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PROTOTYPE SCHEDULING MANAGEMENT AID FOR RISK TRACKING (SMART) TOOL FOR THE USN SURFACE FLEET

by

Ana Veronica Badua

December 2020

Co-Advisors: Nita L. Shattuck
Panagiotis Matsangas
Second Reader: Michael P. O'Neil

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Long working hours, 24/7 shift work, restricted sleep opportunities, and circadian misalignment all lead to degraded Sailor performance and impairments in decision making. These deficiencies threaten the safety of Sailors and a unit's mission readiness, as the recent deadly collisions of the USS *Fitzgerald* and USS *John. S. McCain* exposed. Despite the headway made by the Navy in addressing crew endurance and fatigue issues, there is a capability gap in the surface navy's ability to systematically assess and mitigate crew fatigue during in port and at-sea operations. It is imperative to provide operational leaders charged with ensuring peak mission readiness levels with insights into the current and predicted readiness levels of their Sailors.

This thesis developed a Microsoft Excel-based scheduling decision aid capable of tracking, detecting, and quantifying human performance risk factors associated with work and rest patterns for U.S. Navy Sailors. The Scheduling Management Aid for Risk Tracking (SMART) systematically collects Sailor activity data and provides trend analysis at an individual and organizational level, arming the scheduler with critical insight necessary for better crew resource management. The prototype's tailorable heuristics are designed to identify and quantify human performance risk, enabling leaders to better mitigate risk through data-driven decision making.

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Ana Veronica Badua
Lieutenant, United States Navy
BS, Drexel University, 2013

Submitted in partial fulfillment of the
requirements for the degree of

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December 2020

Approved by: Nita L. Shattuck
Co-Advisor

Panagiotis Matsangas
Co-Advisor

Michael P. O'Neil
Second Reader

W. Matthew Carlyle
Chair, Department of Operations Research

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ABSTRACT

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This thesis developed a Microsoft Excel-based scheduling decision aid capable of tracking, detecting, and quantifying human performance risk factors associated with work and rest patterns for U.S. Navy Sailors. The Scheduling Management Aid for Risk Tracking (SMART) systematically collects Sailor activity data and provides trend analysis at an individual and organizational level, arming the scheduler with critical insight necessary for better crew resource management. The prototype's tailorable heuristics are designed to identify and quantify human performance risk, enabling leaders to better mitigate risk through data-driven decision making.

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LIST OF ACRONYMS AND ABBREVIATIONS

3M	Maintenance and Material Management
AFRL	Air Force Research Laboratory
CFEMP	*Comprehensive Fatigue and Endurance Management Policy*
CNAF	Commander, Naval Air Forces
CO	Commanding Officer
COMNAVSURFLANT	Commander, Naval Surface Force Atlantic
COMNAVSURFOR	Commander, Naval Surface Forces
COMNAVSURFPAC	Commander, Naval Surface Force, U.S. Pacific Fleet
COMUSFLTFORCOM	Command, United States Fleet Forces Command
CR	*Comprehensive Review of Recent Surface Force Incidents*
CS	Combat Systems Department
DDG	Guided Missile Destroyer
DH	department head
DIVO	division officer
DOD	Department of Defense
DON	Department of the Navy
ENG	Engineering Department
ESS	Epworth Sleepiness Scale
EXEC/NAV	Executive/Navigation Department
FAST	Fatigue Avoidance Scheduling Tool
FC	Fire Control Technician
FOM	Figure of Merit
GAO	Government Accountability Office
GQ	General Quarters
GUI	Graphical User Interface
I	Interim Qualified
ILO	International Labour Organization
IMO	International Maritime Organization
IRM	Individual Risk Management
IRMT	Individual Risk Management Tool

ISI	Insomnia Severity Index
JQR	Job Qualification Requirements
MLC	Maritime Labour Convention
MS	Microsoft
NAF	Navy Availability Factor
NATOPS	Naval Air Training and Operating Procedures Standardization
NPS	Naval Postgraduate School
N/Q	Not Qualified/Not Assigned
NSC	Naval Safety Center
NSF	National Sleep Foundation
NSF	Naval Surface Forces
NSMRL	Naval Submarine Medical Research Laboratory
NSWW	Navy Standard Work Week
NTCSS	Naval Tactical Command Support System
NTSB	National Transportation Safety Board
OMMS-NG	Organizational Maintenance Management System-Next Generation
OPNAV	Office of the Chief of Naval Operations
OPS	Operations Department
OPSO	Operations Officer
OPTEMPO	operations tempo
ORM	Operational Risk Management
OWL FM	Optimized Watchbill and Logistics Fatigue Meter
PMS	Planned Maintenance System
POMS	Profile of Mood States
PQS	Personnel Qualification Standard
PRD	Projected Rotation Date
PSQI	Pittsburgh Sleep Quality Index
PT	Plans and Tactics Department
PVT	Psychomotor Vigilance Test
Q	PQS Qualified

