% | 27.6% |

A closer examination of the average increases of daily time spent on unplanned events gives further insight into the increases of time on duty. Additional unplanned events of longer durations are the main difference between the baseline and augmented model which, in turn, are the main driver of any increase of time on duty. The largest increases in time spent handling unplanned events are seen with CSE, MSE, Deck, and Executive on their respective departmental schedules. The Deck and Executive sailors mostly have leadership roles while the CSE and MSE sailors are mostly involved in corrective maintenance and damage control. Because this group of sailors does not stand watch, they are the ones most likely to respond to unplanned events since the port and starboard watchstanders maintain their watch 12 hours per day. This is reflected in the lower average increased hours spent on unplanned events for all watchstanders compared to the departmental (non-watchstander) sailors. Table 19 shows the breakdown of average daily increased hours associated with unplanned events.

Table 19. Daily average increase of hours spent on unplanned events. Results presented as Mean (SD).

| Schedules | Department: Combat | | CSE | | Deck | | Executive | | Logistics | | MSE | | Avg in schedule | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Departmental | 1.4 | (1.1) | 3.3 | (0.6) | 3.5 | (1.3) | 3.7 | (1.1) | 2.2 | (1.2) | 2.8 | (1.0) | 2.6 | (1.3) |
| Port | 1.0 | (0.8) | 1.5 | (0.7) | 2.3 | (1.4) | | | | | 1.0 | (0.6) | 1.2 | (0.9) |
| Starboard | 1.3 | (0.6) | 1.9 | (0.9) | 2.1 | (0.5) | | | | | 1.5 | (0.4) | 1.6 | (0.7) |
| Watch Bridge | | | | | | | | | | | | | 1.8 | (1.3) |
| **Avg in dept.** | 1.2 | (0.8) | 1.9 | (0.9) | 2.6 | (1.3) | 3.7 | (1.1) | 2.2 | (1.2) | 1.8 | (1.1) | 1.8 | (1.1) |

# V. DISCUSSION

Creation of the baseline model and its validation was a crucial first step in assessing whether a model of a crew of 217 aboard a Halifax-class Canadian frigate could be recreated realistically using the IMPRINT Pro Forces module. Following input regarding underway operations from SMEs and face value acknowledgment of the baseline model's parameters, outputs of average time on duty and sleep were generated. This data compared favorably to the study by Wang et al. (2015) in which average daily sleep within departments and across schedule types were very similar. Time on duty was generally higher in our baseline model compared to the reference study. We postulate that the aforementioned finding can be attributed to differences in overall mission scenarios and the total number of drills and evolutions included in the model. Despite these differences, the increased workload and time on duty of the watchstanders was evident in both the reference study and the baseline model output.

## A. IMPORTANT FINDINGS

A closer look at sleep durations at the individual sailor level reveals further issues of concern, even in the "best case scenario" baseline model. The majority of the ship's crew received an average of between seven and eight hours of sleep per day, but there are 14 sailors, all watchstanders save one, who experienced between six and seven hours as their daily average. This highlights the fact that even in the absence of mishaps and actual evolutions (mostly accomplished as planned drills in the baseline model), there is a group of sailors that is sleep deprived on most days. The fact that the vast majority of sailors experiencing reduced sleep were starboard watchstanders is also in line with previous studies (Meredith, 2016; Hollins & Leszczynski, 2014). This is concerning when considering that a ship's crew needs the capacity to increase workload when unplanned events and mishaps take place.

Time on duty at the individual level was quite higher in our study when compared to the 11.3 hours average of the reference study (Wang et al., 2015). A high percentage (71%) of the crew spent more than 11.3 hours on duty, and 59% had between 13 and 15 hours average daily duty hours. This is also an indication that the crew may be close to the limit of its capacity even at the baseline level.

A number of different types of activities and events across the ship contribute to total time on duty, and not all tasks, planned activities, or unplanned events were completed in their entirety. Due to their low priority, some drills were occasionally canceled or constantly interrupted and, therefore, delayed. Afternoon flying stations were canceled or interrupted approximately 10% of the time within a simulation replication, which equates to one canceled flight per 10-day simulation. With a few exceptions, all departments and schedules had less than 100% completion for planned activities such as planned maintenance and departmental work. Non-watchstanding sailors in the Combat System Engineering, Deck, and Maritime System Engineering departments were most burdened with unplanned events (such as corrective maintenance), which brought their departmental work completion below 90% on average. Planned maintenance for CSE and MSE sailors was also cut short by an average of 3% and 10%, respectively.

