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**DEVELOPMENT OF A SIMULATED MANPOWER
MODEL FOR NAVY VESSEL ACQUISITION**

by

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September 2023

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**DEVELOPMENT OF A SIMULATED MANPOWER MODEL FOR NAVY
VESSEL ACQUISITION**

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ABSTRACT

This thesis examines the use of discrete event simulation to provide the Royal Norwegian Navy (RNoN) acquisition process with a more comprehensive basis for making manpower requirement decisions using modeling techniques. We present a method for creating and analyzing manpower models made using IMPRINT Pro Forces. Leveraging information on workload and sleep collected during an underway sail with a Norwegian Coast Guard ship, we created a Baseline and an Augmented model, both simulating a 21-day underway with 22 sailors. The first model included minimal shipboard activities, while the second model incorporated additional activities and unplanned events such as damage control and major engine failures. Results show that the Baseline model allowed sailors to achieve more than the minimum recommended sleep of seven hours per day while working an average of 10.50 ± 1.40 hours per day. In the Augmented model, only one sailor slept less than seven hours per day and worked a mean of 11.02 ± 1.35 hours per day. The models indicate that sailors who stand watch are more prone to overwork and sleep deprivation than other occupational groups. Increases in operational tempo allowed highly prioritized events to be completed, indicating that the vessel was adequately manned. RNoN acquisition should consider developing manpower models for future acquisitions to bolster manpower decision-making.

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LIST OF ACRONYMS AND ABBREVIATIONS

CM	Corrective maintenance
CO	Commanding Officer
DES	Discrete Event Simulation
DNV	Det Norske Veritas
ESS	Epworth Sleepiness Scale
HSI	Human Systems Integration
IMPRINT	Improved Performance Research Integration Tool
IRB	Institutional Review Board
ISI	Insomnia Severity Index
KDA	Kongsberg Defence & Aerospace
LCS	Littoral Combat Ship
LMC	Lean Manning Concept
M	Mean
MCM	Mine Countermeasure
Mdn	Median
NATO	North Atlantic Treaty Organization
NAVMAC	Navy Manpower Analysis Center
NoCG	Norwegian Coast Guard
NPS	Naval Postgraduate School
PII	Personal Identifiable Information
POE	Projected Operational Environment
POMS	Performance of Mood States
PSQI	Pittsburgh Sleep Quality Index
RNoN	Royal Norwegian Navy
ROC	Required Operational Capabilities
SAR	Search and Rescue

SD	Standard Deviation
SMD	Ship Manpower Document
SME	Subject Matter Expert
TMD	Total Mood Score
XO	Executive Officer

EXECUTIVE SUMMARY

Manpower refers to the number of individuals needed to support system operations effectively. While finding ways to reduce excessive costs is vital for major military acquisition programs, disproportionate reduction of manpower should be avoided because it can (1) negatively affect the workload of sailors (through overwork), (2) make vessels especially vulnerable to billet vacancies, and (3) reduce overall system performance. With the Royal Norwegian Navy (RNoN) on the precipice of acquiring a new standardized, modular-based vessel fleet, this thesis aimed to provide insight into the use of discrete event simulation models to afford the RNoN acquisition process with a more comprehensive basis for making manpower requirements decisions. The objective of this thesis was to use a discrete event simulation tool to build, analyze, and compare two manpower models, a Baseline and an Augmented model, in terms of workload, sleep, and task completion. In addition to these two models, an effort was also made to assess the viability of using Improved Performance Research Integration Tool (IMPRINT) Pro Forces to support manpower determination in RNoN acquisition activities.

This thesis expanded on previous research conducted at the Naval Postgraduate School using the IMPRINT Pro Forces module. The research reviewed the importance of conducting manpower analysis during procurement while also examining issues regarding manning ships in the naval fleets. Using the work and rest patterns of actual Norwegian Coast Guard crewmembers for the modeling effort, the thesis discusses the impact of workload and sleep on human performance to provide context for the simulation effort.

The IMPRINT Pro Forces module was deployed in a stepwise approach. In the first step, work and rest patterns were collected from crewmembers on a Norwegian Coast Guard ship similar in scale to the design of future ship acquisitions. This information was used as input to successive IMPRINT models which would be based on workload demands and task performance. Input for the final models also came from subject matter experts, self-reported data, and objective measurements, which provided details of organizational, task, and sleep data.

In the second step, a Baseline model of the ship's crew was developed, simulating them while they were conducting planned tasks, preventive maintenance, and routine training exercises during a 21-day underway. In the final step, the baseline condition was augmented by introducing unplanned events, such as major corrective maintenance and operational tasks. Also introduced into the study were extreme events, such as actual damage control incidents (e.g., fires, floods, and Search and Rescue (SAR) operations). The Augmented model also contained ship-wide exercises, typically planned by a small contingent of crewmembers but occurring randomly for the other members of the crew. The simulation output provided workload data by identifying tasks that had been delayed or failed to receive the attention of the simulated crew. Reduced sleep hours can be an indicator of excessive workload; thus, IMPRINT output allowed for detecting jobs that were more susceptible to fatigue.

The results showed that the simulated crew spent more time on duty (11.02 ± 1.35 hours per day) in the Augmented model than the Baseline model (10.54 ± 1.40 hours per day), an increase of almost 30 minutes per sailor per day, to an accumulated additional workload of 10.56 hours per day (Augmented 90th quantile = 14.96 hours per day) across the crew. Differences among occupational groups showed that watchstanders worked the most hours and were more vulnerable to overtasking. Yet, the influx of activities between the models resulted in only small reductions in sleep duration per day by occupational group. Watchstanders and engineers saw their sleep decrease by 10.2 minutes (10th quantile = 22.8 minutes) while those adhering to a daytime work schedule slept 13.8 minutes per day less (10th quantile = 22.8 minutes).

Based on the findings, the simulated crew in the Baseline model was able to conduct most activities while maintaining healthy sleep habits and avoiding overwork. The results showed that all crewmembers slept more than seven hours per day and achieved high completion rates for irregular activities. Following the introduction of several additional irregular activities and unplanned events in the Augmented model, the results showed a reduction in the crew's ability to complete the full range of tasks. Nevertheless, highly prioritized events were covered sufficiently in nearly all instances. The tasks added in the Augmented model reduced sleep among all sailors, although the reduction targeted the

watchstanding occupational group the most, with some seeing their sleep fall below seven hours per day.

The IMPRINT Pro Forces module can be a valuable tool for assessing manpower requirements during naval ship acquisitions. This thesis suggests that a thorough manpower analysis using IMPRINT requires a two-pronged approach to investigate the long-term effects from a full underway, as well as a shorter timeline representing high activity effects on the crew. IMPRINT has some limitations in replicating a crew's flexibility to reorganize to meet threats while maintaining a level of resolution to identify manpower weaknesses. Additionally, the quality of the data which is input to the model determines the quality of the output. It was challenging to determine when a manpower simulation tool could exceed the subject matter experts' ability to assess manpower needs. However, maintaining a model with evidence of why a certain level of manpower was chosen can be valuable to protect crews from operational requirements creep during the life cycle of a vessel. Use of these types of models becomes especially prudent given the proposed scalability of standardized, modular-based vessels.

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I. INTRODUCTION

A. BACKGROUND

The Royal Norwegian Navy (RNoN) is restructuring its fleet to meet the increasing threat level toward Norwegian assets (Forsvarssjefen, 2019). Russia's 2014 and 2022 invasions of Ukraine have ramifications for Norwegian society, and Norwegian maritime infrastructure has been identified as a potentially vulnerable target. To deter potential adversaries and ensure navigational rights and freedoms, the Norwegian Armed Forces need robust naval capabilities (Forsvarsdepartementet, 2022b). Although Norway's military spending has increased substantially following a corresponding trend in the North Atlantic Treaty Organization (NATO, 2022), Norway must continue to accelerate its modernization efforts even further to keep pace with military technology advancements (Forsvarsdepartementet, 2022b). Civilian industry partners have become increasingly indispensable, and the cooperation between industry and military organizations is vital to keep up with technological development (Forsvarsdepartementet, 2021b). This dynamic will be part of the backdrop for the RNoN's future surface vessel organization, as the Navy and the Coast Guard are expected to increase their collaborative efforts both in operations and procurements (Forsvarsdepartementet, 2022b).

A large part of the RNoN fleet will soon be decommissioned or need mid-life updates. This process includes six mine countermeasure (MCM) vessels, five littoral, three open ocean Coast Guard vessels, and two smaller auxiliary ships. By 2030, the Skjold class coastal corvettes will have reached the end of their planned lifespan after receiving a major overhaul between 2022 and 2024 (Forsvarsdepartementet, 2020). A new vessel concept, flexible enough to carry out a broad spectrum of operations, is an enticing option. Norway has committed to exploring standardized vessels with modular-based technology (Forsvarsdepartementet, 2020). By adhering to a standardized technological infrastructure, integration of emerging technological advances can be streamlined, opening the door to concepts like future MCM "mother vessels" with add-on autonomous and unmanned MCM system modules (Forsvarsdepartementet, 2022a). Standardization can also lead to

significant cost savings and boosts to performance by providing opportunities to align training, maintenance, and support throughout the system's life cycle.

While technological innovation attracts a great deal of attention, people remain the Norwegian Armed Forces' most valuable resource (Forsvarsdepartementet, 2022b). According to NATO's data for 2022, compared to other member countries, the Norwegian military allocates a relatively small percentage of its total spending toward personnel. Hence, it is essential to note that investing in human resources remains one of the most significant expenses in a system's life cycle, as stated by Spindel et al. (2000). The number of individuals necessary to ensure support of system performance is called *Manpower* (DOD Instruction 5000.02, 2015). The term refers not to the current number of personnel in a system or organization, but instead to the number of individuals needed to support system operations effectively. While finding ways to reduce excessive costs is vital for major military acquisition programs, disproportionate reduction of manpower should be avoided because it can (1) negatively affect the workload of sailors (through overwork), (2) make vessels especially vulnerable to billet vacancies, and (3) reduce overall system performance. The RNoN has designed ships' manpower according to the Norwegian "Lean Manning Concept" (LMC), with a goal of reducing manpower expenses as much as possible by having sailors responsible for covering multiple roles. This concept makes crews vulnerable to negative effects even with a slight gap between the manpower requirements and sailors being present onboard *manning* the system (Forsvaret, 2004).

When designing new systems, it is crucial to consider manpower needs. A thorough manpower analysis conducted during the procurement process can help provide evidence for the manpower needed to support performance levels, reduce costs, and minimize the risk of rework. This approach aligns with the guidance outlined in the U.S. Department of Defense (DOD) Directive 5000.01 (2020), which emphasizes the importance of assessing manpower needs when approaching a new acquisition. One way to establish manpower requirements throughout an acquisition is by modeling and simulating multiple manning variations and exploring how these variations affect the completion of mission tasks. One such tool for this activity is the *Improved Performance Research Integration Tool* (IMPRINT), a discrete event simulation tool that can be used to explore manpower

concepts. IMPRINT has been applied successfully on navy vessels, like the U.S. Navy Littoral Combat Ship (LCS), as well as Canadian and Australian frigates (Attwood, 2020; Hollins & Leszczynski, 2014; Kerno, 2014; Meredith, 2016; Poirier, 2020; Ryan, 2014; Shattuck & Matsangas, 2015). By evaluating workload, task completion, and the corresponding crew performance, IMPRINT simulation has provided valuable insights into manning decisions.

The U.S. Navy's LCS was designed as a modular ship intended to be adaptable to several different mission profiles (Oakley, 2021). The Norwegian defense manufacturer, Kongsberg Defense & Aerospace (KDA), has developed the Vanguard vessel concept, which can similarly be enhanced by system modules, allowing it to cover missions in multiple domains (Kongsberg, 2019). The new modular design may be a viable solution for a wide range of operational needs; however, the design differs significantly from legacy ships, making legacy manning concepts insufficient. To address this issue, manpower analysis techniques, such as simulation, can be used early in the acquisition process to better assess manpower requirements and thus allow for improved forecasts of manpower costs and system performance. This can ensure a smooth transition, effective utilization of resources, and mission effectiveness for the future vessel structure.

B. THESIS SCOPE AND OBJECTIVES

A manpower analysis of a modular concept can provide the acquisition process with a head start on one of the main cost drivers of any vessel procurement: manpower requirements. If manpower is not properly addressed, navy crews can become vulnerable to conditions that can greatly impact their performance. One such condition is fatigue, which can be caused by excessive workload and lack of sleep. Fatigue can prevent crews from performing at their expected level and increase the risk of system failures.

This study builds on previous research conducted at the Naval Postgraduate School on workload, work hours, and sleep, which was geared towards creating simulated manpower models (Attwood, 2020; Fletcher, 2018; Hollins & Leszczynski, 2014; Meredith, 2016; Poirier, 2020; Ryan, 2014; Shattuck & Matsangas, 2015). This thesis builds a model for estimating manpower requirements for a sample crew. The input for

constructing the model was verified using data gathered from a Norwegian Coast Guard (NoCG) vessel. A two-part modeling process was employed, first establishing a baseline model which uses strict schedules and irregular but planned tasks, including the everyday activities of the crew. The second phase of the modeling process introduces major activities and unplanned events into an augmented model. Depending on the prioritization of the activities, the model calculates which activities are accomplished in the model and which are canceled or delayed, potentially affecting rest and sleep opportunities for the crew.

The overarching goal of this thesis is to provide insight into methods for the RNoN acquisition process to have a more robust and comprehensive basis for making manpower requirements decisions. The objectives of the thesis are as follows:

- Assess, during the Baseline model configuration, whether the crew is able to conduct its tasks, events, and incidents without a degradation in performance or sleep levels, and if affected negatively, where these effects are presumed to occur.
- Investigate whether the simulated crew is sufficiently scaled to perform the additional tasks integrated into existing baseline activities in the Augmented model. Assess the effect that the total workload in the Augmented model has on the simulated crew's ability to complete activities while also accruing sufficient sleep.
- Evaluate strengths and weaknesses of the IMPRINT discrete event simulation tool to accurately simulate the workload and sleep of a simulated crew in the Baseline model, in accordance with the information collected from a nine-day underway sailing period on a NoCG vessel.

II. LITERATURE REVIEW

The goal of this thesis is to provide a method for determining the manpower required for future vessel acquisitions by the Royal Norwegian Navy. To explain why a data-driven, *Human Systems Integration* (HSI) approach is necessary, this chapter uses examples from the U.S. Navy and information from the RNoN fleet. The literature review covers the acquisition process, with a focus on manpower and manning, before narrowing in on human capabilities and limitations regarding workload and sleep. At the end of the chapter, the study introduces modeling and simulation of human performance and identifies the simulation tool *Improved Performance Research Integration Tool* (IMPRINT). Chapter III presents the utilization of the tool and the data collection effort that provided information to it.

A. RNON ACQUISITION PROCESS AND DEFINITION OF THE OPERATIONAL NEED

The RNoN is due to conduct an organizational update of its vessel structure (Forsvarsdepartementet, 2020), which includes investing in new mine countermeasure (MCM) motherships and other modular-based vessels. It is imperative that Norway is able to perform mine countermeasure operations to ensure allied forces safe access to both its waters and land (Forsvarsdepartementet, 2020). The new system is expected to carry different autonomous and unmanned systems, which will be deployed to explore minefields and neutralize threats to shipping traffic (Hareide et al., 2018). Autonomous systems are intended to operate independently after deployment, reacting to the environment and acting based on a predetermined set of rules. While unmanned systems operate without humans onboard, the controls are still performed remotely by humans, and thus, human-centered design is critically important (Chen, 2022). The importance of the North Atlantic Treaty Organization (NATO), and the reliance on receiving support in case of a military conflict, upholds the need for measures to ensure the security of the arriving forces (Forsvarssjefen, 2019). With the proposition to procure a range of ships mainly aimed at operating within the Norwegian economic and territorial waters, the ability to support maritime military needs is strengthened (Forsvaret, 2022).

To acquire the needed capabilities, the Norwegian Armed Forces adhere to an acquisition model called PRINISX. The acquisition process is phase-driven (Forsvarsmateriell, n.d.), with a structure similar to the U.S. acquisition and the systems engineering processes—consisting of an Idea phase, Conceptual phase, Pre-project phase, Implementation phase, and Termination phase. After the initial idea is shaped in the Idea phase, the next step is to identify the necessary capabilities and develop them into requirements during the Conceptual phase, which is crucial for laying the foundation of program success. A thorough grasp of the requirements and constraints early in the acquisition life cycle can allow for effective trade-offs throughout the development and sustainment phases. Omitting the exploration of capability requirements increases the program’s risk of not meeting funding or performance goals, or both (Cilli et al., 2015). Essentially all military systems involve a human component, from the operator and maintainer to the training instructor. As such, human concerns need to be part of determining the requirements for the system using sound HSI principles (Sevillian, 2011).

B. HUMAN SYSTEMS INTEGRATION

Finding the optimal relationship between human limitations and the affordances offered by systems is contingent on a purposeful HSI process. Even autonomous and unmanned systems cannot operate without some form of human input, whether it is direct control or indirect (e.g., maintenance or training). HSI recognizes that humans are an integral part of any system (Shattuck, Drillings et al., 2015). Initially thought of as the U.S. Army concept of Manpower and Personnel Integration “MANPRINT,” HSI introduces additional domains that are of human concern when operating systems—manpower being one of them.

HSI can be summarized as “providing methods to get human performance data into the decision process in a way sufficiently quantitative that decision-makers can make meaningful and reliable tradeoff decisions” (Booher, 1990, p. 347). HSI significantly affects system performance and life cycle return on investment; however, for HSI to amplify the system properties most effectively, human concerns must be incorporated early in the design process (Sebok & Walters, 2016). Determining which human qualities are

relevant to a system can be challenging while an acquisition program is still in its infancy. Budgetary constraints will often determine the limits to system capabilities, and users can be forgotten when decision makers are deliberating on which technological solution can fit within those constraints. Thus, incorporating HSI in the top-level requirements of a system is vital to not losing sight of human concerns, while allowing for flexibility to alter lower-level requirements throughout the process as more information becomes available (Booher, 2003).

The HSI efforts should be led by program managers in conjunction with dedicated HSI practitioners responsible for maintaining the integration of the user. HSI includes a wide range of efforts based around using anthropological and human performance data to best accommodate the user to perform as part of the system. Sebok and Walters (2016) propose using functional and later task analysis to determine the *manpower* requirements during the design phases, meaning the number and types of personnel (i.e., operators, maintainers, contractors, and instructors) that are needed to contribute to a system. Such efforts must be emphasized throughout the system's life cycle when examining costs and conducting trade-offs. The benefits of doing so can be immense, with one Canadian study showing a 40-to-1 payoff from investing in a comprehensive approach to considering human affordances and limitations when developing systems (Greenley et al., 2008). Given the potential return on investment, the next sections discuss different approaches to determining manpower and why these efforts can fail after ships are launched.

C. MANPOWER REQUIREMENTS AND MANNING

Determining the appropriate manpower for a navy ship is a complex and intricate process, and the number of sailors needed may not ultimately align with the number of sailors *manning* the system. Sailors must be able to operate and maintain the system in a wide spectrum of operations and tasks; however, they do not operate in a vacuum—i.e., the navy's chosen maintenance concept affects the amount of shore support from both the military and commercial sectors that contribute to reducing the work needs onboard (e.g., how much heavy maintenance tasks contracted to shore-based facilities will decrease crew workload). Generally, assigned manpower must be sufficient to support two readiness

states; State 1 battle readiness, in which the whole crew is manning battle stations during a 24-hour effort including resources diverted to damage control. The other readiness state is called State 3 wartime readiness, which has an indefinite timeline and requires the crew to support all underway functions, usually solved through rotating watches (Office of the Chief of Naval Operations, 2014, 2017). Consequently, finding the right balance between the least number of billets to ensure operational readiness and the lowest life cycle costs while optimizing performance relies on sound manpower design principles.

Within the U.S. Navy, the Navy Manpower Analysis Center (NAVMAC) is responsible for building the Navy's workforce structure (Office of the Chief of Naval Operations, 2021). NAVMAC determines *manpower requirements* based on the Required Operational Capabilities (ROC) in a Projected Operational Environment (POE), which is described in a Ship Manpower Document (SMD). This document illustrates the “quantitative and qualitative manpower positions of a sea duty activity or a sea duty activity with ashore duty component(s),” essentially the number of billets and types of roles that must be filled to meet operational demands (Office of the Chief of Naval Operations, 2021).

Whereas the U.S. Navy has allocated specific resources to help determine manpower needs, the RNoN lacks a similarly dedicated organization. The RNoN manpower organization, an inherent part of the RNoN staff, is mainly concerned with human resources activities (e.g., hiring and retention, career guidance, and policy), limiting its manpower analysis reach. While various efforts have been conducted to determine an optimal number of billets after a vessel has been launched, integrating this analysis into the design and acquisition of a vessel is lacking.

In a robust acquisition program with HSI considerations, manpower requirements are the precursor for the effort of manning the system. The number of billets on a ship is a product of the work that has been done analyzing the manpower needed to ensure that operational tasks can be achieved; however, the final number does not rely solely on the human performance aspects. Economic concerns are highly significant, leading to manpower concepts weighted towards minimizing the recurring life cycle cost of manpower. It is also important to recognize the existing discrepancies between required

manpower when assessing the full range of tasks and roles that each billet should be doing throughout the acquisition process and the number of manned billets which is eventually limited by funding and available personnel (Rodney, 2017). An effort to reduce the cost of manpower was attempted by the U.S. Navy through its “optimal manning” concept starting in the early 2000s (Fletcher, 2018). The goal of the optimal manning concept was to reduce spending by having sailors do more with less and finding the “optimal” return on investment, demonstrated in Figure 1. The figure also shows how cost is dependent on scaling manning and capabilities to the operational environment and spanning operations from peace to war (Spindel et al., 2000). While manning is a major cost driver, reducing manning to the point of approaching unmanned vessels can be expensive as well. The optimal manning concept led to initial cost reductions, but depleted ship manning soon triggered a growing lack of maintenance and material readiness which prompted the U.S. Navy to abandon the concept between 2010 and 2014 (Pendleton, 2017).

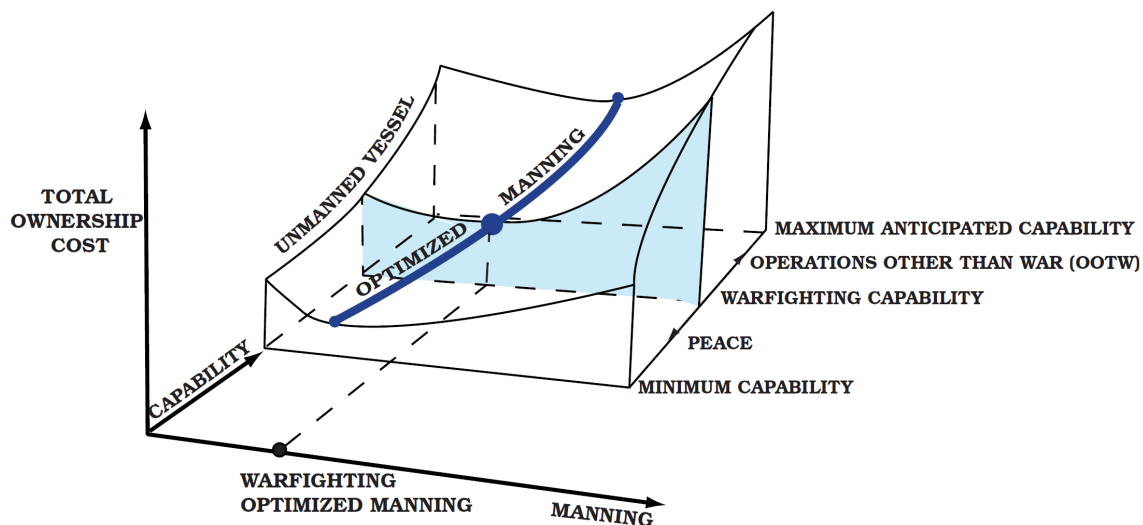


Figure 1. Reasoning behind optimal manning, weighing manning and capability with total ownership costs. Source: Spindel et al. (2000, p. 25).

The Royal Norwegian Navy has two different approaches to manning, depending on whether a vessel is part of the navy fleet or the coast guard—while the NoCG and Navy both fall within the RNoN, they each have different operating procedures. The NoCG

follows a three-week on/three-week off rotation, with strict leave periods in between sea tours. This approach requires two complete crews per vessel, maximizing the amount of time the ships have in the operational area (Tangedal, 2015). In 2022, open ocean NoCG vessels accomplished roughly 300 days of sailing on average (Kystvakten, 2023). This number stands in contrast to the average days of sailing for the traditional navy fleet, for which the RNoN set a goal of approximately 100 days of sailing for the navy frigates (Kvamme, 2022). The Navy fleet deploys one crew per ship, and unlike the NoCG, time ashore does not automatically entail leave periods. Many sailors experience long days while in port, conducting maintenance, training, or preparing for the next mission. Coupled with condensed training opportunities, the fewer sailing days in the Navy results in a higher operations pace, “OPTEMPO,” which Castro and Adler (1999) argue can result in reduced personnel performance and diminished retention rates.