RADM	Relational Administration Data Management
S & A	Sea and Anchor
SAFTE	Sleep, Activity, Fatigue, and Task Effectiveness
SAR	Search and Rescue Swimmer
SDA	Scheduling Decision Aid
SHARP	Sierra Hotel Aviation Readiness Program
SMART	Scheduling Management Aid for Risk Tracking
SORM	Standard Organization and Regulations Manual
STCW	Standards of Training, Certification, and Watchkeeping for Seafarers
SUP	Supply Department
U/I	Under Instruction/PQS Assigned
USCG	U.S. Coast Guard
USFF	U.S. Fleet Forces
U.S.	United States
USN	United States Navy
WCS	Work Center Supervisor
WEPS	Weapons Department
WTRP	Watch Team Replacement Plan
XO	Executive Officer

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EXECUTIVE SUMMARY

The motivation behind this thesis was to reduce the likelihood of surface fleet mishaps like the four that occurred in 2017. Two separate collisions involving the USS *Fitzgerald* (DDG-62) and the USS *John S. McCain* (DDG-56) were fatal and resulted in the deaths of 17 Sailors and injury to many more. These mishaps resulted in degraded operational readiness, reduced mission availability, and increased operational tempos for the already limited available ships. Moreover, the unplanned repair costs for the USS *Fitzgerald* and *the* USS *John S. McCain* were estimated upward of $700 million taxpayer dollars (LaGrone, 2020; Ziezulewicz, 2018; Werner, 2017).

U.S. Fleet Forces command released the *Comprehensive Review of Recent Surface Force Incidents* on November 2, 2017, which outlined their investigative findings and recommendations for corrective actions. One of the findings was that "Fatigue or ineffective fatigue/rest management was embedded in the four key mishaps that occurred in the Western Pacific" (U.S. Fleet Forces Command, 2017, p. 97). During the same month, the Department of the Navy published the *Comprehensive Fatigue and Endurance Management Policy*. This policy established crew rest requirements and workday limits, mandated crew endurance training, and codified the use of circadian-based watchbills and shipboard routines designed to optimize watchstander alertness and sleep recuperation (Department of the Navy [DON], 2017). The policy's intent was to ensure that "Sailors are adequately rested for safe, professional shipboard operations to deliver enhanced warfighting effectiveness" (DON, 2017, p. 1). Commanding Officers are expected to assess and mitigate risk during naval operations by using tools such as the Individual Risk Management Tool and weighing planning considerations like activity time guidelines (DON, 2017). Fatigue risk indicators such as prolonged wakefulness and insufficient sleep are associated with increased human performance risk (Shattuck et al., 2018; Shattuck & Matsangas, 2014).

Currently, there is no systematic way to track work/rest activity information to provide an objective assessment of human performance risk onboard ships. The U.S. surface fleet lacks a diagnostic tool capable of assessing crew work and rest patterns to

mitigate fatigue. This shortcoming results in a large knowledge gap and a missed opportunity to optimize work schedules, improve crew resource management, and mitigate for known fatigue risk indicators. The objective of this thesis was to develop a scheduling decision aid prototype in Microsoft Excel capable of recording work and rest activity data by tracking, detecting, and quantifying human performance risk factors. The intent was to enable schedulers to make data-driven risk management decisions regarding their personnel and evolution scheduling practices while also addressing the "can-do culture" and lack of fatigue management cited in the 2017 *Comprehensive Review* as attributable causes for the mishaps (p. 19).

The Scheduling Management Aid for Risk Tracking (SMART) prototype is a tailorable Excel-based crew resource management tool and data repository for work/rest activity. The activity data can be used to support historical data analysis or analysis of projected work schedules or evolutions. The main advantages of this prototype are that it is scalable for use on various platforms or organizations; it is readily available at no additional cost onboard ships and at shore installations; and it does not require network connectivity which is restricted during certain operations. The main disadvantages for the prototype are that it currently requires manual data entry; relies on self-reported activity data; and requires computer access.

The work/rest activity data repository tracks the following activities: watch (W), work (A), maintenance (M), and sleep/rest (S) in 15-minute increments from 00:00 to 23:45. After the data repository was created, several heuristics were implemented to track, detect, and quantify human performance risk. The four activity thresholds for sleep/rest periods, total work periods, watch rotation type, and number of watch sections are by no means a comprehensive listing of human performance risk factors. Despite this limitation, the activity tracking and heuristics begin to address the problem of inadequate fatigue and rest management in the surface fleet. The numerical thresholds are tailorable but were based on a mixture of policy guidelines and scientific findings.

The main outputs of the prototype are charts illustrating activity trends and averages, risk trends and counts, and a personnel listing by risk category. Users will be able to filter their results by time, organizational level, or by concern level rating or value. The

chart's dynamic design instantaneously returns results based on the user's filter selections. With these outputs, a user can visualize activity and risk trends and can then investigate the causes for those discrepancies. The user can make data-driven crew resource management decisions and implement fatigue mitigation actions.