A closer look at all planned maintenance across the whole ship grouped by department shows that the CSE department median value for maintenance hours is 96%, with the median hours completed standing at 95% for total ship maintenance. Although not modeled, reduced planned (preventive) maintenance in real life will eventually lead to an increase in corrective maintenance of the many sub-systems aboard the ship. For this reason, planned maintenance completion is of particular interest. Once again, the baseline model has shown some shortcomings in this area despite being the least burdened scenario for this notional mission.

Even as a standalone model, the baseline reveals some less than ideal conditions for certain sailors and some deficiencies regarding the completion of planned activities and unplanned events. Although 100% success of all activities and events is unlikely to be an objective during real-world operations, seeing completion rates in the 90% range suggests that the crew has reached the edge of their workload limit.

The augmented model shows differences in sleep and workload that seem modest at first glance. This is not unexpected, given that occasional large differences would be diluted when an average value is calculated over 1,000 replications ("the flaw of averages"). The effect of averaging individual sailors into groups further dilutes the smaller differences that occur at the individual level. On the other hand, increases in failures, delays, and interruptions of unplanned events are more evident when comparing both models as paired metrics. Corrective maintenance events were designed to never fail, meaning that they would eventually be completed. This condition will bring additional delays and interruptions in lieu of failures. In all cases, failure percentages have either remained the same or slightly increased in the augmented model. Lower priority evolutions such as flying stations have shown, in general, more failures, delays, and interruptions.

What is more alarming, however, is that two of the high priority unplanned events, rescue stations and boarding stations, have seen occasional delays and interruptions. If this is deemed unacceptable by RCN leadership, then this is an indication that the current notional crew has exceeded its capacity in this scenario. Although increasing rates of failure have been few, significant increases in delays and interruptions do support our initial hypothesis regarding unplanned events.

All departments showed a combination of decreased hours in their planned activities in order to accommodate the additional time necessary to address the new unplanned events. Departmental work decreased in all departments with the exception of Deck and MSE, the consequences of which, however, are not explored in this thesis. Hours or planned maintenance had to be sacrificed in all departments, between 3.8% and 10.7%, to compensate for hours spent on additional unplanned events. Further examination of these values by maintenance SMEs could indicate the gravity of such a decrease, assessing whether this would be sustainable. In the negative, we would once again see evidence that the crew is incapable of satisfactorily fulfilling their tasks and duties.

Sleep was one of the main metrics of interest used to assess the level of workload that sailors were maintaining. Considering that 14 sailors in the baseline model were already sleep deprived, receiving less than seven hours daily sleep on average, the number of sailors that fell into that category in the augmented model was much larger. A total of 76 sailors (35% of the crew) were considered sleep deprived on a daily basis, 24 of whom are non-watchstanders versus a single sailor in the baseline model. Within this entire group, 50% of sailors are starboard watchstanders and the sum of all watchstanders equates to 68% of all sleep deprived sailors. These findings are in line with two of our initial hypotheses regarding sleep across departments and for watchstanders. Regarding watchstanders, there is particular emphasis on the starboard watch schedule, which is more heavily burdened. This is explainable mostly by the fact that the starboard watch crew's sleep is segmented and occurs during the day. Because more events take place during the day, they are more likely to be awakened if no other qualified sailors are available.

Lastly, the increases in daily time on duty in general agree with decreases in daily sleep durations within departments and schedules. The highest number of sailors (37 out of 60) who saw an increase is found in the departmental schedules, which supports the increase in sleep deprivation for this same category of sailors. This increased time on duty is responsible for bringing 24 of those 37 sailors into the sleep-deprived zone. The same is true of the port watchstanders who are sleep deprived in the augmented model but were not in the baseline model. Although eating and personal time can be sacrificed in order to partake in unplanned events, it is quite clear that increased time on duty will also lead to sacrificing sleep in order to accommodate the increased workload.

## B. LIMITATIONS

This modeling and simulation study has a number of limitations, both because of certain model design decisions and the functionalities of the IMPRINT Pro Forces module itself. The data used to build daily planned schedules, durations of sleep, time on duty, frequency and durations of evolutions or tasks were based on a study performed during training at sea with the same crew size aboard the same class of ship but with a slightly different composition and a different scenario. An ideal source of data would have been actual data gathered during operations for a mission that is conducting patrols in a hostile environment. The time-based data are, hence, not directly comparable although certainly within the same realm.