The Norwegian Navy fleet adheres to the “Lean Manning Concept” (LMC), a Norwegian take on optimizing manning, with the main goal of reducing manpower expenses. Analyses conducted by the Norwegian Defense Department when developing LMC determined that a crew amounting to 60% of the NATO standard was achievable while cutting sustainment costs in half (Forsvaret, 2004). LMC was first adopted by the Nansen-class frigates, and later throughout the Norwegian navy, including MCM vessels (Ombudsnemda for Forsvaret, 2018). LMC leaves the crew extremely vulnerable to any vacancies as every sailor is responsible for multiple onboard roles (e.g., navigator, firefighter, and medic) with little or no redundancy. A recent report from Det Norske Veritas (DNV) (2022) regarding safety culture described an increased workload among sailors due to manning deficiencies. Moving sailors between vessels to fill critical vacancies (cross-decking) will consequently leave operational billets empty on the corresponding vessel. Such instances require other sailors to take on additional responsibilities or roles of the missing personnel, resulting in work not being done or people suffering from excess workload. LMC also necessitates highly skilled and motivated personnel and a comprehensive training program before personnel can take on multiple roles on the ship. Refraining from upholding those principles can have

catastrophic results, as evident from the HNoMS Helge Ingstad shipwreck in 2018, in which the frigate was a total loss.

At 04:01:15, HNoMS Helge Ingstad collided with the tanker Sola TS. The first point of impact was Sola TS' starboard anchor and the area just in front of HNoMS Helge Ingstad's starboard torpedo magazine. HNoMS Helge Ingstad suffered extensive damage along the starboard side. Seven crewmembers sustained minor physical injuries. Sola TS received minor damage and none of the crew were injured. Marine gas oil leaked out into the Hjeltefjord. (Statens Havarikommisjon, 2019b, p. 6)

The commission in charge of the incident report concluded that LMC does not seem conducive to increases in operational activity over longer time periods (Statens Havarikommisjon, 2021). The crash was attributed, among other reasons, to insufficient training and inadequate manning based on the manpower concept (Statens Havarikommisjon, 2019a).

While the RNoN has implemented several measures to prevent future shipwrecks or similarly critical incidents from occurring (Kaalaas, 2021), a new manpower concept has not been developed, and activity-based manpower requirements have not been implemented for impending acquisitions. According to recent reports, the Navy fleet leadership is considering crew rotation as a remedy to the manning challenges (Drevon, 2022). This action increases the viability of investigating the staffing situation on NoCG vessels as a potential blueprint for future vessel procurements. Crew rotation could allow for more time in training as a consequence of more sailing days, while increasing the personnel pool that can be drawn from in case of critical vacancies, without immediately impacting the manning structure of a corresponding vessel. Adherence to sound manpower principles may also lead to optimized performance and improved retention rates, further increasing the overall effectiveness and experience levels of the RNoN fleet. Even with enough manpower on paper, however, it is challenging to assess each sailor's contributions. To achieve this, the U.S. Navy created standard workweeks with clear expectations of the number of hours each sailor should work.

D. CHALLENGES TO DETERMINING MANPOWER

The U.S. Navy constructed the Navy Standard Workweek, which was later converted into the Naval Availability Factor (NAF), for calculating and improving the manpower requirements for vessel classes (Fletcher, 2018). The NAF outlines the work each billet is expected to provide per week, shown in Table 1, but is based on optimal manning conditions; fully manned, fully trained, and sufficiently capable.

Table 1. Naval Availability Factor. Adapted from Office of the Chief of Naval Operations (2021, p. D-3).

Navy Availability Factor:		81
- Productive Availability Factor (incl. watchstanding)	67	
- Training for combat readiness	8	
- Service diversion, consisting of inspections, administrative work	6	
Non-productive hours		87
- Personal time, including messing, sleep, hygiene, PT		
Total weekly hours		168

The NAF provides guidance on how to balance work and personal time; however, it seldom offers an accurate description of the actual workload demanded of sailors, often caused by lower than planned manning numbers on ships (Fletcher, 2018; Pendleton, 2017). Figure 2 visualizes the iterative reduction from what is required, through what manning is actually assigned, to the number of sailors onboard a vessel. According to Belcher et al. (2014), these discrepancies are the results of a wide range of issues, such as medical leave, inevitable fluctuations in recruiting, training throughput delays, misaligned handovers between positions, and unforeseen personnel churn.

Further, Fletcher (2018) introduced *requirements creep* as a contributing factor. The term describes additional systems or operational tasks, which subsequently increase workload. The resultant “readiness gap” promotes a higher workload for the personnel in the system, especially when the initial requirements were streamlined with insufficient manpower analysis to save costs. The Littoral Combat Ship-class (LCS) is among the programs that suffered from a lack of manpower requirements analysis. The ships were

deploying highly technical and automated systems with the hope of reducing manpower. However, as Cordle and Cotter showed in their study from 2019, the technologies were not sufficiently adapted to the capabilities of the sailors responsible for using them, concerns that were compounded by the causes of manning issues described by Belcher et al. (2014).

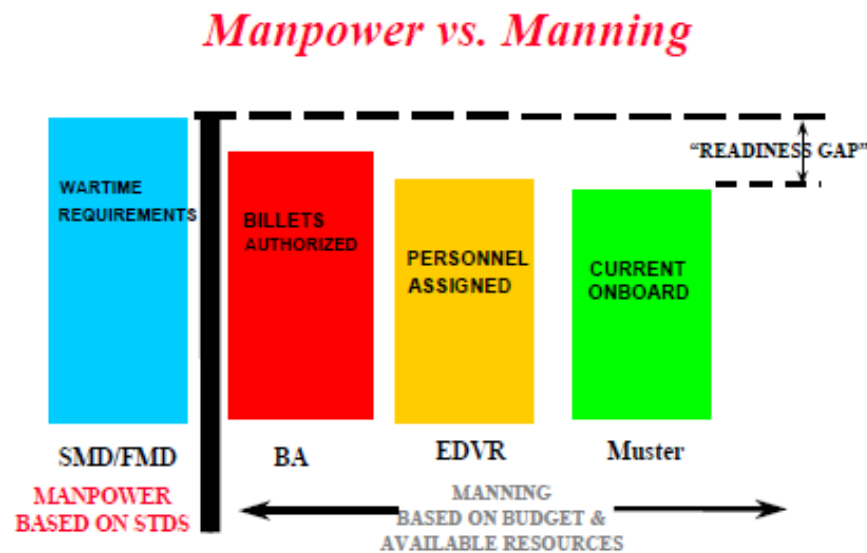


Figure 2. Relationship between the Wartime manpower requirements and the current number of trained personnel on board. Source: Carlton (2012, p. 2).

Although the RNoN has not adopted a version of the U.S. NAF, it continues to have difficulties with manning ships to the stated requirements. Given the remarks made by the commission responsible for investigating the RNoN shipwreck; of a lacking manpower concept, it is obvious that RNoN manpower requirements are based on optimal assumptions. Only a few years after commissioning five Norwegian Nansen-class frigates, the RNoN was forced to add additional berthing spaces to accommodate the additional billets required to operate the additional systems and operational tasks onboard. Such rework is costly and can lead to unintended consequences (Kennedy et al., 2014). For example, the vessels are currently experiencing major occurrences of black mold, which has been found on all ships in the class. To combat the spread, one measure has been frequent replacement of mattresses. The crews have also reported headaches, flu-like

symptoms, and fatigue. While causality has yet to be determined—potential increases in manpower and the resultant reduction in habitability—the symptoms of illness have been especially prevalent on ships with the largest mold outbreaks (Rognstrand, 2021). Considering how vulnerable the LMC is to vacancies, measures should be taken to ensure that manning is safe and effective even when incurring the inevitable “readiness gap.” With plans for the new vessel acquisition to continue adhering to “lean manning” (Forsvaret, 2022), it could be beneficial to require an investigation into the number of work hours expected for each billet and the types of work that constitute sailors’ *workload*.

E. WORKLOAD

Workload can be defined as “the relationship between the resources required to carry out a task and the resources available” (Wickens & Tsang, 2015, p. 277). Workload can be characterized in a variety of ways, such as physical or mental stress, or time spent working on a task (Lysaght et al., 1989). As a construct, it is impossible to observe completely, and workload potential varies from individual to individual in terms of perceptual, cognitive, and physical abilities (Anderson et al., 1997). Kramer et al. propose measuring *mental* workload as “the reduction in the capacity to perform additional tasks using the same processing resource” (1987, p. 146), while heart rate is commonly used to measure *physical* strain (Lysaght et al., 1989). Workload often coincides with the task and how a person experiences the task environment. People’s ability to handle workload is regulated by training level, skill, level of automation of tasks, and ergonomic concerns (Gaillard, 1993), for example, factors that can fluctuate throughout the system life cycle as users and systems change and develop. Thus, determining the system workload for use in manpower requirement decisions is challenging. In the context of the naval operational environment, workload can take the shape of exercising physical force handling equipment, contemplating the best course of action, or counting hours manning the operations room and supporting the ship’s situational awareness. These tasks accumulate into the required total system workload, which is divided among the crew into categories such as watchstanding, maintenance, administrative work, training, etc.

Most navy organizations are composed of highly experienced personnel, new recruits, and everything in between. Consequently, designing and assigning work tasks among sailors will inevitably have some local adaptations to account for the varying degrees of individual differences and levels of expertise. This is essential, on a local level as well as a broader fleet level, to find the optimal workload for both the personnel and ships. Figure 3 shows the relationship between workload and performance according to the Yerkes-Dodson *inverted U hypothesis*. Inadequate workload can have adverse emotional effects on individuals, compounding to negatively affect organizations (Sommers & Vodanovich, 2000; Spector & Fox, 2002; Wiesner et al., 2005). Underutilizing capabilities and inactivity can lead to unforeseen errors caused by omission or boredom (Welford, 1973).

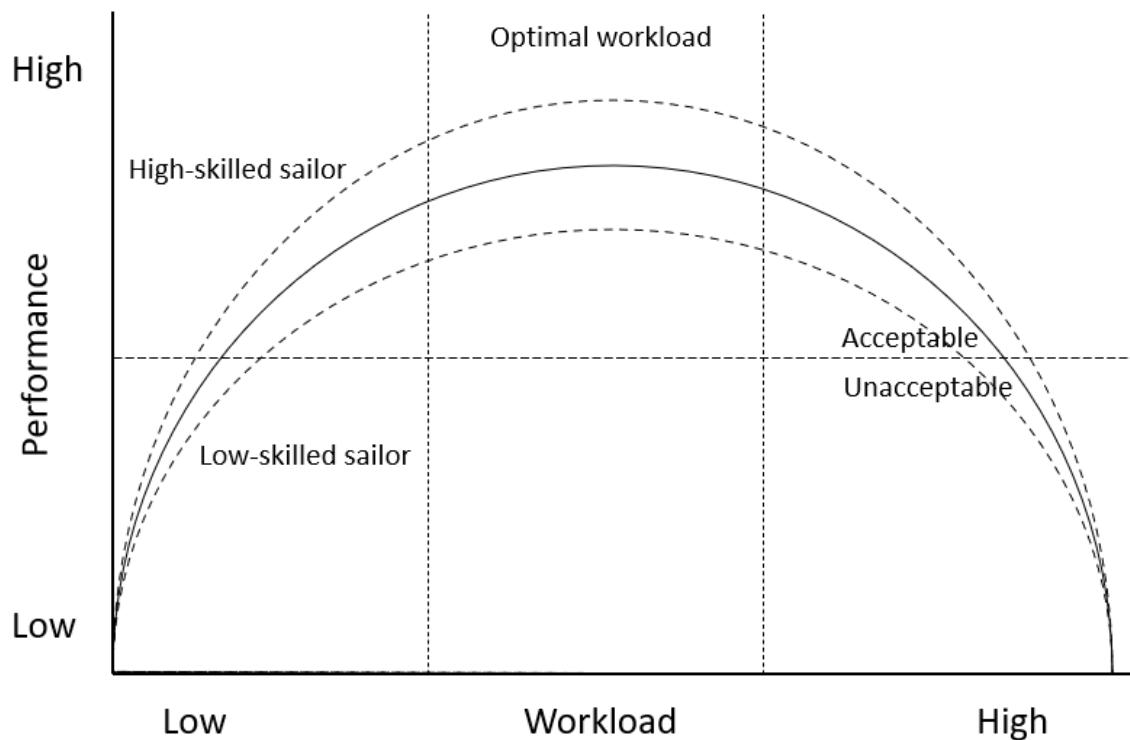


Figure 3. Inverted U relationship between workload and performance based on Yerkes-Dodson Law. Adapted from Welford (1973).

On the other end of the workload scale, being overworked can lead to a similar degradation in performance. Ronen et al. (2012) argue that finding the right level of workload will produce great results, but overloading or oversaturating the work capacity of personnel causes a rapid dip in performance. Eventually, performance drops below the required level, leading to unfinished work, inferior quality control, or unsafe situations. A weakness of the diagram in Figure 3 is omitting the difference between easy and demanding work tasks. Whereas a low-skilled sailor could get optimal arousal and perform well on easy tasks, the same tasks could lead to boredom and low performance among highly skilled sailors. Given this variability in sailors' skills and experience, time can be the most convenient way to measure workload. Hendy et al. (1997) discuss how time pressure, the ratio between the time necessary to complete a work task and the time attributed to the task, is a determining factor for predicting subjective workload and performance. Time is also used as a guideline for rest policies to limit workload, as evidenced in the Norwegian Ship Safety and Security Act, requiring civilian sailors to have no less than ten hours of daily rest and 11 hours daily on a weekly average (Nærings- og fiskeridepartementet, 2021). As seen with the NAF, however, relying only on a generalized time schedule can be misleading. Thus, investigating additional variables that are important for performance, like sleep, can contribute valuable data points to strengthen the validity of workload assessments.

F. SLEEP AND FATIGUE

Sleep can be defined as a “natural, easily reversible periodic state ... marked by the absence of wakefulness and by the loss of consciousness of one’s surroundings..., and is usually considered essential to the restoration and recovery of vital bodily and mental functions” (Merriam-Webster, n.d.). Most multicellular organisms experience some form of sleep pattern in which they feel a need to go to sleep, and humans are no exception (Savage & West, 2007). Human sleep is “controlled by an internal oscillator” (Brzezinski, 1997), which maintains a proclivity to conduct a sleep cycle once during every 24.5–25.0 hour interval.

This biological clock that provides an urge to sleep and awaken each day is called the *circadian rhythm* (Horne, 1988). The circadian rhythm stimulates various biological and physiological functions in the body, such as melatonin release, which controls propensities to sleep or be awake. For humans, melatonin release happens in the evening when the body is accustomed to going to sleep, helping to reduce sleep latency (Foster, 2021). Colquhoun et al. (1969) reported that attempting to sleep outside of the melatonin release window can be challenging, and it can take upwards of 12 days to acclimatize to a new sleep schedule, with symptoms such as discomfort and daytime sleepiness (commonly known as “jetlag” (Mayo Clinic, 2022)). According to a 2015 joint consensus statement from leading U.S. scientists, normal sleep cycles should amount to at least seven hours of sleep for optimal recuperation, although exceeding nine hours did not show additional benefits (Watson et al., 2015). Not only do humans require enough sleep, but it should also be uninterrupted to allow for the different stages of sleep that support cognitive recovery (Landmann et al., 2016; Turner et al., 2007).

Work schedules that do not support circadian rhythms or require sailors to sacrifice sleep to complete the work, will likely have a negative impact on performance (Shattuck, Matsangas et al., 2015). As the pressure to work more increases, other activities, such as sleep, can often be deprioritized (Young et al., 2015). Although science has yet to achieve a full understanding of why we sleep and the impact of sleep on health and performance (Krueger et al., 2016), there is no doubt that a lack of sleep has deleterious effects on human capabilities, decreasing alertness and vigilance (Laharnar et al., 2020). This finding was made evident in a study done by the Norwegian Coastal Administration in 2014, that showed involuntary sleep episodes as the main culprit (37%) for ship collisions and groundings (Kystverket, 2015). Another issue involving sleep in an operational, military context is sleep inertia, which may occur if woken up abruptly after restrictive sleep or interrupting deep sleep. Sleep inertia can cause temporary or persistent drops in performance (Tassi & Muzet, 2000).

Failure to maintain a regular sleep schedule or staying awake for extended periods may lead to the onset of *fatigue*, defined as “a state of reduced mental or physical performance capability, resulting from sleep loss or extended wakefulness, circadian

rhythmicity, workload, or other factors” (Gurubhagavatula et al., 2021, p. 2283). While sleepiness and fatigue share a lot of the same symptoms, fatigue can persist throughout a period of rest or sleep and even hinder restorative sleep (Rosenthal et al., 2008). Being alert and able to process their surroundings is crucial for Navy sailors to make sound decisions. Reduced vigilance can lead to catastrophic situations, putting valuable systems and crewmembers in dangerous situations. In order to minimize risks, it is essential to consider design options and investigate sleep habits and causes of fatigue. This can be done by looking at the current fleet. However, because existing ship classes differ significantly in terms of operations and technical solutions, new designs can be inadequate to install across the fleet. Looking toward the future vessel acquisition, these concerns can be mitigated by developing standardized and modular-based vessels that share much of the same system infrastructure and corresponding manpower requirements.

G. STANDARDIZATION AND MODULARITY

The RNoN is exploring the potential benefits of standardization to leverage mass production, thereby having fewer recruiting and training pipelines to fill a more predictable number of jobs and consolidating production and maintenance facilities. The end result would be higher procurement effectiveness and lower life cycle costs (Forsvaret, 2022). The idea of standardization is not a new one. During World War II, the U.S. Armed Forces stationed in Britain experienced a lack of metal screws with U.S. standard threading. While there had been considerable effort before the war to find a common standard among the North Atlantic nations, American forces found themselves unable to acquire the necessary materials because British manufacturers simply were not equipped to produce them (Jenkins & Williams, 1949).

In recent times, standardization can entail commonality between vessel classes, with open system architectures enabling adaptability and affordability for system upgrades (Forsvarsdepartementet, 2021b). One design approach is to maintain a standard hull, along with a core contingent of operators and systems that are applicable across tasks and operational concepts. Modularity creates the flexibility needed to utilize the vessels for various tasks. Spaces for installing task-specific systems are prepared with common system

interfaces, able to accommodate weapons, sensors, or other system modules. This standardization in design is a critical component in keeping the fleet technologically current, as systems can be easier to remove and replace. Nonetheless, there are limits to the benefits gained from standardization and modularity; as Davendralingam and DeLaurentis (2013) argue, additional modules and systems can “lead to risks of cascading modes of failure,” reducing the viability of leveraging the marketplace for modules that fit the standardized system outside of the original manufacturer.

The RNoN’s new procurement will follow the principle of “as commercial as possible, as military as needed” (Forsvarsdepartementet, 2021b, p. 48). By leveraging the technological developments of the Norwegian shipbuilding industry, RNoN will ensure military needs are met, with investments benefiting the national commercial sector. The approach aims to reduce costs and maintain the fleet size. The cost of procuring vessels with solely military specifications was made abundantly clear in the aftermath of the frigate HNoMS Helge Ingstad shipwreck on November 8, 2018, which resulted in a prohibitive replacement cost of 1.2–1.5 billion USD (PWC, 2019). Instead, a standardized vessel concept can be based on task-oriented modularity to provide capabilities.

This approach diverges from the mission-oriented concept of other modular-based ships, like the Danish Standard Flex 300, claiming swift module changes as a strong suit (Marinehist.dk, 1992) to meet changing operational demands. The U.S. Navy LCS is another example of a vessel designed to adapt to the mission through modularity. However, reduced funding, combined with lower than anticipated technological readiness, has made variations in mission packages practically permanent (Oakley, 2021). The U.S. Navy has recently moved away from planning to rapidly modifying ships from one specialty to another, for instance, from surface combatant to MCM. This altered approach has resulted in a more predictable system in terms of manning. However, the LCS has needed significant adjustments in manpower requirements after being commissioned (Hollins & Leszczynski, 2014), demonstrating the difficulty of assessing the correct manpower for modular-based vessels.

Using the military manufacturer Kongsberg’s Vanguard design as an example, the vessel will have the option to mount additional modules. As seen in Figure 4, the modules

span a wide range of capabilities. The modules will have teams of humans as part of the systems. These additional human detachments must scale to the vessel they are mounted on, with a plan for how they can work cohesively with the existing crew in terms of maintenance and other daily tasks.

MODULES MISSION									
Exercise Authority and Sovereignty	V	V			V	V		V	V
Harbour Protection	V		V	V	V		V		V
Search And Rescue		V	V				V	V	
Hydrographic Survey	V		V				V		
Area Denial		V			V	V		V	V
Anti Submarine Warfare	V						V	V	
Mine Clearance	V		V	V	V		V		

Left to right: Autonomous surface vessel with MCM capability, manned small boat, remote-controlled underwater vessel, autonomous underwater vessel, gun turret 40 mm or 76 mm, Naval Strike Missile (NSM) anti-surface missiles with land attack capability, towed sonar, helicopter, and anti-air missiles.

Figure 4. Vanguard design with modules. Source: Kongsberg (2019).

Without a structured approach to such issues, one can easily foresee a future where all empty spaces have been filled with weapons and fire control systems, without sufficient manpower requirements plans to ensure mission success. This can lead to either under- or overmanning. One solution to produce better assessments can be through modeling and simulation of the manpower.

H. HUMAN PERFORMANCE MODELING AND SIMULATION

In 2020, the Norwegian Chief of Defense opined that the Norwegian Armed Forces should procure systems that are already in use by allied forces. The economic risk of conducting large-scale investments is too high, as exemplified by the failed billion-dollar acquisition of the NH-90 maritime helicopters (Johnsen, 2020). Acquiring proven systems can provide access to existing manpower data or even live data-gathering efforts during

acquisition; however, Norwegian operational policies, cultural idiosyncrasies, and societal expectations can make a direct transfer of manpower requirements inadequate. What is the best way to create a manpower estimate?

Faced with a data set of variables, Grove and Meehl (1996) conducted a meta-study researching the outcomes of two different approaches to clinical predictions. The first approach used human judgments based on the data, combined with the experience of experts. The other method would feed the data through a mathematical algorithm, having a computer predict the outcomes instead. The overall results favored the latter to a significant degree, which Kahneman later reinforced in his *Thinking Fast and Slow*; “to maximize predictive accuracy, final decisions should be left to formulas, especially in low-validity environments” (2011, p. 225). Being able to substantively predict human behavior and performance is the goal of *human performance models*, expanding on the premise that humans are an integral part of any system, and thus key to overall system performance (Laughery et al., 2012).

A simulation model requires quality data to be effective and will improve as more data is supplied to it. The scope of available information will increase throughout a procurement process, as shown in Figure 5, but it is important to be cognizant of the fact that the initial iterations will have reduced validity. With most military systems evolving from prior legacy systems, human performance modeling and other HSI tools could be applied from the inception of the program (Sebok & Walters, 2016).

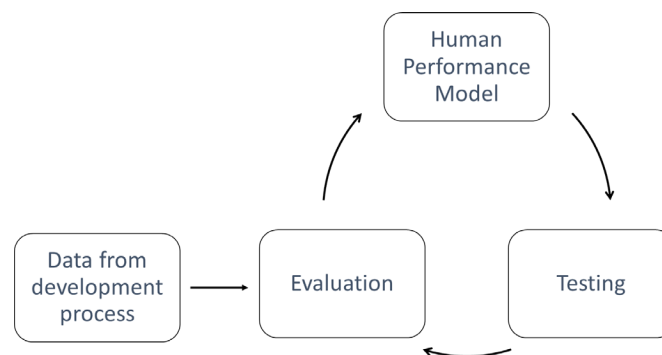


Figure 5. Iterative process of developing human performance models.
Adapted from Laughery et al. (2012).

Simulations of human performance have been used to create manpower requirements by the civilian and military sectors alike for decades. The Transportation Security Administration (TSA) has simulated staffing requirements in airports since 2005 (Kalasky et al., 2010). The naval manufacturer Royce Rolls promotes the importance of conducting simulations early to establish initial proof-of-concept in the pre-contract phase, with higher fidelity simulations following later in the development phase (Cartledge, 2001). In the U.S. Navy, the NAVMAC is tasked with calculating the optimal manpower requirements for navy vessels (Office of the Chief of Naval Operations, 2021), and simulation is part of that scope.