Now that the SMART prototype is complete, we have the option to develop it further, identify and field commercially available software with similar functions, or update existing software (e.g., RADM) with similar functionality. There are several wide-ranging applications for this prototype. For example, the prototype can offer insight into how the recent COVID-19 pandemic has impacted already strained operational schedules and individual workloads. Additionally, the activity information collected in this prototype would reduce the human performance risk data gap and enrich fatigue research models tailored to the military maritime environment. The activity data can also be used to clarify the disparity between the activity hours allocated versus the activity hours accomplished in manpower models to influence manning decisions.

In conclusion, the U.S. Navy must invest in fatigue management tools and methods tailored to the surface combatant community to increase warfighter performance, operational effectiveness, operational safety, and crew endurance. We need to foster innovation and support cultural shifts aimed at decreasing the risk associated with degraded human performance. The SMART prototype is one effort to standardize data-driven human performance risk assessment.

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I. INTRODUCTION

Working onboard a U.S. Navy warship is an inherently dangerous job where the stakes are high and the margin for error is thin. Sailors are tasked with ensuring that their ships can bring the fight to the enemy 24 hours a day, seven days a week when operationally deployed, often under the harshest working conditions.

A. BACKGROUND

The U.S. Navy's surface fleet faced a year of reckoning in 2017, which culminated in the deaths of 17 U.S. Sailors. In the wake of three collisions and one grounding involving U.S. Navy warships, the Vice Chief of Naval Operations (VCNO) commissioned a 33-member review team led by Commander, United States Fleet Forces Command (COMUSFLTFORCOM) to analyze the causes of the mishaps and provide recommendations to "ensure the safety of our [Sailors], safe operations at sea, and the readiness of our forces" (Department of the Navy [DON], 2017b, p. 3). The *Comprehensive Review of Recent Surface Force Incidents* (CR) consisted of 58 recommendations centered on key training, operational safety, ship readiness, and ship culture concerns (DON, 2017b). An adapted list of attributable causes for the mishaps showcase the troubling trend of the negative effects of sleep-deprived and overburdened watchstanders (Table 1). Some factors which impair a warfighter's physical performance and decision making are long working days, severe stress, shift work, restricted sleep opportunities, and circadian desynchrony (Shattuck et al., 2019; Kilgore et al., 2006; Larsen & Tandberg, 2001; Naval Safety Center [NSC], 2009). Compromised human performance and decision making, when combined with other factors like subpar watchstanders, ineffective training programs, and equipment degradations, can lead to suboptimum warfighter performance, increased safety risks to the individual and the organization, and the loss of strategic military assets and human life as exposed by the mishaps in 2017 (DON, 2017b).

Table 1. Matrix of Mishap Attributes. Adapted from DON (2017b).

Mishap Factor	USS John S. McCain (DDG 56)	USS Fitzgerald (DDG 62)	USS Lake Champlain (CG 57)	USS Antietam (CG 47)
Fatigue/fatigue Management	X	X	X	X
Primary Cause: Human Error	X	X	X	X

In the three years since the CR was published, the Navy continues to make great strides towards tackling the issues highlighted in the report. Circadian-based watchbills and corresponding shipboard routines designed to improve watchstander alertness and sleep quality are now the norm rather than the exception. Another significant development was the release of the *Comprehensive Fatigue and Endurance Management Policy* (CFEMP) on November 30, 2017. The Naval Surface Force Commanders of U.S. Pacific Fleet and Atlantic Fleet created the policy which established crew rest requirements, workday limits, crew endurance training, and fatigue mitigation steps with the goal of achieving "optimal crew endurance, performance, and safety" (DON, 2017a, p. 1). This policy marked a major cultural shift for naval surface forces and a stronger commitment to addressing systemic crew endurance issues which have plagued the Navy for decades.

Several previous Naval Postgraduate School (NPS) master's theses that studied the work and rest balance onboard ships arrived at a similar conclusion: USN Sailors routinely worked longer and slept fewer hours than the recommended guidelines (Davey, 2013; Fletcher, 2018; Green, 2009, Haynes, 2007, Mason, 2009). Inadequate manning levels throughout the surface fleet have contributed to increased Sailor workloads, acute and chronic sleep debt, increased fatigue levels, negative mood, and poor sleep quality which have manifested in impaired warfighter effectiveness (Fletcher, 2018; Garbacz, 2019; Murph, 2019; Davey, 2013; Yokeley, 2012; Young, 2013; Green, 2009, Haynes, 2007, Mason, 2009). Inadequate manning also impacts how ships approach creating operational schedules and personnel assignments. In Captain Frank Walter's *Proceedings* article entitled "A Better Way to Build a Watchbill," he writes about how "most ships treat writing

the watchbills for at-sea operations as an economics problem: Watches needing to be filled are the 'demand' and divisions the 'supply'" (Walter, 2020, p. 1). While the effects of insufficient manning will not be remedied overnight, leaders and schedulers can implement steps to mitigate their impact.