As was highlighted by SMEs during initial discussions on ship operations, Officers often work on administrative matters whenever they have time to do so. The daily planned schedules that Officers (including watchstanders) follow only have generic time slots for “work” that do not necessarily accurately capture the way Officers spend their time over a 24-hour period. If Officers are interrupted by an unplanned event, they may afterwards complete the mandatory administrative work they started prior to the interruption. For this reason, the time on duty of Officers is likely underrepresented, and consequently, sleep durations are overly optimistic.

IMPRINT Pro’s Forces module has a category called “Assets,” which may represent tools, equipment, or vehicles needed to accomplish specific tasks. In real-world operations at sea, the availability of tools and equipment may cause delays and interruptions of tasks and evolutions, and this aspect can be modeled within IMPRINT. Detailed knowledge of equipment found aboard an underway Canadian combat ship as well as the specific details of tasks using this equipment is needed in order to properly employ the Assets category. Our models, however, were built with the assumption that all assets were always available. An additional functionality of IMPRINT that was not included in these models is reduction in time needed to complete an unplanned event when adding sailors beyond the minimum required. In the absence of data that indicated how much time may be reduced on any given task when adding sailors filling specific roles, there was no basis to correctly include this aspect in the models.

Some limitations found in these models are caused by functionalities of the IMPRINT Pro package that either do not take some aspects into account or do not allow for specific implementations. One key issue is that daily sleep slots found within each schedule have a start time that implies the start of sleep rather than the start of going to bed. Given the realities of life aboard a ship, elements such as noise, vibrations, sea states, and other factors may all hinder the start of sleep once in bed (Matsangas & Shattuck, 2017). This software assumption increases, to some extent, the true average of daily sleep across the whole crew. The fact that the Activities Trump Matrix (i.e., priority list of activities and events) is fixed for the entire duration of the simulation is potentially problematic regarding the realism of outcomes. For example, a large fire would not always take priority over a flood depending on the circumstances or the fact that the ship has come under enemy contact may also shift priorities for the duration of that engagement. Priorities of tasks, planned and unplanned, would benefit from allowing for some form of dynamic changes. Lastly, there is an issue with the way the IMPRINT Pro Forces module handles the planned activities for each worker. Daily planned activities are set up as a static sequence that is followed in all circumstances. For example, if a sailor conducting planned maintenance from 13:00 to 15:00 gets interrupted after one hour and returns to his planned schedule at 15:00, this sailor would not return to maintenance since the "window" was missed but he would go on ahead with whatever is next in the schedule. In a real-world setting, this type of behavior is very unlikely, and workers would prioritize tasks within the planned schedule rather than follow it blindly.

Using the augmented model as a tool in support of future ship manpower determinations also presents a certain limitation. Although the newly approved Canadian Surface Combatant ship is similar to, and will ultimately replace, the Halifax-class frigates, the differences are too great to use the model directly. A number of modifications to the model would be needed in order to reflect the design and manning intent of the ship. Thankfully, close collaborations between an experienced IMPRINT Pro user and SMEs involved in a given ship's acquisition program should allow for the necessary alterations in a relatively modest amount of time.

# VI. CONCLUSIONS AND RECOMMENDATIONS

## A. CONCLUSIONS

This thesis set out to build models of a Canadian combat ship crew in order to simulate outcomes and analyze them from a manning perspective. The first objective was to determine whether the current crew composition of 217 aboard a Halifax-class ship can satisfactorily complete a majority of planned activities and unplanned events while on a notional 10-day mission at sea. Although on average, a small percentage of unplanned events failed, results showed a marked increase in delays and interruptions for most unplanned events that were not high in priority. Daily scheduled activities such as planned maintenance and departmental work were completed on average between 85% and 96% of the time, which indicates that the crew's capacity to complete most tasks is exceeding its limit in these conditions.

Model outputs showed evidence of higher than average time on duty, as well as lower sleep durations for watchstanding sailors in general, with the issue being particularly prevalent for the starboard watch keepers. A group of non-watchstanding sailors found in the Combat System Engineering, Deck, and Executive departments were the most heavily burdened in average time on duty, which was also reflected by average daily sleep of less than seven hours. These findings support the second objective of identifying which groups, departments, or schedules aboard the ship experience the heaviest workload.

Lastly, our final objective of calculating a predicted outcome caused by the inclusion of mishaps and incidents in the ship model is fulfilled by the direct comparison of both models for unplanned events, planned activities, time on duty and sleep. Our results suggest that a total of 60 sailors will experience a notable increase in average time on duty while 62 additional sailors will fall into the sleep deprivation category as per daily average sleep duration. Watchstanders, the starboard watch in particular, are the most impacted by the addition of mishaps and incidents into the model.