I. IMPRINT PRO FORCES

The Improved Performance Research Integration Tool (IMPRINT) is a “dynamic, stochastic, discrete event modeling tool,” using probabilistic variables and time sequences to represent soldier-system performance (Alion, 2018). Initially developed by the U.S. Army, IMPRINT was later adopted by researchers in other DOD services and federal agencies. The tool simulates successive discrete events, each representing a state of the modeled system, and it changes based on the probabilities of new events occurring for the next iteration of time, for which IMPRINT uses 15-minute increments. IMPRINT simulates activity and event success or failure based on the programmed tasks and events, and the people responsible for conducting the tasks (Hollins & Leszczynski, 2014; Ryan, 2014). As an example, a modeled system malfunction has a 25% probability of taking place, requiring one engineer to repair it. Each 15-minute increment will have a chance of having the malfunction. Depending on whether an engineer is available to draw from the manpower pool, the task will be completed or possibly fail. The IMPRINT Pro Forces module is especially designed to provide outputs and analyses that can direct attention to what area and which personnel in an organization will have the highest probability of experiencing excessive workload. Such information can be utilized in proceeding iterations of the model to produce a more accurate manpower estimate.

Equally crucial, IMPRINT offers the functionality of a trade-off analysis tool. It can provide indications of weaknesses in the current manning of the system or the

consequences of the gap between determined manpower and actual manning of a system. IMPRINT Pro Forces demonstrates how excessive workload will impede the operator's ability to complete all assigned tasks and to find time to rest between watches. This knowledge can enable stakeholders to increase, decrease, or maintain the current number of personnel—depending on requirements and available resources. Feeding the model with enough data can allow for a comprehensive assessment of the performance state of the simulated crew size of the system. For the wider discussion on tools that apply to a Norwegian acquisition process, IMPRINT is viewed as a surrogate for data-driven manpower modeling and should not be assumed as the single best or only option that should be used.

J. DATA-DRIVEN MANPOWER REQUIREMENTS

Although technological advancements may alter naval operations, humans are still crucial to operational success. This thesis emphasizes the significance of conducting a meticulous analysis of necessary manpower, regardless of the system or organization. A well-developed system should adhere to HSI principles and prioritize the user's needs. To achieve this, the procurement process must obtain data by studying actual users. Unfortunately, sailors are often too busy with their duties to contribute to lengthy acquisition processes or test extreme situations to determine the system's limits. Thus, the following chapters of this thesis demonstrate how simulation models can be a viable solution to contribute to the development of more accurate manpower requirements.

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III. METHODOLOGY

A. METHODOLOGY OVERVIEW

To support the acquisition of new vessels in the RNoN, the goal of this thesis is to demonstrate how a constructive discrete event simulation (DES) model can provide insight and contribute to the process of determining manpower requirements. The study deployed the IMPRINT Pro Forces module in a stepwise approach. In the first step, a data collection effort was conducted on a Norwegian Coast Guard ship similar in scale to the design of future ship acquisitions. The data were used to verify the input for the succeeding models would be based on workload demands and task performance. Both self-reported data and objective measurements contributed to the final models to provide organizational, task, and sleep data.

In the second step, the Baseline model of the ship's crew was developed, simulating the ship's crew while conducting planned tasks, expected corrective maintenance, and routine training exercises. In the third step, the baseline condition was augmented by introducing unplanned events, such as major corrective maintenance and operational tasks, as well as extreme events, such as actual damage control incidents (e.g., fires, floods, and Search and Rescue (SAR) operations). The Augmented model also contained ship-wide exercises, typically planned by a small contingent of crewmembers that appeared random for the other members of the crew, and irregular training that was opportunity-based and dependent on external resources. The simulation output provided workload data by identifying tasks that had been delayed or failed to be attended to by the simulated crew. Further, because reduced sleep hours can be an additional indication of excessive workload, IMPRINT output allowed for detecting jobs that were more susceptible to fatigue.

This chapter is divided into two main parts. The first part presents the thorough verification effort done prior to the development of the IMPRINT models, including a nine-day data collection on a NoCG vessel, which provided valuable insight into the workload and sleep of the crew. The underway data collection period also provided information on

jobs, rates, and events on which the models were built. The second part is a detailed description of the development of each of the IMPRINT models and the information that went into the tool to simulate the different model iterations as per Table 2 (Baseline, Augmented).

Table 2. Overview of input of the model iterations

Model	Modeled Activities			
	Planned Activities	Irregular Planned Activities	Irregular Activities	Unplanned Events
Baseline	X	X		
Augmented	X	X	X	X

B. APPARATUS

Several types of equipment were used in the development, verification, and analysis of the IMPRINT models. The sections below describe the software and hardware used in the study.

1. IMPRINT Pro Forces Module

The modeling efforts were carried out on the IMPRINT Pro Forces module version 4.6.60.0, developed by Alion Science and Technology. The Forces module is differentiated from the other IMPRINT modules by allowing for the scheduling of tasks and events for a large number of jobs, which according to the manufacturer, makes it suitable for analyzing the crew performance of a whole ship (Alion, 2018). The program was run on a VMware Workstation 16 Pro v.16.2.4 build-20089737 enabled virtual Windows 10 Home, 64-bit OS, v.10.0.19.045 Build 19045. IMPRINT was unable to be run on the newest Windows 11 OS due to incompatibility issues with the most recent version of the IMPRINT software.

2. Data Sets

The data collected for the verification effort and the input and output of the IMPRINT models were stored in Microsoft Excel 365 version 2202 Build

16.0.14931.20648. Prepared data were analyzed in JMP Pro 16 statistical software (SAS Institute, Cary, NC).

3. Hardware

IMPRINT was run on a Lenovo Yoga 920 laptop, running VMware virtual desktop on top of Windows 11 version 10.0.22000 Build 22000. The laptop was used for all aspects of the model, from structuring input in Excel to assembling and running the model. The only intended deviation was the 999 repeated runs of the model to provide statistical data. Those repeated runs were planned to be conducted on a more powerful desktop PC but ultimately were run on the same hardware as the rest of the model, despite its lack of processing power. The laptop was also utilized for communication with subject matter experts (SME) via its internal web camera, as well as external web camera equipment.

C. MODEL VERIFICATION

The verification process was a multi-pronged effort. Organizational data were collected from a NoCG vessel to get information usable for the creation of the IMPRINT model design. To gain additional information for the models, engagements with SMEs were necessary. Servicemembers from the RNoN were solicited for information used to verify inputs and validate the outputs of the manning models.

1. Norwegian Coast Guard Data Collection

The data collection on the Norwegian Coast Guard was conducted to verify inputs for the IMPRINT baseline model through mapping of tasks and schedules, jobs, roles, and both planned activities and unplanned events. Additionally, sleep habits and mood were investigated to verify the inputs to the models, emulating the toll experienced by the crewmembers during sailing, into the IMPRINT Baseline and Augmented models. If the crewmembers reported significant negative sleep habits or indications of fatigue after having worked onboard, similar mechanisms should have been displayed in the parameters of the model; however, in case of non-significant or light workload results, the model should have subsequently provided ample opportunity to sleep and rest.

a. Study Design

The study design followed a case study pattern consisting of three sections. The first part entailed a battery of questionnaires related to the respondents' demographic data, self-reported sleep habits, and mood states. The initial survey asked participants to indicate their experiences during the last two weeks, during which most of the respondents were on leave. The initial questionnaire was followed by a period in which the participants wore a sleep tracking wearable device (ŌURA rings) to assess sleep patterns objectively. Paper activity logs were also distributed and maintained for the duration of the case study. The logs were intended both as a subjective backup and validation tool in case of sleep tracking equipment errors or failure and, most importantly, to map work tasks and schedules among the participants. At the conclusion of the study, the same questionnaires used in the intake process were once again distributed and filled out. The study design allowed for the comparison between sleep habits and mood while on leave compared to those experienced while onboard. This allowed controlling for changes among the crew which may have been caused by factors pertaining to the ship and its operational activities.

The Naval Postgraduate School Institutional Review Board (NPS IRB) determined the data collection effort as “not human subjects research” as defined under 32 CFR 219 and did not require IRB review and approval; however, measures to protect personally identifiable information (PII) were taken in accordance with requests made by the Norwegian Defense Research Establishment. As “not human subjects research,” the sleep and mood information gathered from the NoCG vessel should not be assessed as generalizable outside the context of the study, and it does not apply to other settings. Nor should the model output be expected to replicate the exact day-to-day experiences of the subjects, as this would require additional efforts and details outside of the scope of this study.

b. Participants

The participating NoCG vessel was chosen by the Norwegian Coast Guard staff by convenience, although the size of the crew and the capabilities of the vessel were part of the determining factors, seen by Coast Guard leadership as relevant for future ship

procurements. There were 22 crewmembers onboard, and all of them gave their voluntary consent to be part of the nine-day study. Of the respondents, there were three officers, five petty officers, two enlisted, seven conscripts, and five civilians.

All NoCG vessels adhere to a three-week rotation, and most of the crewmembers returned from leave on the first day of the study. Of the respondents, four of the conscripts had already been onboard for three weeks, as the conscripts follow a six-week on/three-weeks off rotation. At the conclusion of the study, the crew was scheduled for the remaining 12 days of sailing before a new rotation and an eventual leave period.

c. Equipment

The study used a set of standardized questionnaires to assess sleep habits and mood. The activity logs were developed by the Crew Endurance Research team at the Naval Postgraduate School, with categories of activities that aligned with the aforementioned Navy Standard Work Week/Navy Availability Factor, with minor changes to task types to accommodate the activities performed by the NoCG vessel crew. The participants were encouraged to wear ŌURA rings for collecting sleep data as much as possible, although the aim was for the respondents to log any sleep activity—both their “main sleep” and any “power naps” that might have been taken during the day.

(1) Epworth Sleepiness Scale

The Epworth Sleepiness Scale (ESS) is used to assess the likelihood of adult respondents falling asleep in various situations experienced during the day (Johns, 1991). The questionnaire sets up the questions by asking the respondents to compare their proclivity to fall asleep in contrast to just feeling tired. The questions are rated on a four-point Likert scale from None (0) to High (3) chance of dozing in everyday situations like watching TV or reading. The resulting score estimates whether the respondent might suffer from sleep disturbances, with results exceeding ten indicating elevated symptoms of persistent daytime sleepiness (Johns, 1991).

(2) Insomnia Severity Index

The Insomnia Severity Index (ISI) consists of seven questions asking respondents to rate their insomnia symptoms on a Likert scale. Insomnia as a term is often considered a disorder representing issues with falling asleep or staying asleep, even when there is ample opportunity and desire to do so (Roth, 2007). The scale is divided into two parts, with the first asking about difficulties with falling asleep and staying asleep, rated from None (0) to Very Severe (4). The second part is concerned with the respondent's having insufficient sleep, rated from Very Satisfied (0) to Very Dissatisfied (4). After summing the points, a score of 7 and below indicates an absence of insomnia, 8–14; shows signs of subthreshold insomnia, 15–21; moderate insomnia. A total score of more than 21 is interpreted as severe insomnia (Morin et al., 2011).

(3) Pittsburgh Sleep Quality Index

The Pittsburgh Sleep Quality Index (PSQI) is used for assessing sleep quality among the participants. The questionnaire consists of 19 items resulting in seven component scores: “subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleeping medication, and daytime dysfunction” (Buysse et al., 1989, p. 193). The questions are divided into sub-sections, where the first few questions are sleep-related, asking the respondents to note typical sleep hours and latency. The rest of the questionnaire is mainly rated on Likert scales with fixed “frequency” alternatives. The components sum up to a total “global sleep score,” in which scores surpassing five indicate poor sleep quality (Buysse et al., 1989).

(4) Profile of Mood States (POMS) Scale

The Profile of Mood States (POMS) scale is a 65-item questionnaire used to assess mood states. Sleep deprivation is one of the wide range of symptoms the measure has been deployed to examine (Nyenhuis et al., 1999). POMS is divided into subscales: Tension, Depression, Anger, Vigor, Fatigue, and Confusion. These categories combine into a Total Mood score (TMD); however, the subscales are discriminant and can be used to gauge individual moods (Nyenhuis et al., 1999). Using the 50th percentile of the adult population as the norm, all the mood states except vigor have higher scores constituting a more

negative mood than the average adult. A higher vigor score indicates a more active mood, which would be valued positively.

(5) ŌURA data

Finger-worn physiological tracking devices (ŌURA Health Oy) were used to monitor sleep duration. Wearable devices are a validated source for collecting sleep data in the field, with the ability to discern between an individual being asleep or awake (Miller et al., 2022; Rupp & Balkin, 2011). The ŌURA generation 2 rings were used to provide the study with objective sleep data, as opposed to self-reported sleep from the questionnaires and activity logs. The ŌURA rings are a relatively new product from the manufacturer, ŌURA Health Oy, showing similar sleep detection ability as polysomnography devices frequently used at sleep research clinics (de Zambotti et al., 2019). Although the device is deficient in differentiating between the different stages of sleep as compared to the “gold standard” of laboratory-controlled equipment (Miller et al., 2022, p. 16), the practicality of wearing a simple ring allowed for the study to attain objective sleep data without interfering with routine military operations.

(6) Activity Logs

The activity logs were used for building daily schedules for those parts of the crew adhering to different watchstanding rotations and for otherwise mapping of tasks for each participant. The logs were distributed as pamphlets with one page for registering activities for every day of the study, with three extra days as spares in case of entry errors, etc. The participants also had the option to fill in notes and state the number of caffeine servings ingested that day. The logs divided each day into 15-minute increments, allowing participants to specify activities from the categories in Table 3.

Table 3. Activity categories for which the crew were asked to describe their daily schedule in 15-minute increments

Activity log categories
Operations/events
Administrative work
Physical training/hygiene
Briefs/meetings
Maintenance
Sweepers (cleaning)
Rest
Watch
Eating (messing)
Sleep
Operational exercises

a. Procedures

The data collection period started on August 17, 2022, and was initiated by an introduction brief and walkthrough of the study equipment for the whole NoCG vessel crew. After signing consent forms as voluntary participants (which was required by Norway but waived by the NPS IRB), all 22 crewmembers received ŌURA rings and subsequently had the rings synchronized with their mobile devices for uploading sleep data. Pre-study questionnaires: Demographic questions, ESS, ISI, PQSI, and POMS, were answered consecutively, and the activity logs were distributed. The pre-study created a baseline by recording information on sleep habits from the weeks prior to sailing. The four participants who were remaining on board from the previous rotation were asked to report sleep habits from their previous off-duty period. The crewmembers reported activities each day until the afternoon of August 26, 2022, when the logs were collected; however, partial logs were retrieved by the research team on August 21, 2022, for verification of reported content. The post-study questionnaires and POMS were filled out on August 25, 2022,

when it was convenient for participants between activities. The ŌURA rings were collected on August 26, 2022, registering the previous night as the last sleep activity available in the study.

b. Data Preparation

Preparation of data was done throughout the data collection period. Organizational data were structured in Microsoft Excel, mapping individual billets to rank, department, watch sections, jobs, roles, and qualifications. Sleep and work data entries were manually entered on the logs, with only ŌURA data being completely digital. Completed questionnaires and activity logs were transferred into Microsoft Excel spreadsheet templates based on previous data collection efforts done by NPS researchers.

For ESS and ISI, which were based exclusively on Likert scale values, any missing data points would exclude the participant from the analysis. All 22 crewmembers answered those pre- and post-studies in full. In cases of reporting split sleep due to nightly watchstanding duties, accumulated sleep from both periods before and after the watch would be registered (e.g., sleep from 2100–2330 and 0430–1000 would be registered as eight hours of sleep). If PSQI scores were missing to the degree that calculating overall scores was impossible, the participant was excluded from the analysis. All crewmembers answered the questionnaires sufficiently. For missing answers on the POMS questionnaires, a group average would be used. The method would entail using the items corresponding to the missing questions to create that average (e.g., tension or vigor groups). Two or more missing items in one distinct group would lead to the participant being excluded from the analysis. All individuals answered enough questions to warrant being part of the analysis.

ŌURA data were retrieved as a .csv file from the online ŌURA Teams web platform after the data collection period. ŌURA calculates sleep per day starting after the previous long sleep period. The device also recorded shorter sleep periods in case of napping and instances where watchstanding participants had two longer periods of sleep before and after a nighttime watch. To differentiate between the two episodes of sleep, the study defined napping as periods between zero and two hours of time in bed. Part of the

data preparation attributed occasions of shorter sleep lasting less than two hours to the applicable long sleep activity; hence, a person who took a nap of 30 minutes during the daytime, then proceeded to sleep six and a half hours the following night would achieve an accumulated sleep duration for that 24-hour period of seven hours. Verification of the reported data was done in Excel by correlating the data with the activity logs and excluding data that deviated significantly from self-reported data. While there was evidence of only a single data error, there were other missing data due to uploading issues. For the analysis of ŌURA data, only crewmembers who participated in day-to-day activities throughout and provided one or more viable sleep entries would be included, which left 21 participants for the analysis. After removing ineligible participants and cleaning the data for analysis, the remaining datasets which were used for analysis are summarized in Table 3.

Table 4. Participants for the different data collection methods

	Pre-study	Post-study
Ōura data	-	21
Activity logs	-	21
ESS	22	22
ISI	22	22
PSQI	22	22
POMS	22	22

The reported data were prepared by grouping the participants based on schedules into three occupational groups called “watchstanders,” “daymen,” and “engineering,” as shown in Table 5. The watchstander category entailed working on the bridge at set intervals, including at least one four-hour night watch between 2000 and 0800. The engineering department conformed to on-call sleeping watches during nighttime, with a designated duty to react to any engine failures that might occur. Their schedule was otherwise approximately 0800 to 1700, encompassing their ordinary work tasks. The dayman schedule included day workers; both non-watchstanders and sailors adhering to a daytime watch (i.e., a single four-hour watch between 0800 and 2000). Participants sorted into dayman-shifts had the opportunity to achieve regular sleep during most nights.

Table 5. Number of participants in each category

	Occupational category
Watchstander	7
Dayman	11
Engineering	4

The activity logs were prepared by amassing the 15-minute items into total time spent conducting the various activity categories each day, with additional summary categories termed “on-duty”: operations, administrative work, maintenance, sweepers, watch, meetings, and exercises—and “off-duty”: sleep, rest, physical training/hygiene, and messing. Averages were calculated from the accumulated data both for individual assessment and for the different occupational categories from Table 4.

c. Analytical Approach

The data collection effort afforded a two-pronged analytical approach. First, the data from the ŌURA rings and self-reported activity logs, in addition to SME input and observations, were used for creating inputs to the model. The activity logs provided the outline for on- and off-duty activities used to populate the schedules that are presented in the next part of this chapter which addresses model creation. As a key factor for human performance, sleep was of special interest. Since the sleep tracking wearable devices could distinguish between time in bed and effective sleep, it was important to compare and analyze the two variables. Furthermore, it was essential to decide on which variable aligned best with the self-reported sleep from activity logs, which consequently helped to determine which factor was used when building the IMPRINT models. The input data used in the creation of the models would subsequently be unavailable for comparison to the output of the model.

Variables such as sleep and time in bed were investigated and presented on a whole-crew level as the median and interquartile range (Mdn, IQR), while the activity logs were shown using mean and standard deviation (M, SD). Subsequently, the same variables were analyzed after being divided into occupational groups of watchstanders,

daymen, and engineering to look for differences between them. All variables were evaluated using the Wilcoxon signed rank test, and significant findings were further investigated in the Kruskal-Wallis rank sum for comparing between groups. In the case of significance exceeding $\alpha > 0.1$, Tukey HSD was used for identifying the groups that distinguished themselves from the others.

Second, the questionnaires were presented to give insight into the effects of sailing by gauging the mood and sleep habits of the respondents. The reported answers from the questionnaires should align positively with the workloads of simulated crewmembers from the baseline iteration IMPRINT model. However, the analysis had to be mindful of the increased error caused by time scope differences between the nine-day data collection period and the 21-day simulation. As such, the analysis would mainly be concerned with presenting descriptive statistics of the investigated variables for each questionnaire. Similar to the input data, mean and standard deviation or median and interquartile ranges were used. When comparing pre- and post-study results, the model used the statistical significance level of $\alpha > 0.1$. Subsequently, the Wilcoxon signed rank test and McNemar's test were used for assessing statistically significant changes in sleep quality (PSQI), mood (POMS), or the presence of sleep disturbances (ESS, ISI) after inserting the data into JMP Pro 16.0.0.

2. Subject Matter Expert Engagements

SMEs were frequently queried to provide the necessary level of detailed data for the models. Colleagues from the RNoN, as well as industry partners, were contacted through email, telephone, and video conferencing at the beginning of the development of the models. These communications included such things as in-depth walkthroughs of crew scheduling or quick updates to steer the modeling effort in the right direction and were conducted in interview and discussion formats. Due to scheduling conflicts and time zone differences, it became challenging to sustain an iterative process of frequent testing that was dependent on continuous correspondence with SMEs. However, the initial effort was deemed sufficient to ensure that the jobs, roles, and events used were reasonable and as correct as possible.

Having presented the method for accruing data used in the IMPRINT simulation models, this thesis now demonstrates how the data were assembled for processing in the IMPRINT simulation program to produce the baseline and the augmented models.

D. MODELING

The following section gives an overview of the steps taken to build the models in the IMPRINT Pro Forces module using input provided through observations during the data collection on the NoCG vessel and discussions with SMEs. The development of the models tracked the method first developed by Hollins and Leszczynski (2014) and later refined through numerous efforts conducted by students and researchers at NPS (Attwood, 2020; Hollins & Leszczynski, 2014; Meredith, 2016; Poirier, 2020). The section starts by giving a brief introduction to the modeling approach, followed by a presentation of the inputs used and the stepwise design process of an IMPRINT model.

1. IMPRINT Pro Forces Models Overview

The modeling effort was initiated by defining the differentiating factors between the two models. The Baseline model included several planned activities necessary for the ship to navigate and conduct predictable work tasks to ensure the support of underway operations. It also had to account for daily activities that were more irregular in nature, like training drills conducted by a sub-team of sailors. Such activities seldom have set timeslots at the onset of the sailing period but are done by convenience or need—or at the behest of leadership. These irregular but planned activities can sometimes come into conflict with other activities, causing delays or cancellations, but are unlikely to contribute to additional workload as they replace other administrative tasks. As the standard operational pattern of NoCG vessels, the model needed to simulate 21 days at sea for the 22 crewmembers. The Baseline model included daily scheduled activities like eating, sleep, rest, administrative work, watchstanding, and training, in addition to irregular planned activities like small boat training and weapon drills.

The Augmented model added “unplanned” events to the Baseline model. These events prompt parts of the crew to refrain from the set schedule and attend to these unplanned tasks as they occur. Certain irregular training or exercises can be outside of

the control of the crew, especially those depending on external resources. Exercises emulating operations such as SAR, towing, and external damage control can also be prolonged to the last into activity slots reserved by other tasks or rest and thus affect task performance or total workload. Concurrently, live incidents were part of the augmented model, as the crew must react to provide damage control for fires, floods, and electrical outages. Major material failures were another group of conceivable events that had to be considered during the simulated 21-day sailing period of the Augmented model.

The models were compared to assess how schedules and necessary rest and sleep patterns were affected by the introduction of unplanned events, additional crewmembers, and tasks. Depending on the effects on sleep and performance, data would be telling as to the state of the modeled manning situation.

2. Input to the Models

The data collection effort on the NoCG vessel was the main source of input variables in the model, bolstered by communication with SMEs during and after the underway data collection. Ships in the RNoN fleet have muster cards that list jobs (billets) with their corresponding watchstanding responsibilities and roles that each sailor must adopt, depending on any number of situations. Such cards were the foundation for a Ship Manning Document (SMD) shown in Table 6 and later refined through conversations with NoCG vessel crewmembers, showing jobs, departments, watchstanding schedules, and active qualifications that enabled the individual crew member to take on various roles contingent on operational needs.

Table 6. Sample of jobs, watch schedules, and job roles of the NoCG vessel crew used in the IMPRINT models

Job	Department	Watch Schedule	Job roles								
Operations Officer	Operations	Watch Section 3 (0000–0400)	Navigator			Whole Ship Event	50 cal./ 40 mm Fire director	Medical officer		Fishery inspection officer	
Bosun Officer	Deck	Dayman-Watch Section 2 (1200–1600)	Navigator	Deck Crane	Davit operator	Whole Ship Event	50 cal./40 mm Fire director	Smoke Diver	Boat Driver	Fishery inspection officer	Fishery inspection assistant
Battery Officer	Weapons	Watch Section 4 (0400–0800)	Navigator	Health and hazard inspector		Whole Ship Event	50 cal./40 mm Fire director	Gun firing safety officer		Fishery inspection officer	Fishery inspection assistant
CIS Officer	Operations	Dayman-Watch Section 1 (0800–1200)	Navigator	Comms Officer	Navigator in Training	Whole Ship Event				Fishery inspection officer	Fishery inspection assistant
Chief Engineer	MSE	Engineering	Mechanic	Electrician	Engine Casualty Technician	Whole Ship Event					
1. Engineer	MSE	Engineering	Mechanic		Engine Casualty Technician	Whole Ship Event					

While on board, the crew conducted a host of different tasks; however, most could be divided into the categories shown in Table 7. Due to recurring three-week crew rotations, the NoCG vessel crew would experience only brief daytime port stays, making in-shore work negligible. The handover between the embarking and debarking crews was not part of the modeling due to the lack of watchstanding schedules and the observed fluidity of such a scenario. New and old crewmembers arrived at different time points, and tasks were diametrically different from sailing, although some of them could ostensibly fit into the termed categories.