Despite the headway that has been made in addressing crew endurance and fatigue issues within the U.S. Navy, there is still room for improvement. A capability gap exists in the surface navy's ability to systematically assess and mitigate crew fatigue for in port and at-sea operations. To make meaningful steps in maximizing crew resilience and improving warfighter performance, it is imperative to arm decision makers with ways to develop smarter watchbills and schedules. One way to accomplish this goal would be to incorporate the work and rest activity information of each Sailor into the scheduling tool to balance crew workloads and limited sleep opportunities. Commanding officers (COs) charged with managing and mitigating risk during their military operations lack a data-driven method to assess and evaluate the readiness levels of their Sailors. Moreover, schedulers do not have a standardized way onboard ships to collect and integrate their Sailors' work and rest hours into the watchbill making process. Schedulers need to be mindful of how chronic and acute sleep debt, poor sleep quality, and excessive hours of wakefulness impair warfighter performance. In order to address the "can-do culture" (p. 9) and lack of "fatigue management" (p. 38) cited in the CR as causes for the string of mishaps in from 2007 to 2017, we must provide COs and schedulers the means to make data-driven risk management decisions regarding their personnel and evolution scheduling practices (2017b).

B. SCOPE AND OBJECTIVES

Unlike previous NPS studies that primarily focused on accounting for Sailors' sleep, fatigue, and work/rest patterns during in port (Garbacz, 2019) and underway periods (Haynes, 2007; Green, 2009; Mason, 2009; Shattuck & Matsangas, 2014; Davey, 2013; Yokeley, 2012; Young, 2013; Kerno, 2014), this thesis focuses on the creation of a decision aid that will allow leaders and schedulers to make more informed personnel scheduling

decisions while incorporating the rest and activity thresholds established in the *CFEMP* (DON, 2017a) and from years of validated scientific research.

The objective of this thesis is to develop a prototype scheduling decision aid (SDA) in Microsoft (MS) Excel that will allow schedulers to collect and incorporate a Sailor's prior work and rest history. MS Excel is readily available and widely used on ships and will not require extensive training or expenditures. The intent is to provide a way to systematically assess human performance risk while enabling schedulers to make more informed decisions when creating personnel and ship schedules. The data repository for the crew's work and rest schedules will enable schedulers to systematically record, track and detect human performance risk factors, create rest-optimized work schedules, and perform activity trend analysis based on an individual's work and rest activity data. The desired end state of this research is to have a transparent and data-driven process to manage Sailors' workloads while focusing on fatigue mitigation efforts at the individual and organizational levels during the watchbill creation process.

C. RESEARCH QUESTIONS

With the objective of creating a prototype MS Excel SDA capable of detecting and flagging human performance risk associated with a Sailor's work and rest activity data guiding this research effort, this thesis seeks to answer the following research questions:

- Can a data repository be structured to enable users to track and detect human performance risk factors, create rest-optimized schedules, and conduct activity trend and data analysis based on an individual's associated work and rest activity data?
- What are some human performance risk factors and thresholds that can be applied to the available work and rest activity information?
- What are the required inputs, constraints, and outputs to create a rest-optimized schedule?

- Can information from this thesis be used to incorporate workload management and fatigue mitigation activities during the watchbill and ship's schedule creation process?
- How should the usability, feasibility, and acceptability of this scheduling aid be assessed?

D. THESIS OUTLINE

Chapter I presented an introduction to the study's purpose and scope. Chapter II includes a literature review with relevant information on sleep, human performance risks associated with sleep loss and excessive wakefulness, fatigue risk models and scheduling tools, regulations and policies governing work and rest activity for seafarers, and the watchbill creation and personnel assignment process onboard U.S. Navy ships. Chapter III describes the approach in prototype development and analysis for this study while Chapter IV discusses the results. Chapter V offers insights, discussions, and conclusions from the study. Lastly, Chapter VI offers recommendations and areas for future research based on the study's findings.

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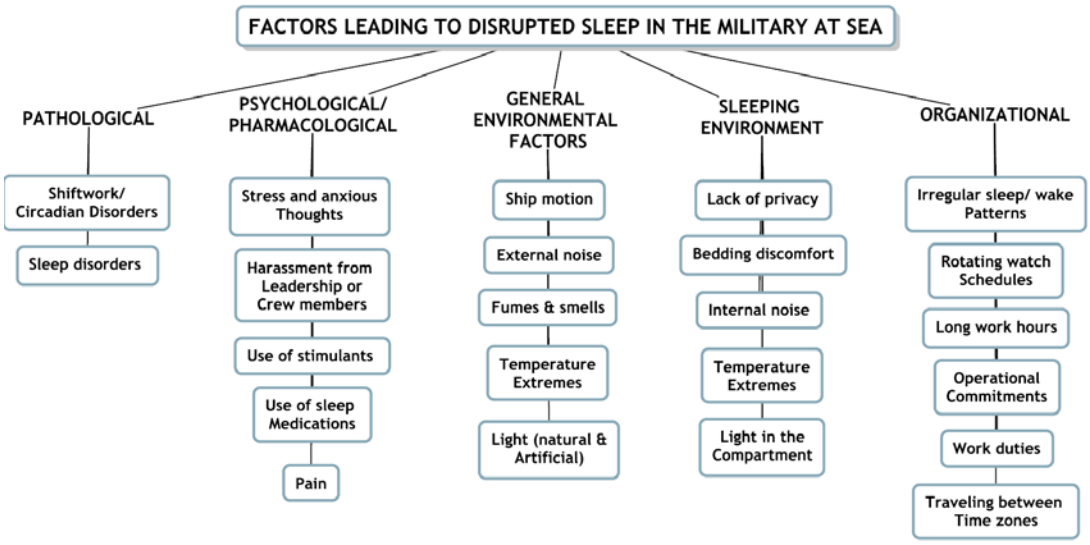
II. LITERATURE REVIEW