## B. RECOMMENDATIONS AND FUTURE WORK

Considering that the Royal Canadian Navy has recently added ships to its fleet and that the Canadian surface combatant is set to replace the Halifax-class in a few years, the use of a modeling and simulation tool such as the one used in this thesis is highly encouraged in support of manpower determination. This is especially critical given that an ambitious reduction in crew size is being considered for the Canadian surface combatant.

To use such a tool in support of manpower determination, a number of modifications to the IMPRINT model built for this thesis must take place. Close collaboration between an experienced modeler and RCN SMEs is needed in order to include the correct parameters and build a scenario of interest that is both credible and plausible. The ideal approach to determine the many parameters such as the type, number, and roles of sailors as well as the timing and duration of tasks would be to capture data at sea aboard the target ship with the proper crew. Further modeling endeavors should also explore the effects of changing the size and composition of a simulated crew while maintaining all other parameters and conditions of the model. This will give insight on manpower determination outcomes on performance metrics such as workload, sleep, and task completion.

Given the effects of averaging data across simulation replications, a deeper analysis would be desirable to capture more local effects of large events or simultaneity of events. Although IMPRINT Pro does not allow this directly without external data processing, looking at sleep and time on duty during the day and following 24 to 48 hours of a major or series of unplanned events would show localized impacts for the sailors involved. Although these types of outcomes do lower the average across replications, the details are hidden by averaging the data.

# APPENDIX

Table 20. Difference in daily sleep duration between the augmented and the baseline models (paired samples Wilcoxon Signed Rank test, all p<0.001).

| Sailor | Schedule | Department | Median daily sleep duration in Baseline model (hours) | Median daily sleep duration in Augmented model (hours) | Mean difference (augmented minus baseline) | 95% Confidence Interval of the difference |
|---|---|---|---|---|---|---|
| ARMAMENT MAINTAINER[1] | STARBOARD | CSE | 7.25 | 6.99 | -0.26 | (-0.32,-0.21) |
| Cook MS[1] | Logistics | Logistics | 7.17 | 6.99 | -0.19 | (-0.24,-0.13) |
| COMMS MAINTAINER[1] | STARBOARD | CSE | 7.25 | 6.98 | -0.27 | (-0.33,-0.22) |
| ARRO1[1] | STARBOARD | Combat | 7.25 | 6.98 | -0.27 | (-0.33,-0.22) |
| SPACE 2 I-C EOOW[1] | STARBOARD | MSE | 7.24 | 6.97 | -0.27 | (-0.33,-0.21) |
| MECHANIC[1] | STARBOARD | MSE | 7.22 | 6.96 | -0.26 | (-0.31,-0.2) |
| W ENG TECH MAINT SSD[1] | PORT | CSE | 8.00 | 6.96 | -1.04 | (-1.09,-0.99) |
| JR ACOUSTIC OP - MESSMAN[1] | STARBOARD | Combat | 7.25 | 6.95 | -0.30 | (-0.35,-0.24) |
| MECHANIC - ROUNDSMAN SSD2[1] | STARBOARD | MSE | 7.21 | 6.94 | -0.27 | (-0.33,-0.22) |
| SR RADAR MAINT HFX[1] | STARBOARD | CSE | 7.21 | 6.94 | -0.28 | (-0.33,-0.22) |
| ARRO2[1] | STARBOARD | Combat | 7.23 | 6.93 | -0.30 | (-0.35,-0.24) |
| BWK1[1] | Watch Bridge | Combat | 8.00 | 6.93 | -1.07 | (-1.13,-1.01) |
| JR CI OP SSD[1] | PORT | Combat | 8.00 | 6.93 | -1.07 | (-1.12,-1.02) |
| BWK2[1] | Watch Bridge | Combat | 8.00 | 6.92 | -1.08 | (-1.14,-1.03) |
| FC SUP2[1] | STARBOARD | Combat | 7.24 | 6.91 | -0.33 | (-0.39,-0.28) |
| JR W ENG TECH SSD[1] | PORT | CSE | 8.00 | 6.91 | -1.09 | (-1.14,-1.04) |
| ELE MAINT TECH1[1] | STARBOARD | MSE | 7.16 | 6.89 | -0.28 | (-0.33,-0.22) |
| QM[1] | Deck | Deck | 8.00 | 6.86 | -1.14 | (-1.19,-1.09) |
| C4I TRACKER2[1] | STARBOARD | Combat | 7.23 | 6.82 | -0.41 | (-0.46,-0.35) |
| MAINT-LOOKOUT3[1] | STARBOARD | Deck | 7.24 | 6.81 | -0.43 | (-0.48,-0.38) |