Table 7. Planned, Irregular, and Unplanned tasks and event categories on the NoCG vessel

Baseline Model		Augmented Model	
Planned Activities	Irregular Planned Activities	Irregular Activities	Unplanned Events
Cleanup after Meal	.50 cal Drill Training	Anchoring Exercise	Actual External DC
Critical Watch	40 mm Drill Training	Collision DC/Blackout Exercise	Actual Internal DC
Eating	.50 cal Exercise	Emergency Steering Exercise	Actual MOB
Hygiene	40 mm Exercise	External DC Exercise	Actual Oil spill
Morning Brief	Abandon Vessel Muster First day	Fishery Inspection	Actual SAR
Personal Time & Fitness	Crew Muster First day	Helicopter Winch Exercise	Actual Towing
Prepare Food	Diving training	Internal DC Exercise	CM Electrical Eq.
Preventive Maintenance	Internal DC/Smoke Diver Training	Medical Casualty Exercise	CM Eq. for Crew and Passengers
Sleep	Lookout Brief Training	MOB Drill Exercise	CM Machinery Main Comp.
Sweepers	Medic Training	Oil spill Exercise	CM Ship Common Systems
Work	MOB Second day	SAR Exercise	CM Ship Eq.
-	Navigation Exercise	Towing Initiation Exercise	CM Systems for Machinery Main Comp.
-	Occupational Hazards Meeting First day	-	E0-Alarm
-	Onboard Hazardous Spill Training	-	Engine LNG Casualty
-	PLT Firing	-	Engine Main Casualty
-	Safety Inspection	-	-
-	Safety Walkthrough First day	-	-
-	Seamanship Training	-	-
-	Small Boat Training	-	-
-	Witness Brief Training	-	-
-	CM Hull	-	-
-	CM Eq. for Cargo	-	-
-	CM Comms/Network	-	-

To provide context to the activities of Table 7, the durations of the tasks and how they corresponded with the inception of various events, required a broad knowledge of the ins and outs of the ship and its operational pattern. To corroborate the cards and SME input, the crew maintained self-reported activity logs during the data collection effort. Additionally, participants wore sleep tracking devices (ÖURA rings) to provide

objective information to support self-reported sleep durations. While the ŌURA rings tracked both sleep and time in bed, the latter was used for modeling to account for the fact that when sailors are in bed, trying to sleep, it effectively removed them from doing other activities. Information on unplanned events was harder to come by, and few occurred during the data collection. Only experienced SMEs could verifiably speak on these matters, and both the Executive Officer (XO) and Operations Officer contributed and validated one another’s input on unexpected incidents and events. Table 8 shows the modeled probabilities as proportions per day of some of the events included in the Augmented model. Since several of these incidents are exceptionally rare, the probabilities must still be assessed as estimates. However, they were intrinsic to modeling in order to test the crew in extreme circumstances.

Table 8. Probability per day of unplanned events and major engine issues occurring

Unplanned Events	Modeled Probability
Actual External DC	1:208
Actual Internal DC	1:200
Actual MOB	1:200
Actual Oil spill	1:200
Actual SAR	1:84
Actual Towing	1:63
Engine LNG Casualty	1:200
Engine Main Casualty	1:200

1. IMPRINT Pro Forces Model Design

The NoCG vessel model built in the IMPRINT Pro Forces module was developed following the blueprint created through previous work at NPS, most closely resembling

the method used by Meredith (2016) and later Poirier (2020). The method was an iterative process, following eight steps: (1) Define the unit used in the model, (2) Develop a list of jobs existing on the unit, (3) Allocate roles to the list of jobs, (4) Create a list of planned activities, (5) Populate a list of unplanned activities and events, (6) Determine the parameters for the unplanned activities and events, (7) Establish the job schedules conducted by the crewmembers, including all planned activities, and (8) Prioritize both planned and unplanned activities and events into an activity trump matrix.

(1) Define the Unit Used in the Model

The model was based on a NoCG vessel with 22 crewmembers, providing the information needed for populating the model with jobs, roles, schedules, and activities. The information was gathered during an onboard data collection period through self-reported activity logs, observations, and dialogues with the crew.

(2) Develop a List of Jobs Existing in the Unit

The IMPRINT Pro Forces module does not allow for crewmembers to be assigned activities directly, but rather through schedules attached to various jobs which must be done at a later stage. Therefore, jobs were first derived from the SMD, then distributed so that each of the crewmembers in the model had an assigned job. In cases where there was more than one job of a type, they were given numbers to indicate duplicates (e.g., Navigator (1) and Navigator (2)).

(3) Allocate Roles to the List of Jobs

For crewmembers to participate in various activities, they must be assigned different job roles depending on what actions they are needed to do. The job roles represent proficiencies that an individual possesses, allowing the person to accomplish the task at hand. Roles can often be filled by more than one specific job. In the NoCG vessel model, both the Navigator and the Trainee were proficient in the job role of small boat driver; however, only the Navigator could conduct navigation of the main ship. Most roles are inherent to a certain job and are part of qualifying for that position. Other roles can signify special qualifications that a crew member had acquired during a

previous position. Table 9 provides examples of some of the numerous roles that must receive attention to complete activities, both planned and unplanned, that go into the model. Each job was assigned one or more roles in accordance with the information that was gathered during the data collection effort. This allowed IMPRINT Pro Forces to then request crewmembers with the right qualifications to fill the needed job roles for completing activities as they occurred in the simulation.

Table 9. Part of the job roles list used for the IMPRINT models

Job Roles
40 mm Gunner
.50 cal Gunner
Anchoring Bridge Officer
Anchoring Deck Crew
Boat Crew
Boat Driver
CO
Comms Officer
Comms Technician
Cook
Davit Operator
Deck Crane Operator
Deck Crew
Diver

(4) Create a List of Planned Activities

Planned activities are all the tasks that are fully scheduled, known to the crew, and comprise what is done on a daily basis on board (Alion, 2018). The list of activities is assigned start and end times and accrues to a total of 24 hours for each crew member. The corresponding schedules are not alike for all individuals, and the same planned activities can occur at separate times, depending on the job and watch rotation. The planned activities used in the models were mostly retrieved from the self-reported activity logs, in addition to observations done by the research team. Unless interrupted by irregular activities or unplanned events, the planned activities would run throughout

the duration of the simulation, ensuring that the crew attended to those activities (e.g., watchstanding, administrative work, eating, and sleeping). Of note was the toggle parameter of “sleep activity,” indicating that the activity represented actual sleep. The sleep activity parameter had a twin for unplanned activities; however, it had a different effect. If the parameter was set to “True,” it allowed IMPRINT to prioritize the crew member(s) with the most sleep at the time (and the requisite job roles) when choosing who should be removed from the sleep activity to address whatever unplanned situation needed attention.

(5) Populate a List of IMPRINT Unplanned Events

IMPRINT can only distinguish between two types of activities or events; those planned according to a fixed schedule and those that have various degrees of chance or probability related to them. Training, briefs, exercises, and live incidents that occur outside of the set planned schedule must be modeled as the latter, IMPRINT unplanned events. Table 7 earlier was developed together with the crew of the NoCG vessel to cover most of the activities and events that occur during an underway. The irregular planned activities, irregular activities, and unplanned events together encapsulated the various episodes that required the crew to muster an effort to rectify or solve an issue. IMPRINT unplanned events differed in complexity and urgency. Some, grouped as unplanned events, were live incidents, like fires or floods, which required a high degree of immediacy and manpower to succeed. Other events that were less pressing, like mundane corrective maintenance tasks and training conducted by a smaller team of sailors, were grouped as irregular planned activities. The list of irregular planned activities captured exercises or drills that mimic whole-ship incidents (e.g., fire drills). In such situations, the crew is expected to act as if it is an actual live event. Although these drills were happening at ostensibly random times, there were timeframes that were kept unavailable for these events to shield the crew from undue lack of sleep and retain a level of readiness. The frequency of the IMPRINT unplanned events was developed in the next step of the model development process.

(6) Determine the Parameters for Unplanned Events

Information on irregular activities and unplanned events was used to populate the activity parameters and is described stepwise in the following paragraphs, in accordance with Figure 1: *Sleep activity, Interrupt strategy, Job roles, Adding crewmembers, Start, Duration, Cancel, Repeat, and Stop repeat.*

The screenshot shows the 'MOB Drill' software interface. At the top, the 'Unit Name' is 'NoCGV' and the 'Activity' is 'MOB Drill'. Below this, 'Sleep Activity' is set to 'False', 'Priority' is '30', and 'Interrupt Strategy' is 'Restart'. The 'Job Roles' section contains a table with columns 'Role', 'Required', and 'Desired'. The 'Adding Crew Members' section has three radio buttons: 'has no effect' (selected), 'reduces Time Proportionally' (with a value of 10), and 'reduces Time Somewhat' (with a value of 3). The 'Asset Features' section contains a table with columns 'Feature', 'Required', and 'Desired'. The 'Start' section has three radio buttons: 'Enter Time', 'Use Distributions', and 'Use Expression (evaluates to hours)' (selected). The 'Expression' field contains the code: `1 return (Model.RandomInteger(2,19)*24 + Model.RandomInteger(08,20));`

Role	Required	Desired
PLT Line Shooter	0	0
Smoke Diver	0	0
Towing Bridge Supp	0	0
Towing Cable Crew	0	0
Towing Navigator	0	0
Towing Winch Ope	0	0
Whole Ship Event	18	23
XO	0	0

Feature	Required	Desired
Basic	0	0

Figure 6. Snapshot of unplanned events parameters.

1. Sleep activity is an option that, when toggled, permits the model to choose the “most rested” crew member among those qualifying to assume the needed role. The functionality counts the time spent sleeping during that current day and assigns the individual to respond by being pulled from a lower prioritized activity. Only E0-alarms were assigned as Sleep Activity, to emulate the sleeping watches to which the engineers adhered, by having the person with the most amount of sleep accrued tend to the

alarm. It was not possible to model a sleeping watch schedule in IMPRINT.

2. Interrupt strategy describes what happens whenever unplanned activities are interrupted by higher priority events. The interrupt strategy can be set to either “resume, restart or abort.” Resuming the activity indicates that the task can be attended to when appropriate personnel become(s) available again. In this case, the task will commence from the point at which it was interrupted and be performed for the remaining duration. Maintenance tasks are good examples of work that can be resumed. Crewmembers can finish previously started work immediately after attending to other events. Some activities must be restarted; for example, small boat driving, once interrupted, would be restarted as the small boat would have to be recovered from the sea and set out again. Both resuming and restarting will attempt to pull crewmembers every 15 minutes within the opportunity window. Having to abort the activity completely is the last option, indicative of a task that is no longer viable or worth finishing, like drills or exercises that, when interrupted, would most likely be canceled altogether.
3. Job roles determine the types and numbers of job roles needed to accomplish the unplanned activity. The program differentiates between the required number and the desired number of roles that are deployed for a given activity or event. Desired roles will be pulled to the activity if they are not occupied with higher priority activities. Increasing the number of crewmembers attending an activity can represent an increased safety aspect, training, or other reasons for prioritizing the task—without necessarily hastening the progress.
4. Adding crewmembers can, for some unplanned activities, result in reduced time to completion. Decreases in time are a function of the percentage or proportion of the additional crewmembers supporting the event.

5. *Start* is the time during the sailing period when the unplanned activity or event can occur and is modeled as a fixed time, an expression, or a probability distribution within a time interval. To assume the randomness needed in the model, probability distributions or expressions providing randomness were used to simulate when the various unplanned activities would transpire. For the example in Figure 6, the built-in random number generator in IMPRINT was accessed through the expression function, allowing the start of the event to occur between the second and the 19th day, between eight in the morning and eight in the evening.
6. Duration of the unplanned activity can be addressed similarly to the start time, as fixed, an expression, or a probability distribution of time.
7. Cancellation of an unplanned activity indicates that the event requirements were not met during the opportunity window. IMPRINT Pro Forces attempts to pull the needed resources every 15 minutes, and if never met, the event will be canceled or “failed.”
8. *Repeat* is an option that can be toggled to allow the model to try to repeat previous unplanned events. If checked, the option will try to restart the activity at a time determined by a fixed interval, an expression, or a probability distribution. The function can be used for modeling drills or other events that are occurring with some frequency.
9. *Stop Repeat* will stop the repetition of unplanned activities per the repeat option above.
- (7) Prioritize both planned and unplanned activities and events into an activity trump matrix.

All planned, irregular activities, and unplanned events were prioritized to create a reasonable pattern of behavior for the crew in the model. If there was a conflict between two or more simultaneous activities/events, the IMPRINT software would prioritize tasks with higher priority in accordance with the trump matrix, causing delays, interruptions, or even incompletions. Planned activities in daily schedules could not

create conflicts among other planned tasks since they were, by design, not overlapping. However, planned activities still received priorities that could affect irregular activities and unplanned events. After the completion or cancellation of an irregular activity, the crew member(s) would return to their planned schedule and the activity planned for that current time slot. As a consequence of the activity trump matrix listed in Tables 10–12 higher priority planned activities could also reclaim personnel from lower priority irregular activities or other events. For example, eating would be prioritized over less important corrective maintenance (CM), even though CM was part of the unplanned list of events. The engineer would interrupt performing the maintenance task during eating and resume the work afterward. On the other hand, a fire would require all hands (except for critical watch functions), necessitating that all other activities would stop until the fire was extinguished. Although irregular activities were used in both the Baseline model and the Augmented model, the priorities remained constant to make adding further activities for the Augmented model more convenient.

Table 10. Planned activities trump matrix

Planned Activities	Priority
Critical Watch	1
Prepare Food	40
Eat	41
Morning Brief	120
Preventative Maintenance	125
Work	126
Cleanup after meal	130
Sweepers	135
Sleep	140
Hygiene	145
Personal Time & Fitness	150

Table 11. Irregular activities trump matrix

Irregular Activities	Priority
MOB (second) day	21
Safety Walkthrough first day	22
Crew Muster first day	23
Abandon Vessel Muster Training first day	24
Occupational Hazards Meeting first day	25
MOB Drill	30
Collision DC/Blackout Exercise	31
Internal DC Exercise	32
External DC Exercise	33
SAR Exercise	34
Towing Initiation Exercise	35
Oil Spill Exercise	36
Helicopter Winch Exercise	50
40 mm Exercise	51
.50 cal Exercise	52
Fishery Inspection	55
Navigation Exercise	70
Emergency Steering Exercise	71
Small Boat Training	72
Anchoring Exercise	73
40 mm Drill Training	75
.50 cal Drill Training	76
Internal DC/Smoke Diver Training	80
Medical Casualty Exercise	81
Medic Training	82
PLT Firing	83
Onboard Hazardous Spill Training	100
Seamanship Training	105
Witness Brief Training	106
Lookout Brief Training	107
Safety Inspection	110
Diving Training	115

Table 12. Unplanned events trump matrix

Unplanned Events	Priority
MOB Actual	5
Internal DC Actual	6
External DC Actual	7
SAR Actual	8
Towing Actual	9
Oil spill Actual	10
Main engine casualty	15
LNG engine casualty	16
E0-alarm on sensors for critical systems	20
Machinery main components CM	26
Equipment for crew and passengers CM	27
Ship common system CM	45
Electrical equipment CM	46
Systems for machinery main components CM	47
Ship equipment CM	48
Hull CM	60
Equipment for cargo CM	61
Comms & network Issues CM	62

(1) Establish the Job Schedules Conducted by the Crewmembers, Including All Planned Activities

All jobs adhered to schedules comprised of items from the planned activities list based on the self-reported activity logs and observations. Some jobs had a specific watchstanding schedule designed for them or included other work tasks. As an example, Gunner 3 adhered to a culinary assistant schedule as opposed to the other gunners conducting watchstanding. Others followed similar schedules but with no planned nightly activities—commonly known as the aforementioned day-working “dayman.” These schedules were modeled with the morning routine at the start of every day, with work during the day, and subsequent rest during the evening followed by sleep at night. While crewmembers working as daymen had similar eating and sleeping patterns, watchstanders had their day altered in accordance with the time of their watch. Examples of a dayman and watchstanding schedules are shown in Table 13 and Table 14. Individuals standing watch during nighttime had sleep periods moved to daytime or split between before and

after the watch. Most schedules allowed for roughly 12 hours of rest time between main bodies of work as per normal underway operations, including sleep and personal time, though there were individual differences loosely based on the collected data. Additionally, messing constitutes off-duty time being conducted in between work hours. The schedules were continuous for the full duration of the simulation, interrupted only by higher priority irregular activities and unplanned events.

Table 13. Dayman worker planned schedule

Activity	Start Time	End Time	Total Activity Time
Sleep	00:00	07:15	07:15
Hygiene	07:15	07:30	00:15
Eat	07:30	08:00	00:30
Work	08:00	08:30	00:30
Morning brief	08:30	08:45	00:15
Work	08:45	11:30	02:45
Eat	11:30	12:00	00:30
Work	12:00	16:30	04:30
Eat	16:30	17:15	00:45
Work	17:15	20:00	02:45
Personal time	20:00	22:45	02:45
Hygiene	22:45	23:00	00:15
Sleep	23:00	00:00	01:00

Table 14. Watch section 0400–0800 planned schedule

Activity	Start Time	End Time	Total Activity Time
Sleep	00:00	03:45	03:45
Hygiene	03:45	04:00	00:15
Critical Watch	04:00	08:00	04:00
Eat	08:00	08:30	00:30
Morning brief	08:30	08:45	00:15
Work	08:45	11:30	02:45
Eat	11:30	12:00	00:30
Work	12:00	16:30	04:30
Eat	16:30	17:15	00:45
Personal Time or training	17:15	19:45	02:30
Hygiene	19:45	20:00	00:15
Sleep	20:00	00:00	04:00

E. RUNNING THE MODELS

The models were run using the discrete event simulation software IMPRINT Pro Forces. To initiate the simulation, it was necessary to specify the 21-day length of the run, along with the chosen modeled force unit, before executing either the Baseline or Augmented model. The output of the program provided information on time spent for several different categories, conducting planned and irregular activities and unplanned events for all crew member jobs. The outcome from the Augmented model demonstrated how unplanned events affected other activities in a more pronounced manner compared to the Baseline model, as would be expected—resulting in incomplete or failed activities and affecting crew sleep and rest patterns. To introduce randomness into the model, a “batch execution program” in IMPRINT Pro Forces was used to achieve as many iterations of the model run as possible. The batch program was limited to 999 replications of the same run, creating 999 folders of output results. The first folder was designated in accordance with a user-chosen individual random number seed, with subsequent iterations increasing the number by 1 (Alion, 2018). The random number seed ensured randomness since the probability distributions in the models created unique results for each run. The output was presented in Microsoft Excel spreadsheet format; however, the sheer number of folders and files created trouble in assessing the results. To concatenate the data from the individual spreadsheets, we used an extractor program that had been previously developed at NPS to concatenate all the information from the 999 folders and produce a .csv file containing the amassed data. The .csv needed to be cleaned up before analysis to ensure that the relevant categories were aligned and organized appropriately.

Having reviewed the method for data collection and the steps for creating an IMPRINT model, this thesis now proceeds to present the results of the data collection and, subsequently, the analysis of the models. The analysis centers around on-duty workload and off-duty hours representing rest, in addition to assessing crewmembers’ sleep habits in preparation for a discussion about crew performance and the adequacy of the current vessel manning. The number of tasks that are interrupted, delayed, or incomplete contribute to the discussion, eventually calling into question the efficacy of using the IMPRINT program or similar simulation tools for determining manpower requirements.

IV. RESULTS

Chapter III presented the procedures for building our models in the IMPRINT Pro Forces module. First, we collected data to inform the input parameters of the IMPRINT models, before creating the models. Some of the information from the nine-day data collection on a NoCG vessel was readily transferable to the baseline model (i.e., jobs and roles, various schedules, and planned activities). Finally, SME input provided information and probabilities for unplanned events which were used in the Augmented model.

A. DATA COLLECTION ON THE NORWEGIAN COAST GUARD SHIP

This first section of this chapter presents the results of the data collection on the NoCG ship. It describes the crew, with a focus on workload and sleep, investigating both subjective activity logs and objective sleep tracking wearable devices to provide work and sleep patterns for the models. The data enabled this thesis to distinguish between sailors with higher resolution than previous efforts using IMPRINT Pro Forces on navy ships. Subsequently, the pre- and post-test study design assessing mood and sleep habits were conducted to support the findings from the activity and sleep measures. It is important to reiterate that the study was deemed not human subjects research and crew data are not generalizable, meaning that the results should not be used to make conclusions about sleep habits or mood among NoCG crews.

The next part is the analysis of the IMPRINT Baseline and Augmented models, based on the results from the first part of the chapter. It starts with descriptive information and rounds out the chapter with a comparative analysis of the two models to provide material for the discussion.

1. Demographics

All 22 crewmembers volunteered to participate in the study and completed the pre-test and post-test questionnaires. One participant, however, was excluded from the workload analysis due to insufficient data, with one other participant not providing any ŌURA data due to a technical issue. The participants were classified into three

occupational groups based on their work schedule; seven participants were included in the “watchstanding” group, 11 were included in the “dayman” group, and four were included in the “engineering” group. The watchstanding group differed from the daymen having at least one regular four-hour watchstanding period at night between 2000 and 0800. The study sample was comprised of 16 (72.7%) males and 6 (27.3%) females, with a median age of 27 years (IQR = 15). Caffeine was used regularly by 19 (86.4%) crewmembers, including coffee, energy drinks, and pre-workout drinks. The median consumption of caffeinated beverages was two per day (IQR = 4.3). Most of the crew (19, 86.4%) had an exercise routine (weightlifting, running, and other cardiovascular activities). The median workout frequency was four days per week (IQR = 2), with each session lasting for a median duration of 60 minutes (IQR = 45).

2. Sleep and Workload

The following sections provide deeper insight into the differences in sleep and workload among the three participant categories: watchstander, dayman, and engineering.

a. Sleep

According to the ŌURA data, eligible participants (N = 21) spent a median of 8.13 hours (IQR = 0.72) in bed per day (including napping and short rests). This aligned well with self-reported sleep duration from activity logs of 7.81 hours (IQR = 0.99) per day, deviating less than 5%. Daily sleep duration assessed by sleep tracking wearable devices was 6.74 hours (median value with IQR = 0.91), which indicated sleep latency and waking periods during the sleep activity caused effective sleep to be 17.1% less than the total time in bed duration.

(1) Ōura data

Figure 7 shows the accumulated time in bed and the daily sleep periods recorded by sleep tracking wearable devices between the occupational groups. Watchstanders had a median time in bed duration of 7.84 hours (IQR = 0.79) and a median daily sleep duration of 6.23 hours (IQR = 0.28). The difference between time in bed and time measured by the ŌURA rings as effective sleep was 25.8%. The dayman category had a median of 8.13

hours (IQR = 0.52) and 7.07 hours (IQR = 1.09), respectively, with a 15.0% difference. Sailors in the engineering group had a median rest duration of 8.22 hours (IQR = 1.68) and a median daily sleep duration of 6.81 hours (IQR = 0.79) for a 20.7% difference between time in bed and daily sleep duration. Time in bed duration did not differ by occupational group (Kruskal-Wallis rank sums test, $\chi^2(2) = .270$, $p = .874$). Daily sleep duration, however, varied by group (Kruskal-Wallis rank sums test, $\chi^2(2) = 4.805$, $p = .091$). Post-hoc analysis using the Tukey-Kramer HSD test showed that watchstanders had significantly shorter daily sleep duration compared to daymen ($p = .078$), but not engineering ($p = .284$). These results indicated that while time in bed duration was statistically equivalent among groups, the median watchstander slept almost 50 minutes less each night than the dayman group. The outcome was in line with watchstanders experiencing the largest proportional difference between time in bed and daily sleep duration, suggesting overall less effective sleep periods.