This literature review will focus on relevant information regarding the importance of sleep, fatigue, and work and rest activity regulations for seafarers, and the watchbill creation process onboard U.S. Navy warships.

A. SLEEP IN THE MILITARY

Decades' worth of research into the military community show that service members are habitually sleep-deprived. The components of duration, timing, and quality play an important role in determining good sleep. Long working hours, operational commitments, and the 24/7 nature of military operations routinely result in inadequate sleep opportunities for service members. The following section aims to highlight the connections between unsatisfactory sleep, circadian misalignment, increased fatigue, and degraded human performance (Shattuck et al., 2018).

Obtaining enough sleep onboard a U.S. Navy warship is often a challenge. Various environmental, organizational, pathological, and psychological/pharmacological factors contribute to disrupted sleep for military personnel at sea (Figure 1). Operational and mission requirements which necessitate 24/7 operations and manning shortfalls regularly result in excessively long workdays, often to the detriment of a Sailor's health and performance (Brown, 2012; Garbacz, 2019; Murph, 2019). Increased workloads and operational requirements leave Sailors more susceptible to acute and chronic sleep loss, which can present a significant threat to safety and operational effectiveness onboard ships (Shattuck & Matsangas, 2014). As naval missions grow more complex and the margin for error decreases, more attention must be devoted to ensuring Sailors receive adequate amounts and quality of sleep. The safe and continued operation of warships requires a cultural shift where mission requirements are balanced with work and rest guidelines to minimize the operational and personal risk and maximize group performance and safety in everyday operations (Good, 2019; Shattuck & Matsangas, 2017).



Sleep disorders, such as insomnia and sleep apnea, and pain, both physical and psychological, can contribute to disrupted sleep. Stimulants include caffeine, energy drinks, or nicotine.

Figure 1. Factors Leading to Disrupted Sleep at Sea. Adapted from Shattuck and Matsangas (2017) and Shattuck, Matsangas, and Dahlman (2018).

1. Sleep Overview

Sleep is a basic requirement for human life. An extensive amount of scientific research suggests that the physiological need for sleep is due to the many benefits it provides. According to Vyazovskiy, "sleep plays an active role in processes such as synaptic plasticity and memory functions, emotional regulation, metabolic functions and energy balance, macromolecule biosynthesis, removal of toxic substances and metabolic waste, or prophylactic cellular maintenance" (2015, p. 171). Forgoing sleep, just like forgoing water and food, will degrade bodily functions and ultimately lead to death. While there are only anecdotal reports of sleep deprivation leading to death in humans, previous animal studies on the topic link total sleep deprivation to death (Everson et al., 1989; Naitoh et al., 1990). Individuals may report feeling less alert or more tired and fatigued when they obtain insufficient sleep. Partial sleep deprivation arises when an individual obtains less sleep than they need while total sleep deprivation occurs when an individual is unable to obtain any sleep at all (Shattuck et al., 2018). When a person is sleep-deprived, they often suffer from increased sleep inertia, or the interim state between wake and sleep where they

have decreased arousal and cognitive function, which can vary in duration based on the severity of sleep deprivation (Shattuck et al., 2018).

As humans age, our sleep patterns change as is indicated by the changing number and duration of wake and sleep cycles in Figure 2 (Miller et al., 2007). Moreover, the amount of sleep humans require for optimal performance shifts as we age. Additional information on sleep physiology and sleep architecture is available in the book *Sleep Disorders and Sleep Deprivation: An Unmet Public Health Problem* (Committee on Sleep Medicine and Research et al., 2006, pp. 33–49). While different people may require varying amounts of sleep for optimal performance, the National Sleep Foundation (NSF) recommends that healthy adults between the ages of 18 and 64 years old get seven to nine hours of sleep per night (National Sleep Foundation [NSF], 2015). On average, Americans reported getting 7.6 hours of sleep per night which is below the NSF's recommended minimum (Sleep Foundation, 2014; NSF, 2015). Moreover, 67% of Americans who reported receiving less than good sleep quality also reported "poor" or "only fair" health; this finding highlights the association between sleep quality and overall health (Sleep Foundation, 2014, para. 2).