| Sailor | Schedule | Department | Median daily sleep duration in Baseline model (hours) | Median daily sleep duration in Augmented model (hours) | Mean difference (augmented minus baseline) | 95% Confidence Interval of the difference |
|---|---|---|---|---|---|---|
| JR W ENG TECH2[1] | PORT | CSE | 8.00 | 6.78 | -1.22 | (-1.27,-1.16) |
| SR FC MAINT[1] | STARBOARD | CSE | 7.28 | 6.78 | -0.50 | (-0.55,-0.44) |
| INFO MGR[1] | STARBOARD | Combat | 7.28 | 6.76 | -0.52 | (-0.57,-0.46) |
| MAINT-LOOKOUT4[1] | STARBOARD | Deck | 7.23 | 6.76 | -0.48 | (-0.53,-0.42) |
| W ENG SYS TECH[2] | PORT | CSE | 7.25 | 6.75 | -0.50 | (-0.55,-0.45) |
| STWD SSD1[1] | Logistics | Logistics | 8.00 | 6.75 | -1.25 | (-1.31,-1.2) |
| JR WENG TECH-MESSMAN[1] | STARBOARD | CSE | 7.26 | 6.74 | -0.52 | (-0.58,-0.47) |
| THROTTLEMAN1[1] | Deck | Deck | 7.50 | 6.73 | -0.77 | (-0.82,-0.72) |
| MECHANIC - LAUNDRY OP[1] | MSE | MSE | 8.00 | 6.71 | -1.29 | (-1.34,-1.23) |
| THROTTLEMAN2[1] | PORT | Deck | 8.00 | 6.71 | -1.29 | (-1.34,-1.23) |
| MSEO WRITER[1] | STARBOARD | MSE | 7.26 | 6.71 | -0.55 | (-0.6,-0.49) |
| JR RADAR MAINT1[1] | STARBOARD | CSE | 7.21 | 6.71 | -0.50 | (-0.56,-0.45) |
| JR ACOUSTIC OP SSD1[1] | Combat | Combat | 8.00 | 6.71 | -1.29 | (-1.34,-1.24) |
| BOSN MATE SSD[1] | Deck | Deck | 8.00 | 6.69 | -1.31 | (-1.37,-1.26) |
| STMN SSD1[1] | Logistics | Logistics | 8.00 | 6.68 | -1.32 | (-1.37,-1.26) |
| SONAR MAINT HFX[1] | STARBOARD | CSE | 7.21 | 6.68 | -0.54 | (-0.59,-0.48) |
| BOSN MATE[1] | PORT | Deck | 7.49 | 6.68 | -0.82 | (-0.87,-0.77) |
| LOOKOUT1[1] | Deck | Deck | 8.00 | 6.66 | -1.34 | (-1.39,-1.28) |
| ACOUSITC OP SSD[1] | STARBOARD | Combat | 7.25 | 6.66 | -0.59 | (-0.64,-0.53) |
| JR SONAR MAINT SSD[1] | STARBOARD | CSE | 7.04 | 6.66 | -0.38 | (-0.44,-0.33) |
| JR COMMS MAINT SSD[1] | STARBOARD | CSE | 7.20 | 6.66 | -0.54 | (-0.6,-0.49) |
| CLK1[1] | Logistics | Logistics | 8.00 | 6.64 | -1.36 | (-1.41,-1.3) |
| COOK LS3[1] | Logistics | Logistics | 7.07 | 6.63 | -0.44 | (-0.49,-0.38) |
| CHIEF BOSN MATE[1] | Deck | Deck | 8.00 | 6.62 | -1.38 | (-1.43,-1.32) |
| DECK OFFR-OOW[1] | Watch Bridge | Deck | 8.00 | 6.62 | -1.38 | (-1.43,- |