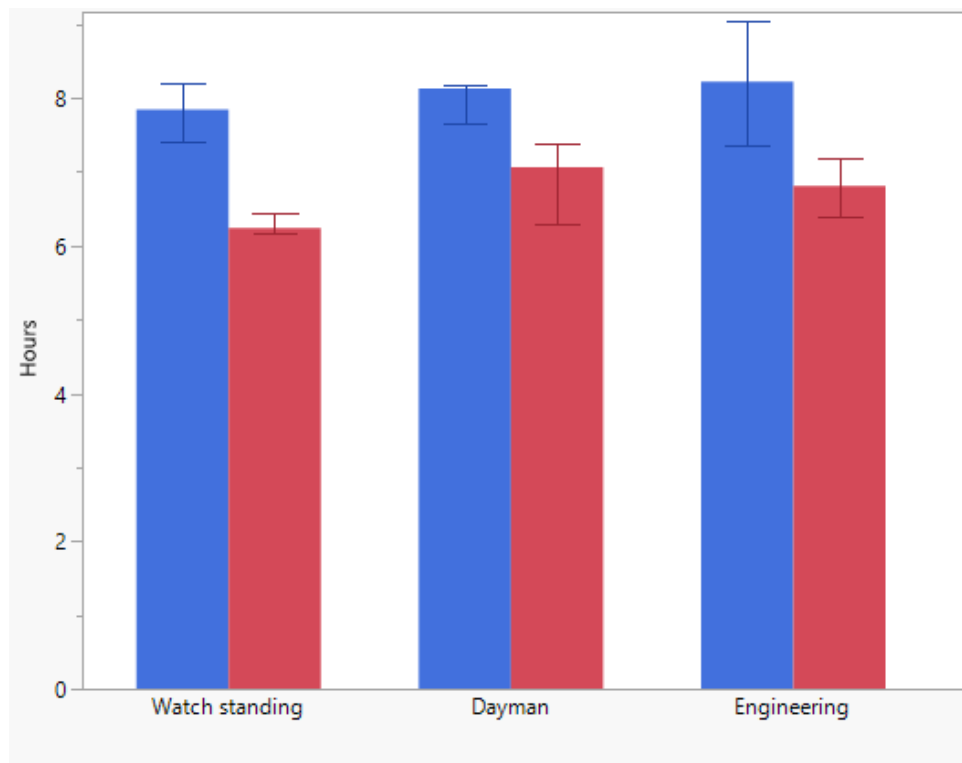


Figure 7. Time in bed (blue) and sleep (red) duration by occupational groups. Vertical lines denote the IQR.

From a longitudinal viewpoint spanning the data collection period, sleep durations did not seem to follow any trends, as the line plot of Figure 8 illustrates. The line representing the dayman group shows a peak registered on the fourth day, which was the result of an approved “rest day” by leadership. As evidenced by the data, the other occupational groups did not seem to partake in the rest day as sleep did not increase.

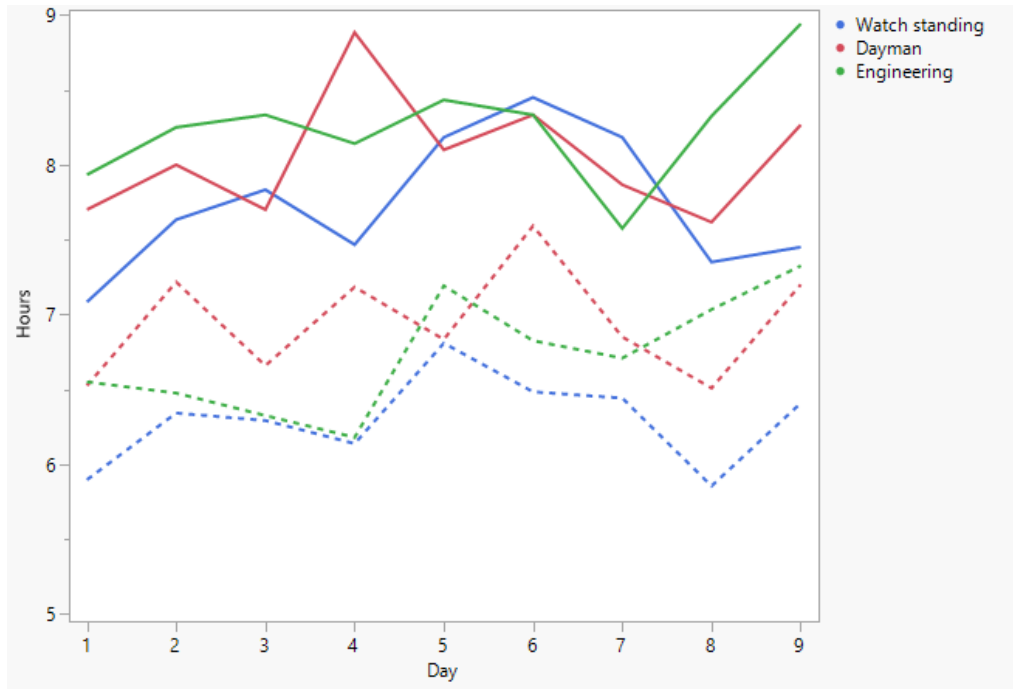


Figure 8. Time in bed (solid line) and daily sleep (dotted line) for occupational groups throughout the nine-day data collection period

ÖURA data showed that of a total of 226 registered sleep episodes used in the analysis, there were 47 rest/sleep episodes with durations less than two hours (i.e., naps) that contributed to the daily time in bed and sleep durations among participants. In total, 13 (62%) participants napped (Mdn = 2, IQR = 1). Some participants had only one nap, whereas others had up to 12 naps; daymen registered the most naps with 31, followed by watchstanders napping 14 times, and engineering with two naps during the nine-day sail. Figure 9 shows the differences between the occupational groups, with a median napping duration for watchstanders of 0.49 hours (IQR = 0.40), daymen 0.52 hours (IQR = 0.67),

and engineering 0.95 hours (IQR = 0.6). The data presented in the bottom part of Figure 9 displays the sleep duration gained from napping activities, as watchstanders accrued a median sleep duration of 0.092 hours (IQR = 0.31), daymen a median of 0.1 (IQR = 0.28), and the engineering group a median of 0.4 (IQR = 0.17). One instance of a participant experiencing a sleep interruption due to a maintenance issue caused a recorded sleep duration of less than two hours. Due to this not being deliberate napping, the occurrence was not registered as a nap or short sleep. Watchstanders responsible for nighttime watches reported deliberately taking long rests that exceeded two hours, with some even sleeping before and after their watch for more than two hours to meet their needs. These longer rests included sleep latency, which warrants discussion about how they contributed to the larger discrepancy between time in bed and daily sleep duration for watchstanders compared to other occupational groups.

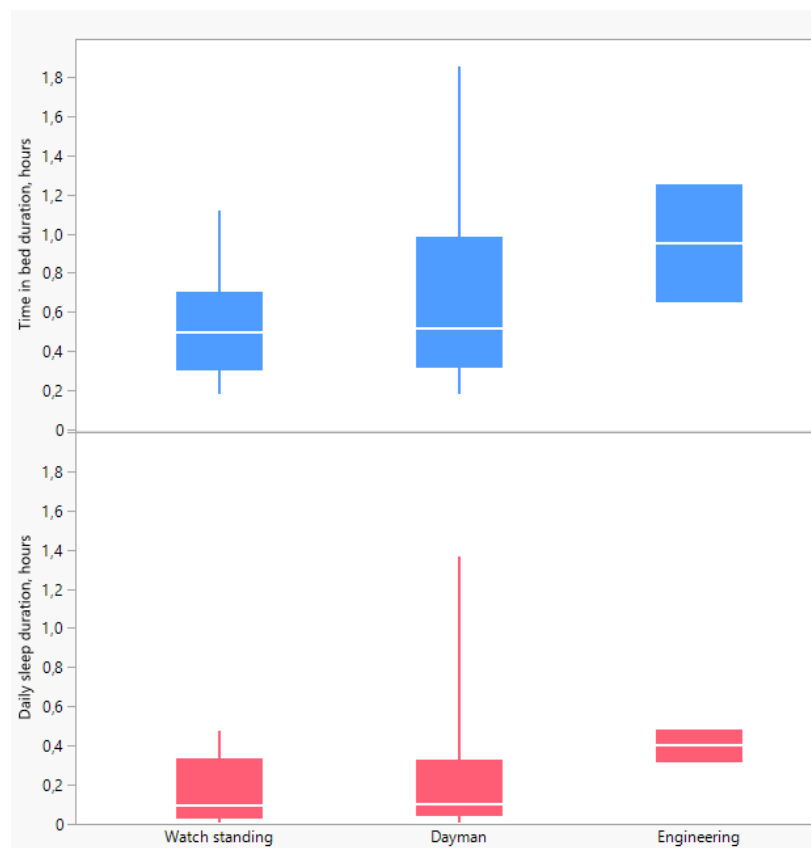


Figure 9. Median (IQR) time in bed and sleep duration contribution from napping by occupational group

(2) Activity Logs

As shown in Figure 10, the activity logs mirrored the $\bar{O}$ URA data showing marginal differences in terms of the time in bed duration for daymen and engineering. Watchstanders accounted for a median time in bed of 7.5 hours per day (IQR = 0.93). Daymen recorded a median of 8.11 hours per day (IQR = 1.06), and engineering 7.81 hours per day (IQR = 1.00). There was only one participant who reported napping, represented as shorter rest episodes of less than two hours in duration, but was still included in the dataset used in Figure 10. This proves the value of including objective sleep measurements, although the data suggest that the crewmembers included napping in their reported sleep. Otherwise, they overestimated sleep when registering daily activities.

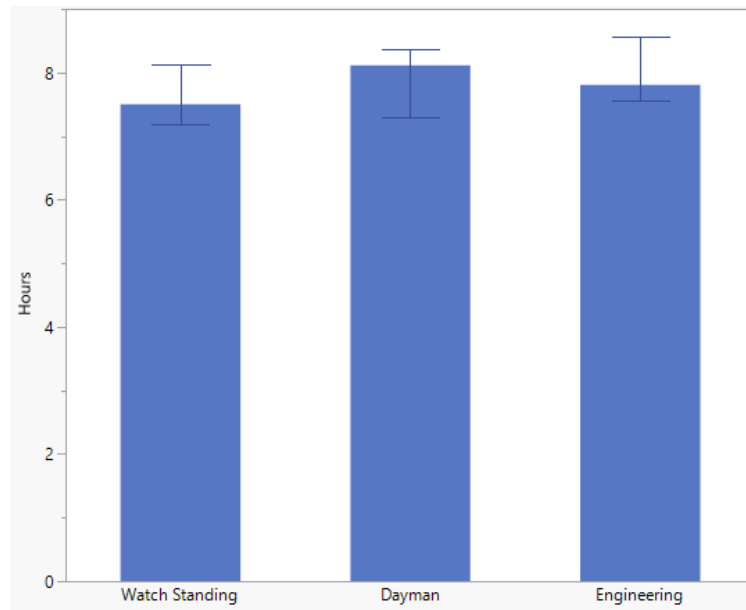


Figure 10. Daily sleep duration reported in activity logs, by occupational group. Vertical lines denote the IQR

However, since the activity logs corroborated the results from the $\bar{O}$ URA data, time in bed data was used when building the schedules in the IMPRINT models. Due to napping and shorter rests being conducted infrequently and unevenly among the participants, incorporating naps in the daily schedules of crewmembers would not give a proper representation of the crew's sleep habits. IMPRINT is incapable of modeling random sleep

instances; thus, scheduling sleep in one period would be the optimal solution. Nevertheless, watchstanders dividing their sleep periods before and after nighttime watches had those sleep periods modeled separately since it appeared to be a repeated sleeping pattern.

b. Workload

Sailors reported their activities in the activity logs. This data aggregated by activity category are shown in Table 15. The average total on-duty workload, including watchstanding, administrative work, maintenance, exercises operations, and cleaning, was 10.1 hours per day (SD = 1.79), constituting 42.1% of the day (ranging from 34.7% to 49.6%), while the remaining time onboard, outside of sleep, was spent resting, messing, and other off-duty activities (M = 13.9 hours/day, SD = 1.79) totaling 57.9% of the day (ranging from 50.4% to 65.3%).

Table 15. Total daily on-duty workload and off-duty activities⁷

Activity	Activity duration	Activity duration
	M ± SD in hours/day	%/day
Administrative work	1.87 ± 2.26	7.8 %
Briefs/meetings	0.78 ± 0.75	3.3 %
Exercises	0.40 ± 0.33	1.7 %
Messing	1.78 ± 0.70	7.4 %
Maintenance	3.01 ± 2.60	12.5 %
Operations	0.49 ± 0.53	2.0 %
Resting	2.97 ± 1.69	12.4 %
Sleep	7.82 ± 0.54	32.6 %
Sweepers(cleaning)	0.23 ± 0.48	1.0 %
Training/hygiene	1.32 ± 0.91	5.5 %
Watch	3.32 ± 3.12	13.8 %

The time spent on each activity varied among the three occupational groups (watchstanders, daymen, engineers), with the average day divided into the activities shown in 11. While time spent sleeping was comparable across occupational groups, the most considerable differences were seen in watchstanding, rest, maintenance, and administrative work. The aggregated mean on-duty and off-duty hours among occupational groups are shown in Table 16. It is worth noting that watchstanders put in a significant amount of time on duty compared to the other categories, surpassing the hours worked by daymen and exceeding the engineering group by over 50%.

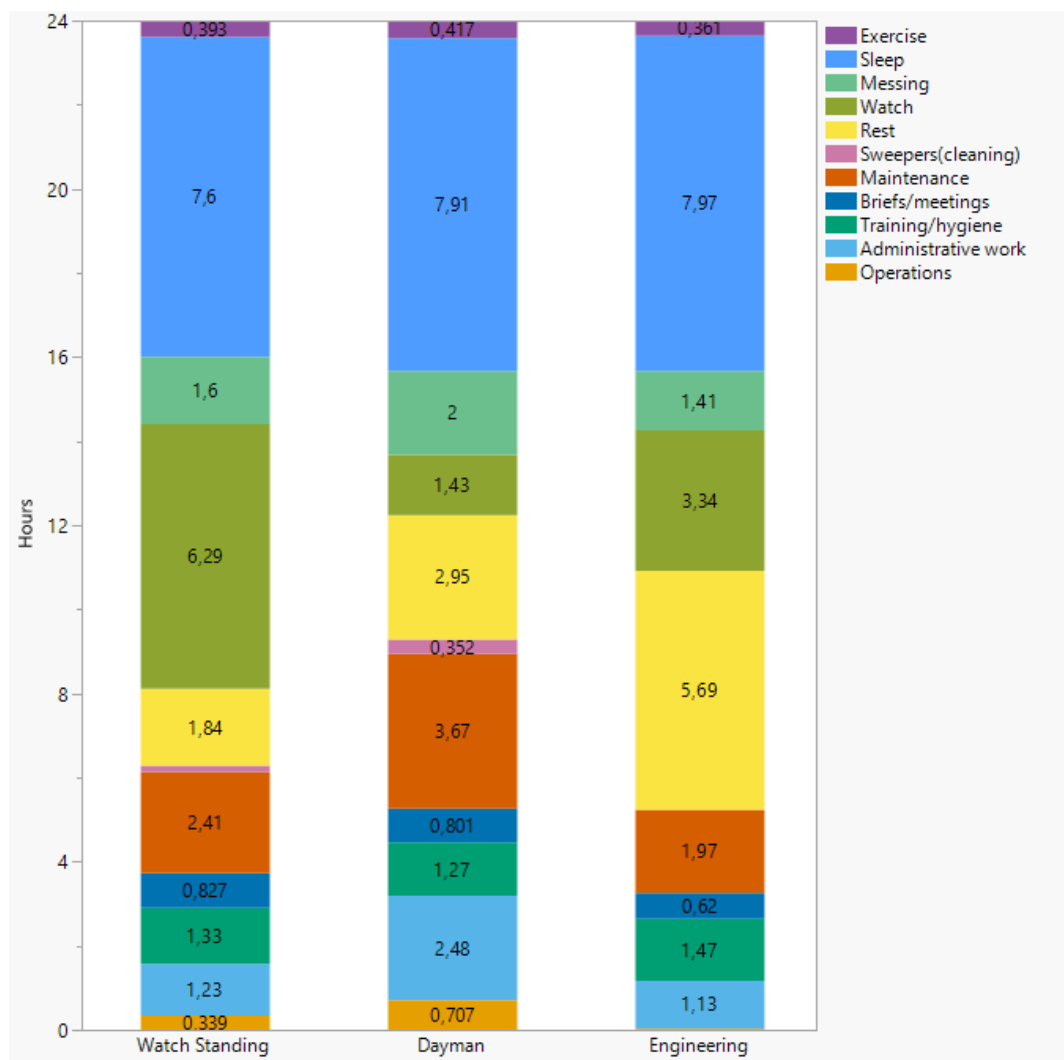


Figure 11. Mean hours of the various activities conducted during the nine-day sail, by occupational group

Table 16. Mean daily on-duty hours and off-duty hours

Occupational group	On-duty	
	M $\pm$ SD in hours/day	Off-duty M $\pm$ SD in hours
Watchstanding	11.63 $\pm$ 0.94	12.37 $\pm$ 0.94
Dayman	9.86 $\pm$ 1.36	14.14 $\pm$ 1.36
Engineering	7.46 $\pm$ 1.05	16.54 $\pm$ 1.05

3. Daytime Sleepiness

The Epworth Sleepiness Scale was used to assess daytime sleepiness. A score of ten or more indicates symptoms of elevated daytime sleepiness. The ESS scores ranged from 0 to 13, and as shown in Figure 12, one sailor (4.5%) showed symptoms of elevated daytime sleepiness at pre-test. In the post-test, four sailors (18.2%) reported symptoms of elevated daytime sleepiness which were significant (McNemar's test, $p = .083$). However, there was no significant difference between the scores at the beginning and end of the nine-day underway (Pre-study: Mdn = 5.5, IQR = 4.5; Post-study: Mdn = 5.5, IQR = 5.5; Wilcoxon signed rank, $S = -1.50$, $p = .960$). Further, the ESS score did not differ among occupational groups at the beginning of the study (Kruskal-Wallis rank sums test, $\chi^2(2) = 3.52$, $p = .172$) or at the end (Kruskal-Wallis rank sums test, $\chi^2(2) = .943$, $p = .624$).

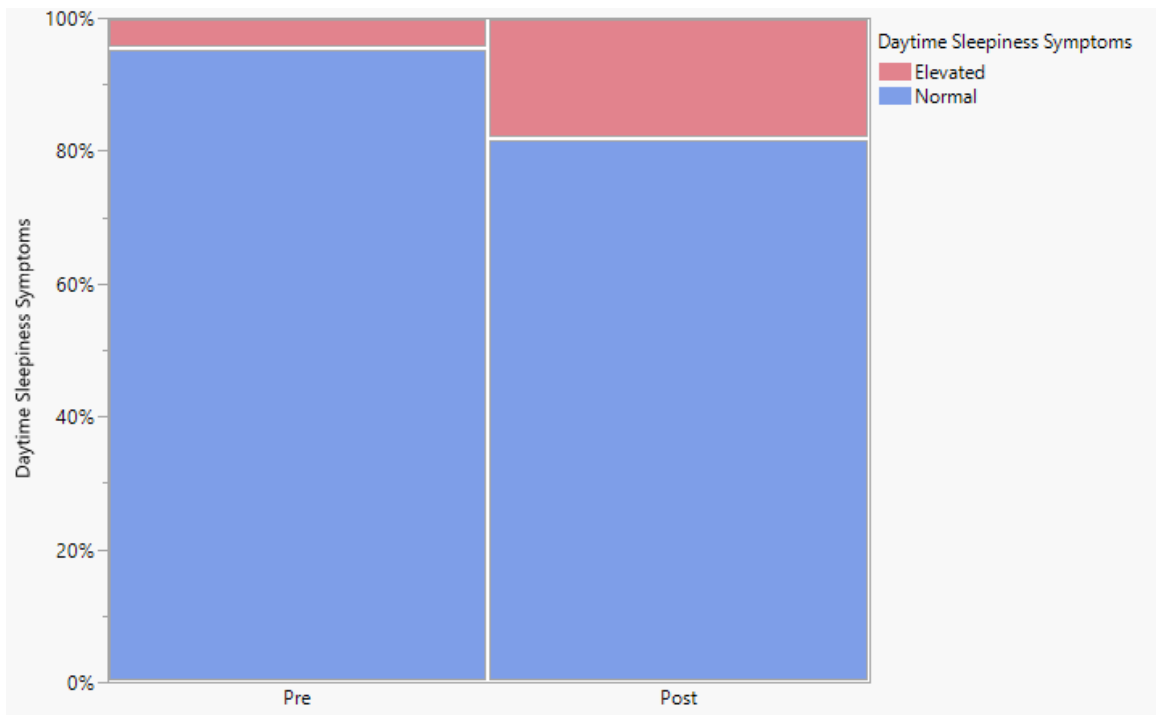


Figure 12. ESS results for pre-test and post-test

4. Insomnia Symptoms

Insomnia symptoms were assessed with the Insomnia Severity Index (ISI). Scores of 0 to 7 indicate no signs of insomnia, between 8 and 14 indicate subthreshold insomnia, and 15 to 21 indicate moderate insomnia. The ISI scores ranged from 0 to 17, with a median score of 4 (IQR = 6) and 6 (IQR = 8) in the pre-test and post-test, respectively. Six (28.6%) participants showed symptoms of subthreshold or moderate insomnia at the pre-test, with the number increasing to eight (38.1%) in the post-test (McNemar's test, $p = .753$). However, the differences in the ISI scores between the start and end of the nine-day underway period were not statistically significant (Wilcoxon signed rank test, $S = 31.500$, $p = .314$). Similarly, there were no significant differences between the scores of watchstanders, daymen, and engineering (Kruskal-Wallis rank sums test: Pre-test $\chi^2(2) = 1.05$, $p = .591$; Post-test $\chi^2(2) = 4.26$, $p = .119$). None of the participants had severe insomnia symptoms as their scores did not exceed 21. These results are shown in Figure 13.

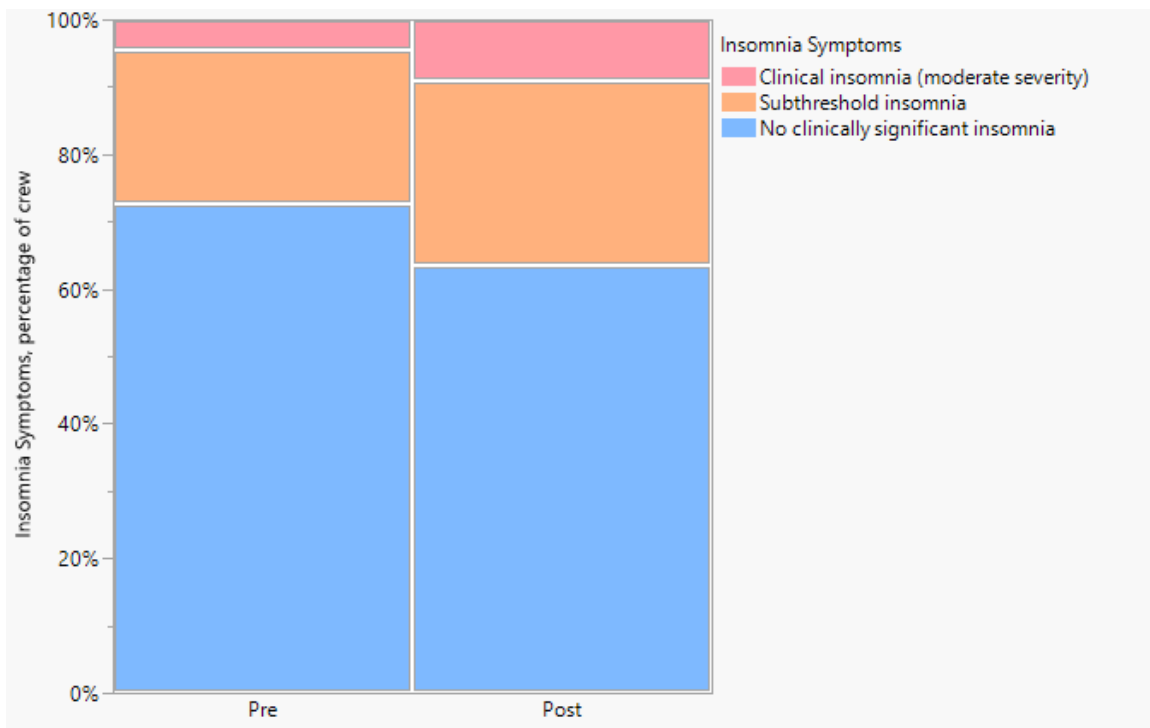


Figure 13. ISI score-based insomnia groups pre-test and post-test

5. Sleep Quality

The Pittsburgh Sleep Quality Index (PSQI) was used to assess sleep quality. The median PSQI score at the beginning of the study was 4.5 (IQR = 3) and 6 (IQR = 3) at the end of the study. The increase in PSQI scores suggests that sleep quality was worsening during the nine-day study (Wilcoxon signed rank test, $S = 77.500$, $p = .008$). Even though the number of crewmembers classified as poor sleepers increased from nine (40.9%) at the beginning of the study, to 12 (54.5%) at the end, this difference was not statistically significant (McNemar's test, $p = 0.317$). PSQI scores did not differ between occupational groups (Kruskal-Wallis rank sums test: Pre-test, $\chi^2(2) = .462$, $p = .793$; Post-test, $\chi^2(2) = 5.48$, $p = .760$), indicating that no group had their sleep worsen more than others. Based on PSQI scores, the percentage of good and bad sleepers pre- and post-test is shown in Figure 14.