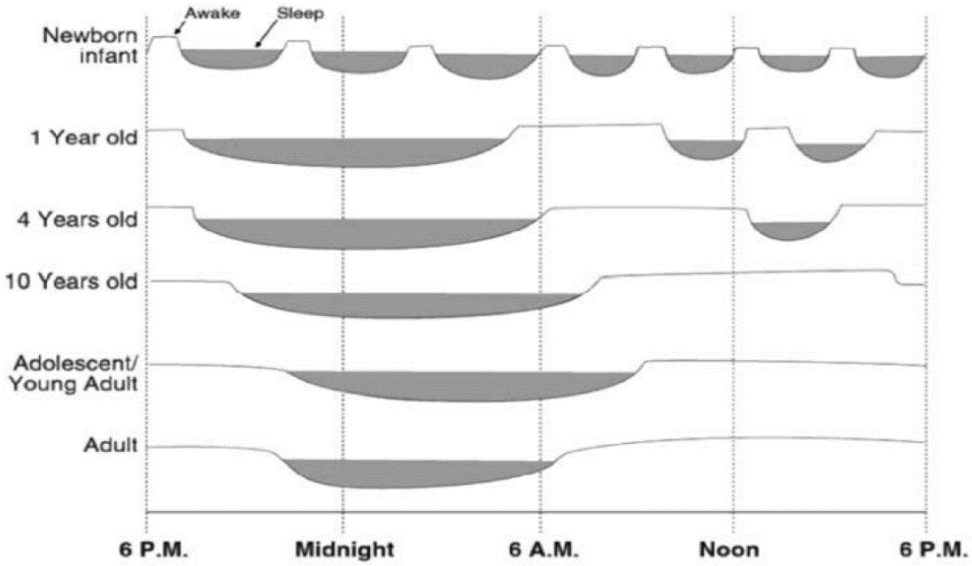


Figure 2. Sleep Requirements throughout Life. Source: Miller, Matsangas, and Shattuck (2007).

A large percentage of U.S. Navy personnel fall in the 25- and- younger age group while the rest of the USN population falls between the range of 26 to about 40 years old (Figure 3). While the NSF recommends that both age groups obtain between seven to nine hours of sleep per day to function optimally, several studies involving the work and rest activity of naval personnel routinely show that Sailors receive significantly less than the recommended amount of sleep per day (Figure 4).

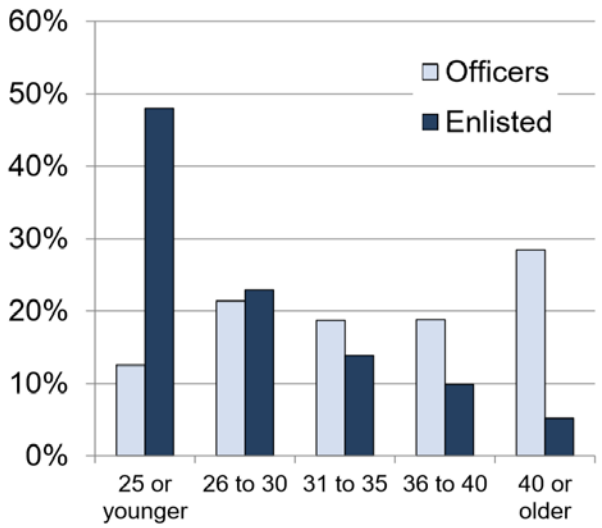
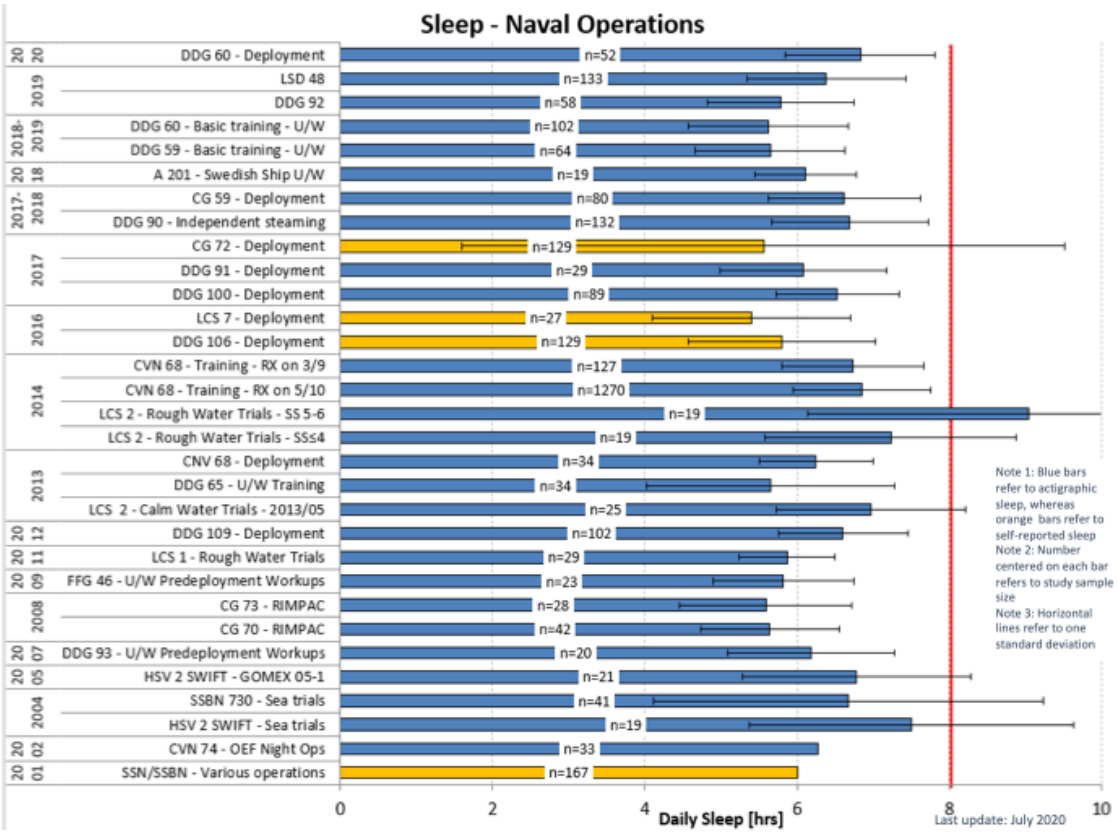