| Sailor | Schedule | Department | Median daily sleep duration in Baseline model (hours) | Median daily sleep duration in Augmented model (hours) | Mean difference (augmented minus baseline) | 95% Confidence Interval of the difference |
|---|---|---|---|---|---|---|
| | | | | | | 1.32) |
| JUNIOR CISN OPERATOR4[1] | PORT | Combat | 7.49 | 6.62 | -0.86 | (-0.92,-0.81) |
| JR ACOUSTIC OP2[1] | Combat | Combat | 7.22 | 6.62 | -0.60 | (-0.65,-0.54) |
| JR CI OP1[1] | STARBOARD | Combat | 7.25 | 6.61 | -0.64 | (-0.69,-0.58) |
| LOOKOUT2[1] | PORT | Deck | 7.49 | 6.61 | -0.89 | (-0.94,-0.84) |
| COXN[1] | Executive | Executive | 8.00 | 6.60 | -1.40 | (-1.45,-1.35) |
| CO[1] | Executive | Logistics | 8.00 | 6.60 | -1.40 | (-1.45,-1.35) |
| STMN2[1] | Logistics | Logistics | 8.00 | 6.60 | -1.40 | (-1.46,-1.35) |
| SR ELECTRONIC SENSOR OP-MESSMAN[1] | STARBOARD | Combat | 7.25 | 6.56 | -0.68 | (-0.74,-0.63) |
| COXN WRITER[1] | Executive | Executive | 8.00 | 6.55 | -1.45 | (-1.5,-1.39) |
| STMN SSD2[1] | Logistics | Logistics | 8.00 | 6.50 | -1.50 | (-1.55,-1.44) |
| CLK2[1] | Logistics | Logistics | 8.00 | 6.48 | -1.52 | (-1.57,-1.46) |
| BWK SSD[1] | Watch Bridge | Combat | 8.00 | 6.48 | -1.52 | (-1.58,-1.47) |
| JR W ENG TECH1[1] | CSE | CSE | 8.00 | 6.45 | -1.55 | (-1.6,-1.5) |
| EXCHANGE MGR[1] | Logistics | Logistics | 8.00 | 6.42 | -1.58 | (-1.63,-1.52) |
| STWD SSD2[1] | Logistics | Logistics | 7.04 | 6.42 | -0.62 | (-0.68,-0.57) |
| XO[1] | Executive | Executive | 8.00 | 6.36 | -1.64 | (-1.69,-1.59) |
| LIFEBUOY1[1] | STARBOARD | Deck | 7.25 | 6.35 | -0.90 | (-0.96,-0.85) |
| MACHINERY SPACE SUP-EOOW SSD1[1] | PORT | MSE | 7.19 | 6.29 | -0.90 | (-0.96,-0.84) |
| LIFEBUOY2[1] | STARBOARD | Deck | 7.24 | 6.29 | -0.96 | (-1.01,-0.9) |
| JUNIOR CISN OPERATOR SSD1[1] | STARBOARD | Combat | 6.81 | 6.28 | -0.54 | (-0.59,-0.49) |
| JUNIOR CISN OPERATOR SSD 2[1] | STARBOARD | Combat | 7.09 | 6.27 | -0.81 | (-0.87,-0.76) |
| STWD2[1] | Logistics | Logistics | 6.86 | 6.25 | -0.61 | (-0.67,-0.56) |
| JR FC MAINTAINER2[1] | STARBOARD | CSE | 7.25 | 6.20 | -1.04 | (-1.1,-0.99) |
| ASPO2[1] | STARBOARD | Combat | 7.23 | 6.19 | -1.04 | (-1.1,-0.99) |

| Sailor | Schedule | Department | Median daily sleep duration in Baseline model (hours) | Median daily sleep duration in Augmented model (hours) | Mean difference (augmented minus baseline) | 95% Confidence Interval of the difference |
|---|---|---|---|---|---|---|
| LOOKOUT4[1] | STARBOARD | Deck | 6.66 | 6.19 | -0.47 | (-0.53,-0.42) |
| JR ELECTRONIC SENSOR OP2[1] | STARBOARD | Combat | 6.90 | 6.19 | -0.72 | (-0.77,-0.66) |
| ASST CBM[1] | STARBOARD | Deck | 7.28 | 6.17 | -1.11 | (-1.16,-1.05) |
| LOOKOUT3[1] | STARBOARD | Deck | 6.89 | 6.14 | -0.75 | (-0.8,-0.7) |
| JR W ENG TECH3[1] | STARBOARD | CSE | 7.21 | 6.11 | -1.09 | (-1.14,-1.04) |
| JR ARMAMENT MAINT2[1] | STARBOARD | CSE | 7.20 | 5.98 | -1.22 | (-1.27,-1.17) |
| JR W ENG TECH4[1] | STARBOARD | CSE | 7.20 | 5.94 | -1.27 | (-1.32,-1.21) |

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