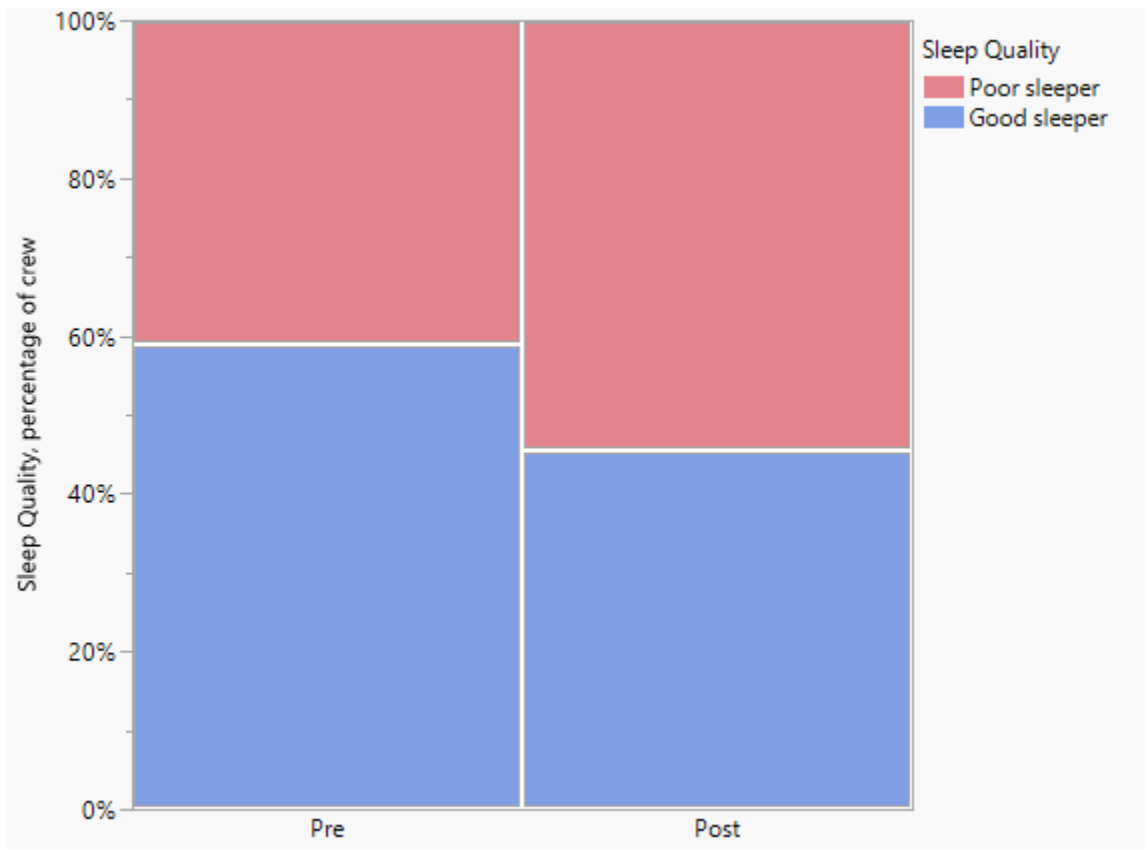


Figure 14. Percentage of good and poor sleepers according to PSQI scores

6. Mood States

The Profile of Mood States (POMS) was used to evaluate participant mood and compare POMS scores with adult norms. As shown in Table 17, we did not identify any statistically significant differences between pre-test and post-test POMS scores in terms of Anger-hostility ($S = 16.500$, $p = .602$), Confusion-bewilderment ($S = 41.500$, $p = .180$), Depression ($S = 11.000$, $p = .727$), Fatigue ($S = 22.500$, $p = .476$), or Total Mood Disturbance ($S = 17.000$, $p = .593$). The Tension scores decreased significantly from the pre-test to the post-test, indicating improved mood related to Tension between the pre-test and post-test ($S = 71.500$, $p = .016$). Vigor showed a significant decrease ($S = 73.500$, $p = .013$), indicating a negatively affected mood related to Vigor during the nine-day sail.

Table 17. POMS raw scores

Mood Scale	Pre-test, Median (IQR)	Post-test, Median (IQR)	Wilcoxon signed rank test p-values
Anger	5 (5)	4 (5)	$p = .602$
Confusion	6 (3.5)	5.5 (5.25)	$p = .180$
Depression	3 (7.25)	2.5 (10)	$p = .727$
Fatigue	4.5 (8.5)	6.5 (10.25)	$p = .476$
Vigor	17 (4.25)	14 (5.5)	$p = .013$
Tension	7.5 (5.5)	5.5 (5)	$p = .016$
Total Mood Disturbance	9 (32.5)	11.5 (38.5)	$p = .593$

The percentage of sailors with POMS scores above or below the 50th percentile of adult norms is shown in Figure 15, with green indicating a positive trend compared to the adult norm. Vigor is inverted as feeling more vigorous would be associated positively with mood. Of the 22 participants, 11 (50%) sailors had Tension scores above the 50th percentile of adult norms in the pre-test and seven (32%) in the post-test. There were six (27%) sailors who scored above the 50th percentile of the norms in Depression in the pre-test and eight (36%) in the post-test. There was no difference in Anger between the pre-test and post-test, with four (18%) participants above the 50th percentile in both conditions. For Vigor, seven (32%) participants scored above the norms in the pre-test and three (14%) in the post-test. There were seven (32%) sailors scoring above the norms in Fatigue and nine (41%) in the post-test. Among the sailors, 14 (64%) had Confusion scores above the norms in the pre-test and 11 (50%) in the post-test. Last, eight (36%) sailors reported having a Total Mood Disturbance (TMD) score above the 50th percentile of the adult norms in the pre-test and ten (45%) sailors in the post-test. Using the McNemar's test, we did not identify any statistically significant differences in the percentage of participants above or below the 50th percentile of adult norms between the pre-test and post-test. These results are shown in Table 18.

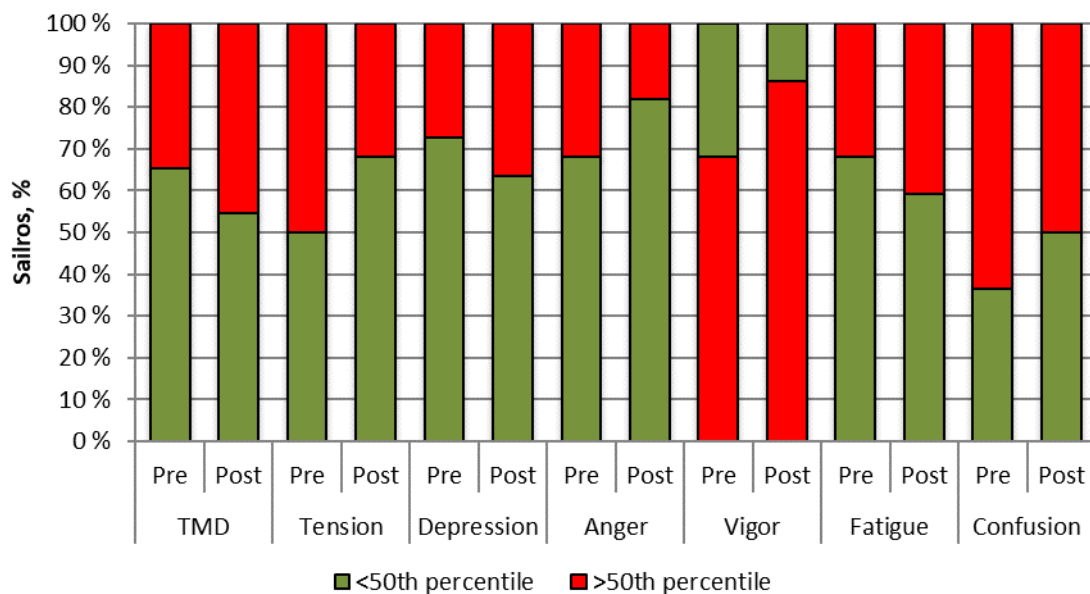


Figure 15. Percentage of participants with POMS scores above or below the 50th percentile of adult norms

Table 18. Number of participants with POMS scores above the 50th percentile of adult norms

Mood Subscale	Pre-test, ≥50th percentile	Post-test, ≥50th percentile	McNemar's test p-value
Anger	4	4	$p = 0.990$
Confusion	14	11	$p = .257$
Depression	6	8	$p = .414$
Fatigue	7	9	$p = .414$
Vigor	7	3	$p = .103$
Tension	11	7	$p = .103$
Total Mood Disturbance	8	10	$p = .414$

The supporting verification is summed up in Table 19, presenting the results from the pre- and post-test questionnaires. The significant variations in sleep habits and mood stemmed from differences in raw scores for Vigor and Tension in the POMS test; however, the number of crewmembers above or below the adult norm did not change significantly. When assessing the overall battery of post-test questionnaires, we found few indications of any change in the crew's sleep habits or mood caused by the nine-day sail when compared to the results from the pre-test.

Table 19. Overview of study variables (N=22 participants)

Study variable	Pre-test	Post-test	
ESS score, Mdn (IQR)	5.5 (4.5)	5.5 (5.5)	.960 ^A
EDS (ESS score > 10), # (%)	1 (4.5%)	4 (18.2%)	.083 ^B
ISI score, Mdn (IQR)	4 (6)	6 (8)	.314 ^A
ISI score ≥ 15, # (%)	6 (28.6%)	8 (38.1%)	.753 ^B
PSQI Global score, Mdn (IQR)	4.5 (3)	6 (3)	.008 ^A
Poor sleepers, # (%)	9 (40.9%)	12 (54.5%)	.317 ^B
POMS scores, Mdn (IQR)			
Total Mood Disturbance	9 (32.5)	11.5 (38.5)	0.593 ^A
Anger-hostility	5 (5)	4 (5)	.602 ^A
Confusion	6 (3.5)	5.5 (5.25)	.180 ^A
Depression	3 (7.25)	2.5 (10)	.727 ^A
Fatigue	4.5 (8.5)	6.5 (10.25)	.476 ^A
Vigor	17 (4.25)	14 (5.5)	.013 ^A
Tension-anxiety	7.5 (5.5)	5.5 (5)	.016 ^A
POMS scores, ≥ 50th percentile adult norm, # (%)			
Total Mood Disturbance	8 (36%)	10 (45%)	.414 ^B
Anger-hostility	4 (18%)	4 (18%)	.990 ^B
Confusion	14 (64%)	11 (50%)	.257 ^B
Depression	6 (27%)	8 (36%)	.414 ^B
Fatigue	7 (32%)	9 (41%)	.414 ^B
Vigor	7 (32%)	3 (14%)	.103 ^B
Tension-anxiety	11 (50%)	7 (32%)	.103 ^B

^A Wilcoxon signed rank test

^B McNemar's test

B. IMPRINT PRO FORCES RESULTS

The analysis of the model output aims to provide better insight on manpower challenges and to increase the quality of information on which manpower requirements determinations are made. The analysis consists of three parts. The first two parts follow a comparable pattern: the Baseline and Augmented models are described by the output from each model's 999 simulation iterations regarding workload and sleep for the whole crew. Emphasis is placed on mean hours per day, with standard deviations for each activity; however, instances of extremes are also interesting to investigate, demonstrating the adequacy of the manning solution in situations where the organization is stressed. Also, analysis explores differences related to sleep and workload among the occupational groups. Finally, the model outputs are analyzed to assess whether crewmembers complete all activities, which is another metric of whether the crew size is sufficient to meet workload demands. The model allocates each activity with a classification depending on whether there are enough sailor resources to conduct the activities when they occur, allowing for an analysis of completion percentages. Given sufficient resources for the duration of the task, the activity completes successfully. If there is a lack of the needed sailor roles at the onset of the activity, the activity may be delayed for a set duration, after which it fails or completes as the sailors become available. Activities can also be interrupted in situations where higher priority activities or events occur, leading to a failed state.

The final part of the section compares the two models to evaluate whether there are differences in variables of interest such as sleep and workload when introducing unplanned events. The analysis aims to identify manpower challenges in the organization when faced with major unplanned events and an increased workload in the Augmented model compared to the Baseline model. Chapter V comments on the differences between the model outcomes and uses previous study efforts with IMPRINT Pro Forces to compare input data and results from the Baseline and Augmented models before presenting the model's limitations.

1. Baseline Model

The Baseline model was used to describe a minimum of activities that take place during a NoCG vessel patrol focusing on planned activities (e.g., administrative work tasks and preventive maintenance). Several planned but irregularly occurring activities were added to represent maintaining the sailors' individual skills and abilities. The Baseline model allowed for an initial assessment of workload and sleep and emulated a situation with little stress and sufficient opportunities to rest.

a. On-duty Hours per Day

During the 21-day simulated sail, sailors spent on average 10.50 ± 1.40 hours per day on duty. Table 20 shows the span in on-duty hours for the simulated crewmembers. Gunner 1 worked the most (12.75 ± 0.12 hours/day), with the Electrician (8.01 ± 0.01 hours/day) and the Chief Engineer (8.01 ± 0.01 hours/day) having the fewest on-duty hours per day (range = 4.74 hours/day). Most sailors had low standard deviation values (from 0.01 to 0.17 hours/day), indicating few irregular activities affecting on-duty hours. The 90th quantile was used to explore the effects of the 90th quantile on-duty time for each simulated sailor, meaning that there was a 10% chance (based on all runs of the model) of working the reported hours or more. Large differences in workload between the average value and the 90th quantile indicated that these sailors were vulnerable to higher workloads in extreme situations (i.e., the job included roles in high demand when the sailor would otherwise be off duty). The crew on-duty hours per day for the 90th quantile was 10.64 ± 1.45 hours, the mean difference among all sailors being 0.10 hours per day compared to the crew mean. Gunner 2 (with a difference of 0.22 hours/day) had the highest discrepancy between the average and the 90th quantile on-duty hours, while the Electrician had the lowest (difference = 0.01 hours/day).

Table 20. Average and 90th quantile On-duty time in hours per day by simulated crewmembers

Job	Occupational Group	On-duty time in hours/day	
		M $\pm$ SD	90th quantile hours/day
Gunner 1	Watchstanding	12.75 $\pm$ 0.12	12.91
Corpsman 2	Watchstanding	12.60 $\pm$ 0.07	12.70
Ship Petty Officer 1	Watchstanding	12.10 $\pm$ 0.08	12.21
Battery Officer	Watchstanding	11.65 $\pm$ 0.11	11.80
XO	Dayman	11.55 $\pm$ 0.04	11.62
Operations Officer	Watchstanding	11.50 $\pm$ 0.12	11.67
Gunner 2	Watchstanding	11.50 $\pm$ 0.17	11.57
Bosun Officer	Dayman	10.87 $\pm$ 0.07	10.97
Deck Trainee 2	Dayman	10.84 $\pm$ 0.06	10.93
Deck Trainee 1	Dayman	10.84 $\pm$ 0.06	10.93
SRO 1	Dayman	10.83 $\pm$ 0.06	10.91
SRO 2	Dayman	10.81 $\pm$ 0.05	10.88
Ship Petty Officer 2	Dayman	10.81 $\pm$ 0.05	10.88
CO	Dayman	10.81 $\pm$ 0.04	10.87
CIS Officer	Dayman	10.78 $\pm$ 0.03	10.83
Corpsman 1	Watchstanding	10.43 $\pm$ 0.11	10.58
Gunner 3	Dayman	9.67 $\pm$ 0.11	9.82
Culinary Specialist	Dayman	9.53 $\pm$ 0.04	9.59
Mechanic	Engineering	8.07 $\pm$ 0.08	8.21
1. Engineer	Engineering	8.07 $\pm$ 0.08	8.20
Chief Engineer	Engineering	8.01 $\pm$ 0.01	8.02
Electrician	Engineering	8.01 $\pm$ 0.01	8.02

Table 21 shows the occupational groups ordered by workload hours per day. Clearly, watchstanders (11.77 ± 0.75 hours/day) work the most, followed by daymen (10.67 ± 0.55), and engineers (8.04 ± 0.07 hours/day). Watchstanders also have the highest standard deviation in the average on-duty hours per day compared to the two other occupational groups, suggesting a bigger discrepancy between the watchstanders working the most and the watchstanders working the least. Watchstanders had the highest on-duty hours per day for the mean 90th quantile (11.92 ± 0.79), while the engineering group showed little variation, indicating that the crewmembers had approximately the same number of on-duty hours per day for both the mean and mean 90th quantile (8.11 ± 0.11).

Table 21. The Baseline model mean On-duty hours per day, by occupational group

Occupational Group	On-duty hours/day	
	M $\pm$ SD	Mean 90th quantile hours/day
Watchstanding	11.77 ± 0.75	11.92 ± 0.79
Dayman	10.67 ± 0.55	10.75 ± 0.57
Engineering	8.04 ± 0.07	8.11 ± 0.11

b. Off-duty Hours per Day

Corresponding to the on-duty hours, the off-duty time among the crew averaged 13.46 ± 1.40 hours per day. As presented in Table 22, the engineers spent the most time messing (M = 2.24 ± 0.02) and had the most personal time (4.98 ± 0.06), in addition to sleeping 8.25 hours per day (± 0.01) on average, which was more than or equal to that of the other occupational groups. While daymen slept (8.06 ± 0.30) approximately 11 minutes less than the engineering group each day, the watchstanders achieved on average 7.46 hours (± 0.54) of sleep a day, roughly 47 minutes less than the engineers.

Table 22. Mean hours per day and standard deviations of Baseline modeled Off-duty activities, by occupational group

Occupational Group	Messing	Hygiene	Personal Time &	
			Fitness	Sleep
Watchstanding	1.49 ± 0.26	0.39 ± 0.13	2.90 ± 0.77	7.46 ± 0.38
Dayman	1.69 ± 0.08	0.50 ± 0.00	3.08 ± 0.78	8.06 ± 0.30
Engineering	2.24 ± 0.02	0.50 ± 0.00	4.98 ± 0.06	8.25 ± 0.01

Overall, the crew spent 1.73 ± 0.30 hours per day messing, with hygiene making up 0.46 ± 0.09 hours per day and Personal Time and Fitness 3.37 ± 1.03 hours per day. All occupational groups slept on average well above the minimum recommended sleep of seven hours per day (Watson et al., 2015), and the average sleep among all simulated sailors in the Baseline model was 7.90 ± 0.43 hours a day. None of the crewmembers slept less than seven hours per day, while six sailors (27.3%) accumulated less than 7.5 hours of sleep per day. The number increased to seven sailors for the 10th quantile (31.8%), supporting the notion of low variation between the average and extreme simulation runs in the Baseline model.

c. *Completed, Delayed, and Failed Tasks*

As shown in Figure 16, even the Baseline model contains irregular events that were delayed or failed to complete. When two or more activities occur at the same time, the resource needs must be deconflicted. IMPRINT uses the trump matrix to decide which activities are prioritized to simulate the crew choosing where to direct their effort. Delays happened when there were not enough sailor resources, simply indicating a lack of the needed roles during the planned start time for that activity. A task would be delayed until the resources became available or failed after a set time. Lower priority activities, such as 40 mm drill training (Failed = 16.3%) that drew from an in-demand job role resource (Gunners 1 and 2 were doing critical watches, which were the highest priority activity), experienced higher delay and failure rates than others. Tasks with high completion percentages, such as Comms and Network corrective maintenance (CM) tasks, could be pulled from readily available resources. Comms and Network CM could draw from CIS Officer and both SROs, with the latter two not standing watches, which resulted in a completion percentage of 100% during

the 999 simulated runs of the Baseline model. The tasks from Figure 16 with the lowest completion percentages, Onboard Hazardous Spill Training (Completion = 65.5%), Seamanship Training (69.4%), Diving Training (71.5%), and Safety Inspection (73.3%), have in common that they required several job roles to complete, and all demanded contributions from at least one watchstander, in addition to having low priority.

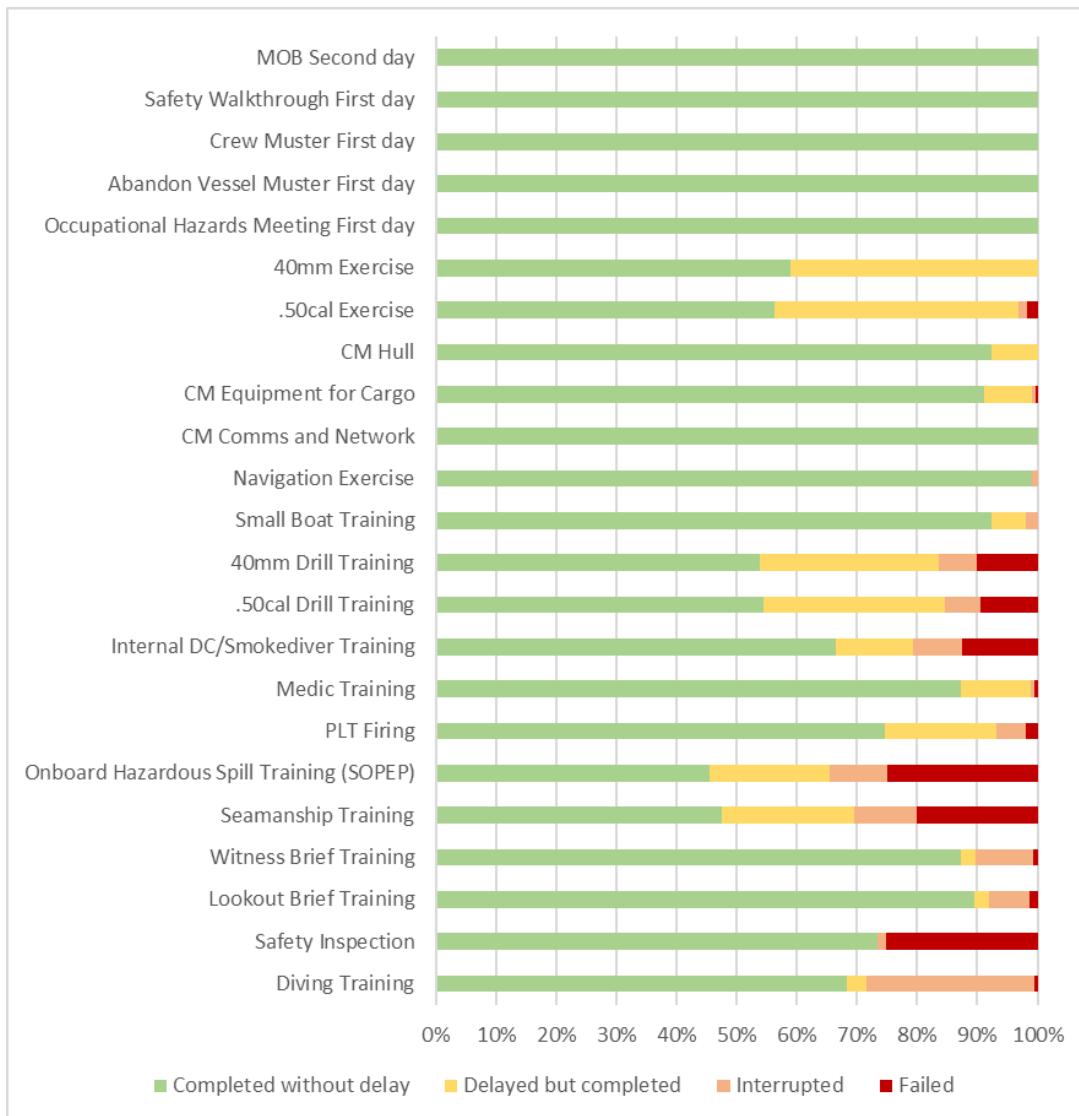


Figure 16. Baseline model's activities in order by trump matrix priorities, showing percentage of irregular activities completed, delayed, interrupted, and failed

2. Augmented Model

The Augmented model included unplanned events in addition to the scheduled and planned irregular activities included in the Baseline model. The Augmented model was used to assess a more realistic operational environment compared to the one described in the Baseline model. We ran the simulation 999 times. The activities and events included in the Augmented model were sourced from SMEs, supported by observations made by the research team during the data collection period (i.e., fishery inspections). Some of the tasks necessitated a whole ship approach lasting hours to complete, while others demanded a more specialized set of skills, with fewer resources to draw from, like engine failures requiring corrective mechanical proficiency.

a. On-duty Hours per Day

The simulated crew worked on average 11.02 ± 1.35 hours per day. The mean number of on-duty hours ranged from 8.44 ± 0.23 hours per day for the Chief Engineer to 13.03 ± 0.19 hours per day for Gunner 1. Four sailors worked more than 12 hours per day on average across all simulation runs, while six sailors surpassed 12 hours, when assessing only the 90th quantile of runs. In both cases, the sailors were part of the watchstanding occupational group, with Gunner 1 working the longest days with 13.30 hours per day for the 90th quantile. The crew 90th quantile on-duty hours per day was 11.22 ± 1.29 hours per day, with the mean difference being 0.29 hours per day among the sailors. These results are shown in Table 23.