Figure 3. Naval Postgraduate School Sleep Studies from 2002 to 2017. Source: Shattuck and Matsangas (2017).

Previous NPS studies on the work/rest patterns of U.S. Navy Sailors also revealed that Sailors suffer from impaired sleep quality (Murph, 2019; Young, 2013; Yokeley, 2012; Roberts, 2012). The phenomenon of operating with sleep debt is not isolated to one ship type and occurs regardless of a ship's operational phase (Figure 4). All NPS sleep study participants received below the recommended eight hours of sleep, as denoted by the vertical red line in Figure 4, with the exception of the 2014 Littoral Combat Ship (LCS) 2 Rough Water Trials group. The greater than average number of sleep hours was largely attributed to the high sea state during the study where many of the crew members experienced motion sickness and were relegated to their sleeping quarters (Figure 4). The recommended sleep times and amounts of sleep are important considerations when

comparing typical Sailor underway and in port work schedules. Due to the 24/7 nature of maritime military operations, most Sailors are required to work on shifts where their wake/sleep cycles rarely align with the recommended wake/sleep cycle for adults (Shattuck et al., 2014). These out-of-phase work and sleep schedules result in chronic circadian misalignment in the form of 18 to 20-hour long days with little opportunity for adequate rest and recovery (Shattuck et al., 2014).



Note 1: Blue bars refer to actigraphic sleep, whereas orange bars refer to self-reported sleep.

Note 2: Number centered on each bar refers to study sample size.

Note 3: Horizontal lines refer to one standard deviation.

Figure 4. Naval Postgraduate School Sleep Studies from 2001 to 2020. Source: N. Shattuck, PowerPoint slides (November 16, 2020).

The pattern of operating while sleep-deprived is not isolated to U.S. Navy personnel but is also common among other military service branches. An assessment of the average

daily sleep duration of over 6,000 active duty service members, from 33 studies with data collected during a range of different military operation types, underscored the pervasiveness of military members operating in a sleep-deprived state (Shattuck et al., 2018). Most participants fell below the 7-hour recommendation for good health; none of the participants exceeded the 8-hour standard for maximum cognitive functioning (Figure 5). Sleep deprivation and chronic sleep restriction are often associated with degraded waking neurobehavioral functions which manifest as sleepiness and reduced attentiveness, cognitive speed, and memory impairments (Goel et al., 2013). Furthermore, service members consistently get less sleep when compared to their civilian counterparts with a large percentage receiving five or fewer hours of sleep a day (Figure 6). Obtaining adequate sleep continues to be a major risk factor for safety mishaps and regularly affects a Sailor's performance and productivity.