Table 23. Mean On-duty time per day for the NoCG crew in the Augmented model

Job	Occupational Groups	On-duty hours per day Mean $\pm$ SD	90th quantile hours per day
Gunner 1	Watchstanding	13.03 ± 0.19	13.30
Corpsman 2	Watchstanding	12.81 ± 0.14	13.01
Ship Petty Officer 1	Watchstanding	12.55 ± 0.21	12.83
Battery Officer	Watchstanding	12.28 ± 0.25	12.61

Job	Occupational Groups	On-duty hours per day Mean $\pm$ SD	90th quantile hours per day
Gunner 2	Watchstanding	11.92 $\pm$ 0.26	12.27
Operations Officer	Watchstanding	11.90 $\pm$ 0.21	12.16
XO	Dayman	11.69 $\pm$ 0.14	11.86
Ship Petty Officer 2	Dayman	11.60 $\pm$ 0.28	11.93
CIS Officer	Dayman	11.57 $\pm$ 0.28	11.91
Deck Trainee 2	Dayman	11.56 $\pm$ 0.27	11.89
Deck Trainee 1	Dayman	11.43 $\pm$ 0.24	11.73
Bosun Officer	Dayman	11.36 $\pm$ 0.22	11.65
SRO 1	Dayman	11.22 $\pm$ 0.20	11.50
SRO 2	Dayman	11.02 $\pm$ 0.16	11.23
CO	Dayman	11.01 $\pm$ 0.15	11.21
Corpsman 1	Watchstanding	10.93 $\pm$ 0.22	11.24
Gunner 3	Dayman	9.95 $\pm$ 0.20	10.24
Culinary Specialist	Dayman	9.82 $\pm$ 0.18	10.06
Mechanic	Engineering	8.86 $\pm$ 0.30	9.25
1. Engineer	Engineering	8.83 $\pm$ 0.30	9.22
Electrician	Engineering	8.68 $\pm$ 0.23	8.99
Chief Engineer	Engineering	8.44 $\pm$ 0.23	8.74

Table 23 supports the notion from the Baseline model that watchstanders standing watch for four hours between 20 at night and 8 in the morning, worked more than the other occupational groups. This finding is confirmed in Table 24, as the average watchstander has a mean on-duty time of 12.20 ± 0.69 hours per day, followed by the dayman group averaging 11.11 ± 0.65 hours/day, and engineers (8.70 ± 0.31 hours/day). Results from the 90th quantile analysis of daily on-duty hours reinforces the trend, with watchstanders working on average 12.39 hours per day or more for the top 10th percentile simulated 21-day runs, in contrast to sailors included in the dayman ($11.38 \pm$

0.66) and engineering (9.05 ± 0.24) groups. Interestingly, the difference between the mean on-duty hours of the occupational groups and the corresponding 90th quantile results increased the most for engineering (difference = 0.35 hours per day), then daymen (difference = 0.27), with watchstanders increasing the least (difference = 0.19). This finding indicates that the added activities affect the groups with fewer work hours more, which might be expected as watchstanders had a higher probability of forsaking other work tasks instead of rest when attending to the new activities and events in the Augmented model.

Table 24. Mean On-duty hours per day, by occupational groups, and the mean 90th quantile

Occupational Group	On-duty hours/day	
	M $\pm$ SD	Mean 90th quantile
Watchstanding	12.20 ± 0.69	12.39 ± 0.63
Dayman	11.11 ± 0.65	11.38 ± 0.66
Engineering	8.70 ± 0.31	9.05 ± 0.24

b. Off-duty Hours and Sleep

The crew was off duty for 12.98 ± 1.35 hours per day, which included messing (1.71 ± 0.34), hygiene (0.45 ± 0.07), personal time and fitness (3.43 ± 1.05), and sleep (7.70 ± 0.44). Sleep made up a large portion of the off-duty activities, and there were distinct differences among the occupational groups as presented in Table 25. Watchstanders slept on average 7.24 ± 0.52 hours per day, daymen slept 7.90 ± 0.32 hours per day, and engineers 8.09 ± 0.15 hours per day. The other off-duty activities are also presented in Table 25. The largest differences among the groups were found in time spent messing and personal time between watchstander ($M = 1.43$ and $M = 2.83$) and

engineering ($M = 2.09$ and $M = 4.65$), with the latter spending 46% more time on average messing and 64% more on personal time and fitness.

Table 25. Mean hours and standard deviations of Off-duty activities, by occupational groups

Occupational group	Messing	Hygiene	Personal Time & Fitness	Sleep
Watchstanding	1.42 ± 0.26	0.37 ± 0.12	2.71 ± 0.77	7.29 ± 0.33
Dayman	1.62 ± 0.08	0.48 ± 0.02	2.95 ± 0.88	7.83 ± 0.37
Engineering	2.09 ± 0.08	0.49 ± 0.01	4.64 ± 0.21	8.08 ± 0.16

Figure 17 shows the mean daily sleep duration of each crew member during the 21-day Augmented model simulation. Sleep duration is not necessarily directly related to the on-duty hours, meaning that sleep can be scarce due to the sailor prioritizing other on-/off-duty activities. For example, Ship Petty Officer 1 had the lowest daily sleep duration (6.90 ± 0.12 hours/day) but worked less (12.55 ± 0.21 hours/day) than Gunner 1 (13.03 ± 0.19 hours/day) who slept more (7.20 ± 0.09 hours/day).

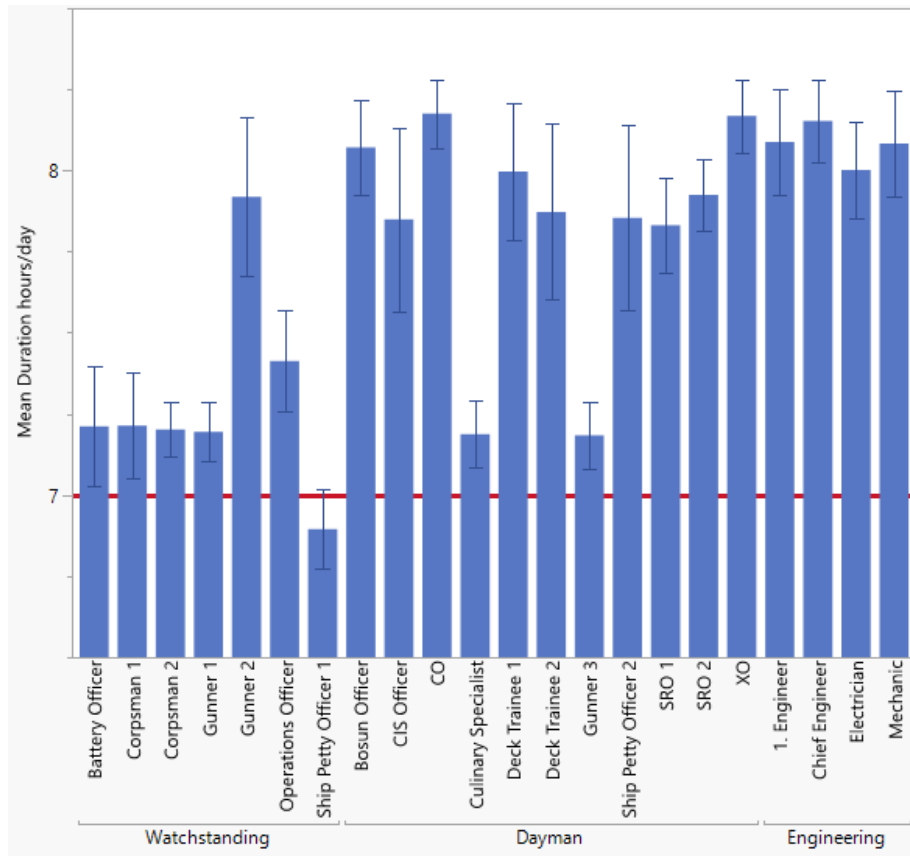


Figure 17. Sleep means and standard deviation (vertical lines) of each crew member, by occupational group. Seven-hour sleep criterion (red line)

While Figure 17 shows that only one sailor slept on average less than the recommended seven hours of sleep per day, Table 26 shows that there were several crewmembers who went below or were close to the seven hours criterion, when assessing the 10th quantile of model runs. Thus, three or more sailors slept less than seven hours—providing information about the vulnerability of the crew in extreme cases.

Table 26. Means and 10th quantile of sleep duration, by occupational groups

Sleep hours	Percentage of crew		Occupational group	
	Mean	10 th quantile	Based on Mean results over all model runs	Based on the 10 th quantile model runs
> 8	31.8%	9.1%	3 Dayman 4 Engineering	2 Dayman
8-7.5	31.8%	40.9%	1 Watchstanding 6 Dayman	1 Watchstanding 4 Dayman 4 Engineering
7.5-7	31.8%	36.4%	5 Watchstanding 2 Dayman	3 Watchstanding 5 Dayman
< 7	4.5%	13.6%	1 Watchstanding	3 Watchstanding

c. Completed, Delayed, and Failed Tasks and Events

We introduced a range of irregular activities and unplanned events to the Augmented model to supplement the activities of the Baseline model. Figure 18 lists each activity with corresponding percentages of complete, delayed, interrupted, and failed tasks. The activities are ordered by priority in accordance with the trump matrix; unplanned events named “Actual” are at the top of the chart with the highest priorities. These are live operations that seldom occur, although when they do it is paramount that the NoCG vessel has the necessary resources available: Actual Man Overboard (MOB), Actual Internal Damage Control (DC), Actual Search and Rescue (SAR), and Actual Towing all complete in more than 99% of the runs, with Actual oil spill (96.2% completion rate) lagging slightly behind. Among the activities with lower completion percentages, the SAR exercise stands out with especially low completion rates (36.4%). The reason for the high SAR failure rate is the lack of boat crew, the roles often filled by conscripts who adhere to watchstanding, which results in prioritizing critical watches and subsequent failed events.

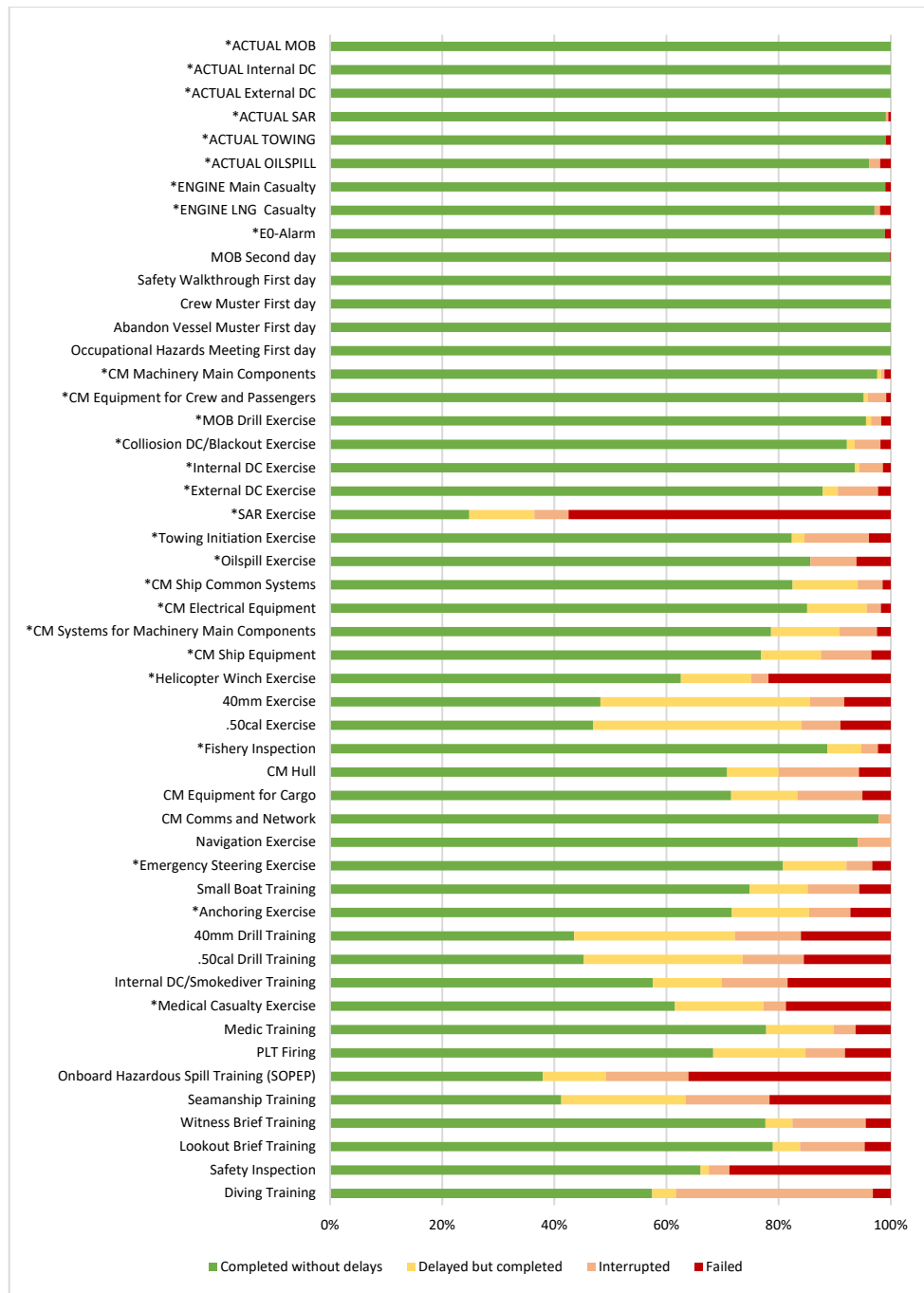


Figure 18. Augmented model's activities and events, in order by trump matrix priorities, showing percentage of irregular activities and unplanned events completed, delayed, interrupted, and failed.

Below the SAR exercise, activities have decreasing completion rates corresponding to their lower priority in the trump matrix. Weapons exercises and training with .50 cal and

40 mm suffered from heavy delays but had adequate completion rates when compared to activities of similar priority, at 85.5% and 84.1% for exercises and 72.2% and 73.6% for training, respectively. Among lower prioritized activities, Fishery inspection (94.8%) and CM Comms and Network (97.8%) show high completion percentages in the 999 simulated runs of the Augmented model, indicating readily available job roles to conduct the activities, seemingly avoiding competition from most other tasks. Fishery inspection was important as it was one of the only activities outside of the unplanned events that occurred at night, thus affecting the sleep of the participants. How those effects alter the Augmented model compared to the Baseline model is explored in the next section.

3. Model Comparison and Analysis

The Baseline and Augmented simulated model runs resulted in, respectively, more than 6,100,000 and 6,300,000 rows of data representing discrete events. Comparing the models can provide information on which crewmembers were more vulnerable as the operational tempo increased, in terms of workload and sleep as it pertains to performance. The crew spent more time on-duty (11.02 ± 1.35 hours/day) in the Augmented model than the Baseline model (10.54 ± 1.40 hours/day), an increase of almost 30 minutes per sailor per day to an accumulated added workload of 10.56 hours per day (Augmented 90th quantile = 14.96 hours/day) across the crew. Table 27 shows the differences among the occupational groups in the two models. Engineers had their mean on-duty hours per day increase the most (39.6 minutes/day) and watchstanders the least (25.8 minutes). The effect was reinforced by the 90th quantile, in which engineering saw on-duty hours increase by more than an hour per day (60.6 minutes) per crew member. The 90th quantile of the Baseline model was not included due to the minimal variation in working hours.

Table 27. Mean On-duty hours per day, by occupational group, and the mean 90th quantile

Occupational Group	Baseline		Augmented	
	M ± SD	M ± SD	Mean 90th quantile	
Watchstanding	11.77 ± 0.75	12.20 ± 0.69	12.39 ± 0.63	
Dayman	10.67 ± 0.55	11.11 ± 0.65	11.38 ± 0.66	
Engineering	8.04 ± 0.07	8.70 ± 0.31	9.05 ± 0.24	

As the Augmented model encapsulated all the activities of the Baseline model in addition to new ones, the Off-duty time decreased from the Baseline (13.46 ± 1.40 hours per day) to the Augmented model (12.98 ± 1.35 hours per day). When divided among messing, hygiene and personal time, the reductions between the Baseline and Augmented models become arbitrary due to the importance of the activities combined with minimal time reductions. This comparison is shown in Table 28. Engineering personal time had the largest difference of 20.4 minutes per day, a decrease of 6.8%.

Table 28. Mean Off-duty hours per day from messing, hygiene, and personal time & fitness, by occupational group

	Messing		Hygiene		Personal Time & Fitness	
	Baseline	Augmented	Baseline	Augmented	Baseline	Augmented
Watchstanding	1.49 ± 0.26	1.42 ± 0.26	0.39 ± 0.13	0.37 ± 0.12	2.90 ± 0.77	2.71 ± 0.77
Dayman	1.69 ± 0.08	1.62 ± 0.08	0.50 ± 0.00	0.48 ± 0.02	3.08 ± 0.78	2.95 ± 0.88
Engineering	2.24 ± 0.02	2.09 ± 0.08	0.50 ± 0.00	0.49 ± 0.01	4.98 ± 0.06	4.64 ± 0.21

The comparison of sleep duration is of interest due to its significance in relation to performance and is shown in Table 29. The influx of activities in the Augmented model, however, resulted in only small reductions in sleep duration per day by occupational group.

Watchstanders and engineers saw their sleep decrease by 10.2 minutes (10th quantile = 22.8 minutes) and the dayman group by 13.8 minutes per day (10th quantile = 22.8 minutes).

Table 29. Mean sleep hours per day, by occupational group, and the mean 10th quantile

Occupational Group	Baseline	Augmented	
	M ± SD	M ± SD	Mean 10th quantile
Watchstanding	7.46 ± 0.38	7.29 ± 0.33	7.08 ± 0.26
Dayman	8.06 ± 0.30	7.83 ± 0.37	7.59 ± 0.34
Engineering	8.25 ± 0.01	8.08 ± 0.16	7.87 ± 0.07

When assessing individual jobs, we find the differences become more pronounced, ranging from Gunner 2 sleeping 2.7 minutes less in the Augmented model (10th quantile = 11.0 minutes) to the Culinary Specialist sleeping 33.7 minutes less per day (10th quantile = 42.7 minutes). Table 30 shows the differences among the crew, and the variation between those in the same occupational groups. While the dayman group slept on average 13.8 minutes less per day, the Culinary Specialist, Ship Petty Officer 2, CIS Officer, and Deck Trainee 2 all had reductions in sleep of 20 minutes or more per day (10th quantile = >40 minutes).

Table 30. Reduction in sleep duration per hour among crewmembers between the Baseline and the Augmented models

Job	Occupational Groups	Baseline-Augmented difference in hours per day $\pm$ SD	Baseline-Augmented 10th quantile hours per day
Culinary Specialist	Dayman	0.561 $\pm$.003	0.712
Ship Petty Officer 2	Dayman	0.392 $\pm$.009	0.806
CIS Officer	Dayman	0.391 $\pm$.009	0.806
Deck Trainee 2	Dayman	0.371 $\pm$.009	0.755
Gunner 2	Watchstanding	0.335 $\pm$.009	0.668
Battery Officer	Watchstanding	0.282 $\pm$.006	0.535
Electrician	Engineering	0.248 $\pm$.005	0.454
Deck Trainee 1	Dayman	0.246 $\pm$.007	0.545
Corpsman 1	Watchstanding	0.195 $\pm$.006	0.418
Operations Officer	Watchstanding	0.174 $\pm$.006	0.380
Bosun Officer	Dayman	0.165 $\pm$.005	0.357
Mechanic	Engineering	0.164 $\pm$.005	0.388
1. Engineer	Engineering	0.159 $\pm$.005	0.382
SRO 1	Dayman	0.156 $\pm$.005	0.359
Ship Petty Officer 1	Watchstanding	0.103 $\pm$.004	0.275
Chief Engineer	Engineering	0.097 $\pm$.004	0.281
XO	Dayman	0.067 $\pm$.004	0.220
SRO 2	Dayman	0.064 $\pm$.004	0.225
CO	Dayman	0.060 $\pm$.003	0.203
Gunner 3	Dayman	0.058 $\pm$.003	0.207
Corpsman 2	Watchstanding	0.045 $\pm$.003	0.181
Gunner 1	Watchstanding	0.044 $\pm$.003	0.184

When comparing task completions between the models, we find only those included in both are eligible. Table 31 shows the percentages side by side, where the Baseline model has an overall completion percentage of 90.3%, while the Augmented model completed 83.4% of the activities. The largest discrepancies appear in CM Hull (19.1%), 40 mm Exercise (16.0%), and .50 cal Exercise (14.1%). The reductions in completion rates for these categories were expected due to the introduction of higher priority activities and unplanned events in the Augmented model; however, it is interesting to note the discrepancy pertaining to weapons exercises and training.

Table 31. Comparison of completion percentages for irregular activities contained in both the Baseline and Augmented models

Activity	Baseline completion percentage	Augmented completion percentage
40 mm Exercise	100.0 %	84.0 %
Abandon Vessel Muster First day	100.0 %	100.0 %
CM Comms and Network	100.0 %	98.5 %
CM Hull	100.0 %	80.9 %
Crew Muster First day	100.0 %	100.0 %
MOB Second day	100.0 %	99.9 %
Occupational Hazards Meeting First day	100.0 %	100.0 %
Safety Walkthrough First day	100.0 %	100.0 %
CM Equipment for Cargo	99.1 %	86.1 %
Navigation Exercise	99.1 %	95.2 %
Medic Training	98.9 %	89.2 %
Small Boat Training	98.0 %	86.8 %
.50 cal Exercise	96.8 %	82.7 %
PLT Firing	93.1 %	83.9 %
Lookout Brief Training	92.0 %	84.3 %

Activity	Baseline completion percentage	Augmented completion percentage
Witness Brief Training	89.6 %	82.7 %
.50 cal Drill Training	84.5 %	74.3 %
40 mm Drill Training	83.7 %	72.6 %
Internal DC/Smoke Diver Training	79.3 %	71.3 %
Safety Inspection	73.3 %	67.0 %
Diving Training	71.5 %	62.2 %
Seamanship Training	69.4 %	64.2 %
Onboard Hazardous Spill Training (SOPEP)	65.5 %	53.2 %

V. DISCUSSION

To provide insight regarding manning on ships of the Royal Norwegian Navy, the Forces module of the IMPRINT Pro discrete event simulation tool was used to simulate the crew (22 crewmembers) of a Norwegian Coast Guard vessel. The primary objective of the study was to assess whether the simulated crew was able to conduct its duties. Additionally, the study aimed to evaluate IMPRINT as a tool for making manpower assessments in RNoN acquisition processes.

Data were collected with the purpose of developing the model, to include both self-reported daily activities and objective sleep data recorded with the ŌURA rings in conjunction with ship documentation and dialogue with subject matter experts. This approach diverged somewhat from previous research efforts using IMPRINT on naval vessels. In particular, Attwood (2020) used available crew information and actigraphy data previously collected by the Royal Australian Navy in 2016, to build the models simulating an eight-day mission. Hollins and Leszczynski (2014) relied on self-reported activity logs collected by the Center for Naval Analyses and SME input, data that were later refined by Meredith (2016). While all the aforementioned studies included unplanned events, they did so to a lesser degree and with fewer activities compared to the present study. This thesis shared similarities with the study conducted by Poirier (2020) on a Canadian frigate, in which a baseline and augmented model were developed. However, his augmented model captured a shorter timeframe with an even higher level of operational tempo, introducing daily unplanned events like damage control or major engine malfunction incidents during a ten-day underway—far removed from the level of activity that was deemed feasible for modeling a Norwegian Coast Guard vessel.

A. IMPORTANT FINDINGS

The first objective of this study was to assess whether the Baseline model crew was able to conduct its activities without a substantive degradation in performance or sleep levels. The on-duty time for the crew was 10.50 ± 1.40 hours per day, with only a marginal increase when assessing the 90th quantile of model runs (10.64 ± 1.45 hours/day). Also,

the crew slept on average 7.90 ± 0.43 hours per day. These findings suggest that the irregular activities included in the Baseline model did not affect general crew work and rest. However, differences existed among occupational groups. Specifically, watchstanders worked more hours (11.77 ± 0.75 hours/day on duty) and had shorter sleep (7.46 ± 0.38 hours/day) than the other two occupational groups (dayman group: 10.67 ± 0.55 on-duty hours/day and sleep 8.06 ± 0.30 hours/day; engineering group: 8.04 ± 0.07 hours/day work and 8.25 ± 0.01 hours/day sleep). This could indicate that watchstanders were more vulnerable to an increase in workload, simply because they had less off-duty time to re-allocate to work, and that the eight-hour sleep “window” was likely to be disturbed by ship activities as it stretched into daytime—almost all ship-driven activities were conducted exclusively between 0800 in the morning and 2000 at night.

The Augmented model reinforced the recurring trend of watchstanders working the most (12.20 ± 0.69 hours/day), followed by daymen (11.11 ± 0.65 hours/day), and engineering (8.70 ± 0.31 hours/day). Among the occupational groups, it was the engineering group that saw the biggest work hour increases in part due to the introduction of additional corrective maintenance tasks and major engine failures. Although engineers experienced the largest increase in work hours, the Augmented model demonstrates that existing high workload jobs are still the most susceptible to overwork, with watchstanders having the highest variability within their group in terms of work hours, meaning some were working substantially more than others. If those roles hold important safety functions (as is usually the case with watchstanders), it could be conceivable to bolster such positions on a ship. Removing one individual would distribute the workload to others with the same skillset, usually in the same high workload roles. This finding emphasized the need for redundancy for those roles to meet the inevitable readiness gap between the manpower requirements and the actual manning of most ships.

Compared to the Baseline model, on-duty hours increased on average by 28.8 minutes in the Augmented model (40.8 minutes for the 90th quantile). For the full crew of 22 sailors, the total increase in on-duty hours was 10.56 hours per day, indicating an increase in workload approximating the value of one dayman’s on-duty hours. Within the Augmented model, the difference between the on-duty hours of the mean and the 90th

quantile was only 17 minutes per day (difference = 0.29 hours/day). Nonetheless, aggregated across 22 sailors over a 21-day sail, the difference accounts for roughly 126 hours of additional work. This equates to one person working a full 40-hour workweek, with no lunch breaks and some added overtime. Ostensibly, workload will not increase by a constant, but rather spike during events, with the result indicating that such increases should be investigated further.

Also, our results showed that even though on-duty hours increased, the decrease in sleep duration was modest. Specifically, the increase in workload did not translate to a proportional decrease in sleep. Both engineers and watchstanders slept only 10.2 minutes less in the Augmented model, even though engineers saw an almost 2-to-1 increase in workload over watchstanders, compared to the Baseline model. This could be an indication of surplus work capacity within the engineering group.

Overall, our modeling results suggested that crews were adequately scaled to absorb the additional activities and events presented in the Augmented model. Only one sailor averaged less than seven hours of sleep (three sailors at the 90th quantile); concurrently, seven crewmembers slept more than eight hours on average. Insight into discrepancies between those sleeping the most and those sleeping the least could contribute to identifying surplus work capacity among the crew. This could lead to opportunities for task realignment rather than increasing manpower to mitigate sleep deficiencies. Although the NoCG makes an effort to prioritize healthy sleep habits and achieve rest times in accordance with Norwegian Maritime policies, our modeling results showed that watchstanders were susceptible to exceeding 12 on-duty hours a day, with some watchstanders even working 13 hours per day. Given our knowledge of the deleterious effects of sleep deprivation on human performance and on increasing the risk of mishaps, in addition to the fact that mishaps at sea tend to be more frequent in conditions where there is poor ambient light (Vinagre-Ríos et al., 2021), the study of ways to reduce the workload and highlight sleep among those standing watch at night could be beneficial to improving performance.

We assessed the percentage of completed tasks to identify vulnerabilities in the crew composition. Weapons training (.50 cal and 40 mm) completion rates decreased

substantially (between 10.2% and 16.0%) from the Baseline to the Augmented model. With two of three gunners standing watch and requiring support from officers, whose main role was navigation, these activities became vulnerable when emerging tasks demanded higher priorities or drew from the same resource pool. For example, several tasks (e.g., anchoring, towing, emergency steering, and helicopter winch exercises) required bridge personnel (lookouts and navigators). This trend could be seen for other lower priority activities that drew from a common resource pool.

To cite a case, corrective maintenance of hull-related systems suffered a more than 20% reduction in completion rate as it fell below the other corrective maintenance tasks vying for the Mechanic role. Concurrently, corrective maintenance of communications systems did not have the same decline in completion rate (100% to 98.5%), as the relevant roles saw less demand, while the navigation exercise (99.1% to 95.2%) usually had parts of the required resources available on the bridge. Tasks with a higher percentage of failure were, for the most part, recurring training or corrective maintenance that could be postponed when in conflict with more pressing needs. The Augmented model demonstrated that critical tasks were successfully completed by the crew, which reinforced the impression from the workload and sleep results. While weapons training was important, completing between eight and nine of ten drill sessions was reasonable, provided the efforts of the small crew surged sufficiently to meet the challenges of actual events as they occurred.

B. OTHER FINDINGS

The study provided insight into a method for acquiring input for discrete event simulation models to support manpower determination. This section discusses the data collection and the quality of the information used in the models to evaluate the use of IMPRINT Pro Forces for an RNoN acquisition.

1. Data Collection

The data used for modeling the NoCG crew differed in terms of sleep and work hours compared to the trend of previous IMPRINT models' input based on navy crews. Data from wearable devices, backed by self-reported activity logs, described a median time

in bed among the crew of around eight hours ($\bar{O}$ ura rings Mdn = 8.13 hours in bed (IQR = 0.72), activity logs Mdn = 7.81 hours of sleep (IQR = 0.99)). The sleep duration corresponded to the expected eight hours of allocated sleep in the U.S. Navy Naval Availability Factor (NAF) (Office of the Chief of Naval Operations, 2021), numbers which previous studies found unattainable in their model input data (Attwood, 2020; Poirier, 2020). Similarly, the crew of the NoCG ship reportedly spent less time on duty (10.1 ± 1.79 hours/day) compared to the previous studies. The workload was also lower when compared to the NAF that assumed 11.57 hours of on-duty hours, with corresponding off-duty hours exceeding the rest requirements of an average 11 hours per day as described in Norwegian policies for civilian shipping (Nærings- og fiskeridepartementet, 2021). Thus, it was apparent that the expectation related to operational tempo was different between NoCG and Navy vessels. Models developed from NoCG data should not be used indiscriminately for Navy crews. Still, insight could be drawn from observed trends of increasing work hours and decreased sleep when the activity level increased.

Our results showed that only self-reported sleep quality, average daytime sleepiness, and mood in terms of vigor and tension worsened during the underway. However, while raw scores were statistically significant (PSQI $p = .008$, POMS Vigor $p = .013$, POMS Tension $p = .016$), they did not contribute to an increase in the number of sailors experiencing changes in sleep quality or mood. This could mean that while sleep quality decreased for some, they still experienced sufficient sleep to be deemed as adequate. The number of sailors experiencing daytime sleepiness increased (ESS $p = .083$), even though the raw scores did not change by a statistically significant amount. These results showed sailors' daytime sleepiness increased by a small amount, subsequently pushing a few sailors over the daytime sleepiness threshold. We did not identify any statistically significant changes in the number of sailors reporting worsening sleep quality, insomnia symptoms, or the remaining mood states, nor in any comparison between occupational groups.

These findings suggest that, in general, the crew's state did not change substantively during the nine-day sailing period. The reason for collecting data on crew state was to assess issues and factors affecting the sleep and workload achieved onboard.

Insight into mood and sleeping habits can provide valuable data as to whether manning is adequate to support performance. However, there were several confounding factors that were not assessed in our study. Hollins and Leszczynski (2014) administered a survey investigating crew opinions on watch rotations, sleep, and workload, a more direct approach to assess the crew's attitude towards their current work situation. Other confounding variables were environmental factors, such as high seas. Such variables can be detrimental to both sleep quality and mood, no matter the workload or opportunity to sleep. While it was important to find measures that could support activity data suggesting a crew is under or overmanned, confounding factors had to be controlled to ensure the results were sufficiently valid. For example, since the data collection was conducted during calmer seas (Sea state < 4), it would be valuable to collect data during rougher seas to compare and assess crew performance—as higher sea states tend to increase sleep duration among sailors (Matsangas et al., 2015). Therefore, we could not provide conclusive or causal reasons for the differences we observed without additional information.

The data collection used both self-report logs and the ŌURA rings to measure sleep. A comparison between these two sources for sleep duration showed a ~5% difference between self-reported sleep from the logs and time spent in bed as measured by the rings. Also, actual sleep duration measured by the Ōura rings showed a substantial difference between time in bed and sleep duration of up to 25.8% for watchstanders. While time in bed was used for the modeling effort to better accommodate time away from work, high sleep latency among watchstanders should be investigated further. To improve operational performance, the RNoN should emphasize the importance of sleep for operational readiness and overall health.

2. Quality of Model Input

Models are only as good as the data on which they are based. A great benefit of models is that they can take advantage of large data sets to produce more accurate statistical estimations. Even though the parameters of our models were based on a limited data set, future data collection can be used to refine these models.

The biggest weakness of our models was the short data collection period, extrapolating sleep and activity logs from nine days into a 21-day simulation. Data collected over longer underway periods could improve the quality of the model parameters. Also, studying multiple NoCG vessels and incorporating the operational experience of SMEs would improve the validity of model parameters, while being cognizant of differences in operational tempo between NoCG and naval ships. While data on recurring activities could be collected longitudinally, SMEs were required for modeling of infrequent or rare major unplanned events and operational incidents; consulting a mishap database could contribute information in this regard. Overall, this thesis provided insight into methods for a data-driven approach to creating manpower estimates, though it is obvious that more information must be collected—and that results from a NoCG crew would largely be unapplicable to similar sized vessels geared towards navy use.

Using multiple sources of information in the creation of the IMPRINT models was one of our models' strengths. While the ŌURA rings provided objective data on sleep duration, it is important not to generalize our conclusions due to the small sample size of our field data collection. Having participants wearing sleep tracking wearable devices during their time on leave could contribute to assessing differences in sleeping patterns away from the ship, supporting the pre-test questionnaire results and provide insights into the three-week rotation system.

Some of the parameters used in our models were based on observations made by the research team, such as jobs with inherent flexibility and autonomy (CO and XO) that were frequently supporting operations and training outside of their outlined dayman schedule. Also, there were rest breaks within work or maintenance periods that seldom were registered in activity logs. However, to acquire every nuance of the sailors' daily routines, more resources would be required on the side of the research team. Collecting data on activity logs is two-edged; they can be useful for providing a simplified overview of crew duties, but at the cost of data quality. For example, only one of 13 participants with naps in their ŌURA data reported taking naps in the activity logs—which amplified the uncertainty of more unreported napping when ŌURA rings were not used. Another example was differences in the approach to reporting activities, such as “watchstanding”

or “work.” The IMPRINT models we developed did not include watchstanding for the engineering group, even though some had reported standing watch in their activity logs. However, observations from the nine-day sail made it clear that the engineering crew attributed watchstanding to having the responsibility to be aware of engine alarms rather than being physically present in the machinery control room. As an example, even though it was important to be vigilant in the machinery control room, it would not take precedence over certain major incidents as systems were present throughout the ships alerting the crew in case of alarms. Thus, watchstanding in the engineering group was modeled as work, with the understanding that engineers would be present in the machinery control room during major incidents as part of the whole ship effort.

The IMPRINT models were based on the crew that was present during the data collection. The original manpower requirements would have afforded the crew one additional gunner, further dividing the watchstanding tasks among more crewmembers. When assessing the total workload of the crew, it was important to understand that the required work hours were not a set number, rather they scaled to the number of sailors on board. While some tasks, like watchstanding, could be distributed among more sailors to reduce the individual workload, other activities, such as whole ship operations or exercises, by design, entailed increased overall workload since the whole crew participated to the same effect. By not including people who were unavailable, the model was a better representation of the actual workload of the remaining crew. It could also be argued that it represented the reality of having to sail with less-than-complete manning. Crewmembers being on leave or being unavailable seemed inevitable, and some vacancies were more critical than others. It is worth emphasizing that the NoCG vessel, with its rotating crew structure, was more robust than having one crew per ship. However, organizations should always strive to use design to alleviate future manpower concerns, even though, in the case of rotation, critical crewmembers can do double shifts to cover for missing personnel.

C. STUDY LIMITATIONS

The initial intent of this study was to investigate the integration of a mission module onto the NoCG crew, while identifying the “core crew” from the current manning of 22

sailors. The lack of information on future mission modules, such as a Mine Countermeasure module, made this effort unfeasible, presenting too many unknown variables. However, the IMPRINT models could contribute to determining an eventual “core crew” with the current data collected, by removing tasks and activities inherent to NoCG operations. Yet, doing so would introduce considerable uncertainties. A naval warfare scenario, or even a combat training environment entailing State 1 or 3 readiness, would cause the operational tempo to transcend that of the NoCG vessel, losing validity in the process. Nonetheless, the information offered by the modeling method should be applicable to demonstrate the third objective of this thesis: to evaluate the efficacy of the IMPRINT modeling software to simulate the workload and sleep of a crew, thereby providing information to be used in an acquisition process.

1. Modeling Limitations

Another limitation of this study was not accounting for “unmet workload” (i.e., excess workload that was left undone). Since the NoCG emphasized the importance of rest periods, including sleep, there might be tasks that were not prioritized and thus not included in the model. The study did not include measures of such instances even though insufficient manning compared to total workload is common among navy vessels (Fletcher (2018)). Future studies could improve the models we developed by incorporating information on excessive workload. One method of collecting such information is questionnaires asking crewmembers about excessive workload (e.g., “*are you able to complete all the work tasks that are within your power to do?*”). Subsequently, objective data such as unmet maintenance tasks and task completion rates could be deployed as opposed to only modeling tasks that were *completed*. In reference to future acquisitions, even the most advanced data models could benefit from accompanying observations of actual workload, such as self-reported workload assessments to support the findings from the models. These assessments can be performed on legacy vessels, other nations’ existing ships, or by using prototyping and user contributions.

In addition to SME input, the IMPRINT models presented in this thesis were constructed based on a brief sailing period. However, to improve the models for use in

acquisitions, further task analysis needs to be accomplished. Specifically, the number of roles necessary for conducting activities should be considered. Hence, if certain maintenance tasks require four pairs of hands, and they necessitate skilled labor to complete within a reasonable time, then a reduction from four to three engineers is impossible. Such problems necessitate important tradeoff decisions—is it worth adding an extra sailor over the life cycle of the system, or must the system be redesigned to reduce maintenance needs, but at an upfront cost?

Also, it is important that a modeling effort remains cognizant of the fact that most tasks need to take place; as the number of activities and events increases, the list of low priority tasks will lengthen while the timeline gets congested, amplifying the likelihood of failed tasks. Thus, finding the balance between probabilistic activities and bundling tasks as planned and scheduled activities (i.e., “work”) appears important in creating a successful manpower model. The Augmented model demonstrated that the SAR exercise activity had particularly low completion rates. Practically speaking, had this happened during an actual SAR, the crew would have been pragmatic and allocated non-boat crew to watchstanding, as evidenced by the significantly higher completion percentage of the actual event. The underlying reason for the frequent failures to complete the SAR task can be traced to the combination of long durations to complete the task and resource requirements. As a whole-ship exercise, requiring two boat crews with drivers, it can quickly come in conflict with higher priority activities and thus expose the vessel to delays, interruptions, and consequently, failures to complete the exercise. The flexibility in IMPRINT also warrants discussion, as crews can be flexible and do internal rotations to afford a boat crew, something the model does not allow. The solution to this problem is to model every sailor as having a “whole-ship event” role; in this way, the model can draw from every available sailor during a whole-ship activity, instead of from distinct resources. This affords more flexibility and a more realistic behavior pattern; however, it removes some of the resolution of the model to identify weaknesses. Thus, the model must be fine-tuned, depending on the needed information—either longer patrols as in this thesis or more specific instances of one or a few days with selected activities and events.

Another issue of concern was the relatively small differences in workload and daily sleep hours between the Baseline and the Augmented models. The 21-day simulation hid some of the possible issues that some occupational groups or jobs might have had, as days with several unplanned events and irregular activities became evened out over the 21 days. Even with 999 iterations of the simulation, there were few chances to provide information on a situation where “everything went wrong,” as IMPRINT lacked an easy way to track those incidents or days with exceptionally high activity. However, presenting the overall results of a 21-day sail was still valid since it described the crew’s ability and opportunity to recover. Even so, it would be valuable to investigate shorter time periods, such as a SAR operation lasting several days instead of hours. This is particularly true knowing that just a few nights of insufficient sleep can cause sleep deprivation with corresponding effects on performance. IMPRINT could provide insight into what would happen in those extreme cases if modeled specifically.

2. IMPRINT Pro Forces Limitations

Occasionally, IMPRINT unexpectedly shut down. On restarting, the program replicated seed numbers making duplicates of model iterations. The iteration processed during the abrupt shutdown also contained data based on fewer days than the full 21-day underway, leading to outliers in terms of time spent on the various activities. Duplicates would lead to a skewing of the results, especially if those iterations contained statistical outliers and were removed to assess the results. After trial and error, the Baseline and Augmented models were created with all iterations having distinct seed numbers and no errors.

The IMPRINT Pro Forces model schedules were 24 hours and started anew on hour zero (0). This limited the assessment of sleep and workload on a day-to-day basis, as a sleep schedule from 2300 to 0700 resulted in one hour of sleep from 2300 to 0000 on Day 1, and seven hours of sleep the next day. To capture a realistic sleeping pattern, the data had to be summed up to account for the accrued sleep during the 21-day simulation and the number subsequently divided by 21 to get the average sleep per day for each sailor. While this approach could be sufficient for a wider analysis, it could also mask situations in which

unplanned events hinder most sleep or lower priority activities. For example, the lack of resolution prevented the study from assessing if sailors were able to attain uninterrupted sleep. Subsequent days of sleep interruptions could lead to significant sleep deficiencies in the short term; however, averaged over 21 days, the decrease in sleep could become less of a factor.

Further, planned activities lacked an interrupt strategy, meaning that they could not be resumed after being interrupted by an activity with higher priority, one which lasted for longer than the remaining duration of that planned activity. Eating was an activity that in reality would be resumed if the opportunity arose, with the crew member having a snack before continuing work. Instead, IMPRINT would report that the eating activity was aborted and failed for that instance if the messing period had elapsed at the end of the prioritized activity. Even though eating was not the most critical activity to fail in the model, it still would indicate excessive workload, even if the crew member was able to get some food after all.

IMPRINT should also allow for randomness of scheduled tasks. Messing and sleeping were two examples of activities that were seldom done at the exact same time every day, with the option to program napping proving beneficial and a better representation of some sailors' sleeping habits. Allowing for varying duration of scheduled tasks, work could more realistically capture lower priority irregular activities, avoiding activity congestion as discussed earlier. IMPRINT was also limited in terms of recreating realistic "sleeping watch" routines, drawing from a person who was asleep for unplanned activities. While the "sleep activity" toggle allowed for waking up the person who had slept the most, this would not necessarily represent the schedule of sleeping watches.

Some tasks were omitted, mostly because they demanded that personnel be away from the ship. During the data collection, some sailors would be conducting training ashore for brief periods. Although the workload would allow for their absence, it remained a limitation in the model as IMPRINT was unable to remove jobs temporarily. In general, NoCG vessels accomplished several tasks that were conducted away from the ships themselves. This could be visitations on other ships, which would remove the personnel from the ship location—making them unreachable to participate in events on the NoCG

vessel. While this could somewhat be alleviated by prioritizing those specific activities higher than some of the unplanned events, such actions could have the consequence that crewmembers would “leave the ship” during unplanned events like damage control or firefighting—which is unlikely to occur.

Recurring activities modeled with randomness in start time, duration, and repeat interval, combined with the 21-day duration of the simulated model, led to emergent outcomes. Frequently occurring activities would iterate and result in skewed start times at the end of the 21 days. In the case of certain runs, such a scenario created unrealistic situations. This was solved by implementing deviation restrictions in the modeling expression of the initial occurrence, although this should be improved in a future version of IMPRINT.

Moreover, IMPRINT Pro Forces did not have the capability to model sleep latency, thus reported sleep hours might have been exaggerated. This pertained particularly to events interrupting sleep, where the sleep activity would restart immediately upon the completion of events, which in reality would include a variable amount of sleep latency. The results did not account for the number of cases of “broken sleep,” where sleep periods were interrupted, thus negatively affecting the required seven hours of undisturbed sleep for a performance-supporting sleep habit.

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VI. CONCLUSION AND RECOMMENDATIONS

Manpower is an important component of ship performance and a major driver of a vessel's life cycle cost. This thesis used a modeling and simulation approach using discrete event simulation to support manpower decision making, by exploring a process of data collection and design of manpower models for a Norwegian Coast Guard vessel. This thesis has demonstrated the strengths and weaknesses of utilizing the IMPRINT Pro Forces discrete event simulation tool for creating crew models, starting with an approach to data collection to build the necessary input.

The NoCG 9-day data collection indicated that the crew had few sleep habits or workload issues, although the possible unmet workload was not accounted for in the data. There were some differences in workload and sleep among occupational groups. Overall, however, the crew was able to achieve its operational tasks.

A. SUMMARY OF THESIS OBJECTIVES

The first objective was to assess whether simulated crewmembers were able to perform their duties when workload included scheduled activities and irregularly occurring planned activities and still maintain healthy sleep habits. The Baseline model output showed that all crewmembers slept more than seven hours per day and achieved high completion rates on the irregular activities.

The next objective was to assess workload and sleep habits following the introduction of several additional irregular activities and unplanned events in the Augmented model. Results demonstrated a reduction in the crew's ability to complete the full range of tasks. Nevertheless, highly prioritized events were covered sufficiently in nearly all instances. The added tasks reduced sleep among all sailors, although the reduction affected the watchstanding occupational group the most, with some watchstanders sleeping less than seven hours per day. However, the decline in sleep duration was more an outcome of being vulnerable to workload increase, with some crewmembers already having the least amount of sleep, as opposed to experiencing a disproportionately higher workload than the other occupational groups.

The final objective was to determine the strengths and weaknesses of the simulation software. The IMPRINT Pro Forces module can be a valuable tool for assessing manpower requirements related to an acquisition of vessels with added modules. This thesis concludes that a complete analysis requires a two-pronged approach investigating long-term effects from a full sail, in addition to a shorter timeline for high activity repercussions on the crew. IMPRINT had some limitations in replicating the flexibility of crews to reorganize in order to meet threats while maintaining a level of resolution to identify manning weaknesses. Additionally, the quality of the data input to the model limited the quality of the output, and it was challenging to determine when a manpower simulation tool could transcend SMEs' ability to assess manpower needs. However, maintaining a model with evidence for why a certain level of manpower was decided upon could be a valuable tool to protect crews from operational requirements creep during the life cycle of a vessel. This would be especially prudent given the proposed scalability of standardized, modular-based vessels and the intention of future utilization of added modules with advanced technology.

B. RECOMMENDATIONS

Further refinement of the parameters used for modeling crews in IMPRINT Pro Forces module should be done to enhance the internal and external validity of the tool for future acquisitions. This recommendation would include balancing the number of activities and unplanned events, their duration, and the effects from adding more or less manpower to complete tasks. Ship manning modeling and simulation efforts should include concurrent field data collections, task analysis on ships, and collaboration with SMEs. In addition to more extended simulations like the one conducted in this thesis, a parallel effort should be carried out focusing on high operational tempo situations. This would include those “actual” unplanned events modeled for the crew but with fewer subsequent days to better assess the impact on the crew. This approach would remove the issue of averaging out high spikes in activity, providing additional information for trade-off decisions during acquisition.

The use of IMPRINT to create manpower estimates cannot be fully validated until it has been used in an acquisition, following the steps outlined in this thesis: data collection,

modeling, analysis, evaluation, and repeat. At the same time, it warrants a discussion of whether data-dependent simulation tools such as IMPRINT are even applicable for smaller navies due to limited data availability and a lower number of vessels. The counter argument is that standardization increases the value of building human performance models. Amassing data on one ship will carry a higher degree of external validity when multiple ships and vessel classes share common systems. The models allow for the verification of manpower concepts rather than making decisions based on assumptions. Over time, the RNoN, possibly in partnership with allies that have similar systems, should ensure manpower determinations can be made utilizing large repositories of activity data. In the future, with increased modularity-based vessel structures and a will to leverage emerging technologies, the RNoN should employ manpower models to rapidly assess manpower estimates and tradeoff opportunities when replacing or upgrading modules.

Sharing workload data with our collaborators in the civilian contracting space is key. Since the RNoN relies heavily on contractor support for developing and constructing systems, making sure that military contractors have access to some of the human performance data that the navy possesses will allow them to contribute manpower estimates for system modules. Implementation of modules, from the initial acquisition and future procurements along the system's life cycle, can be streamlined if the manufacturers can provide manpower estimates that include the integration of module manpower detachments into existing manpower structures. However, this coordination must go both ways, as the RNoN obtains access to early estimates to do their own manpower assessments from both an SME and data tool viewpoint to achieve tradeoff opportunities.

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