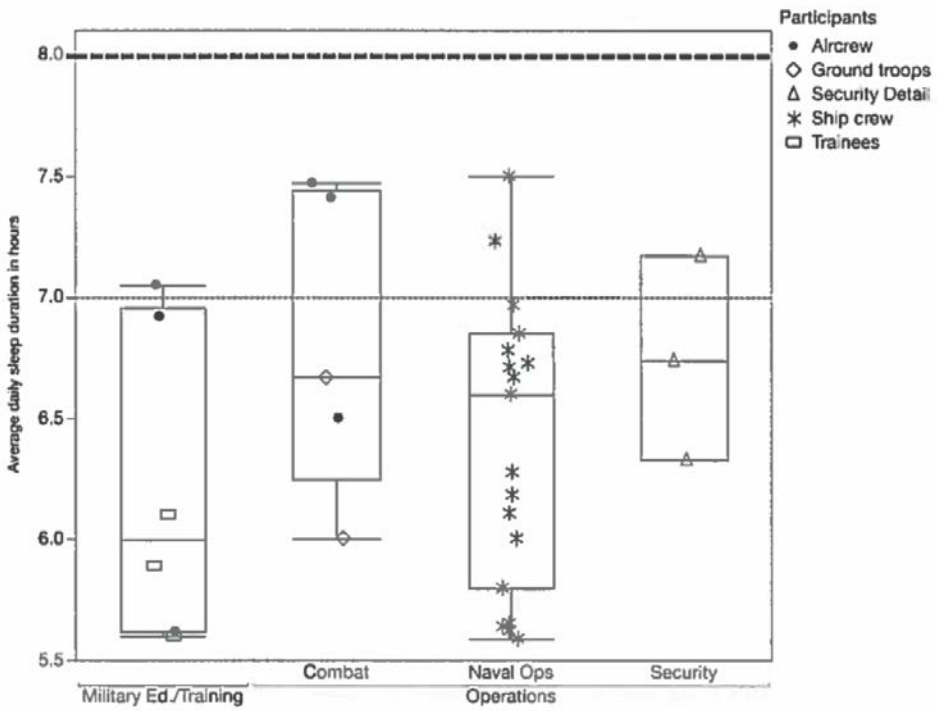


Figure 5. Average Daily Sleep Duration in Various Military Environments. Source: Shattuck, Matsangas, and Dahlman (2018).

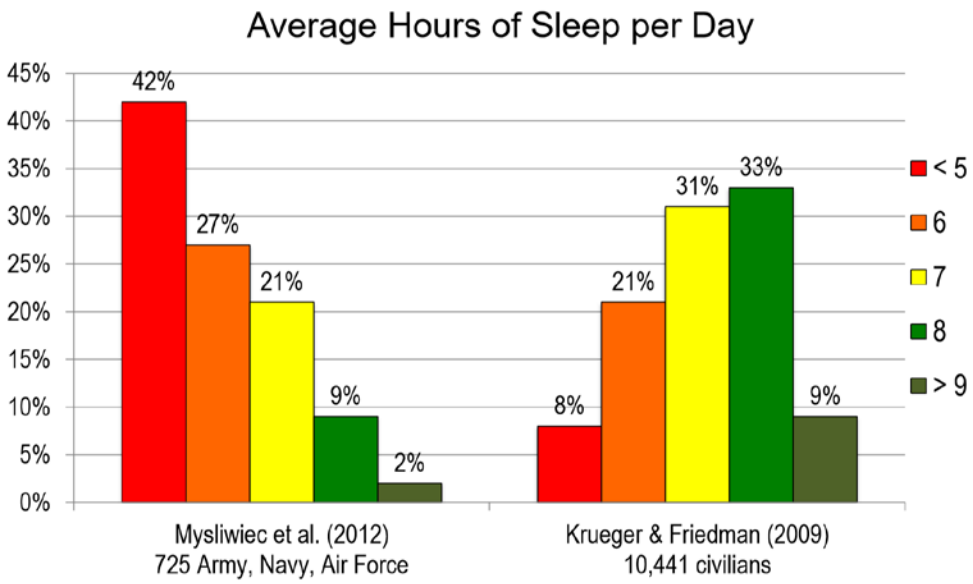


Figure 6. Average Hours of Sleep per Day Comparison between Civilians and Military Personnel. Source: Shattuck and Matsangas (2017).

2. Impacts of Insufficient or Poor Sleep

According to Goel and colleagues, research over the past decade has associated circadian desynchrony with conditions such as weight gain, obesity, diabetes, hypertension, and heightened mortality (Goel et al., 2013). Research suggests that disruptions to an individual's circadian rhythm results in altered melatonin production and disrupted sleep-wake cycles (Shattuck & Matsangas, 2014). Compared to those individuals who work during the day, night shift workers often experience more sleep deprivation, shorter periods of sleep, more fragmented sleep, and higher levels of fatigue (Arendt et al., 2006). The negative outcomes associated with shiftwork becomes more significant because the shift workers may suffer from circadian scarring. Circadian scarring can result in sleep problems that affect a person beyond their work shifts and even years after they leave the work force (Shattuck et al., 2018; Monk et al., 2013). Moreover, shiftwork and night shifts are associated with higher levels of physiological fatigue, increased weight gain, higher risk of developing health disorders such as obesity and heart disease, and negative social outcomes like decreased marital satisfaction (Howarth et al., 1999; Shattuck & Matsangas, 2014).

A large body of work exists on the deleterious effects of sleep deprivation and sleep disruption on humans. Table 3 provides an overview of risk factors which contribute to sleep disruption and deprivation. The short-term effects of insufficient sleep range from the inability to learn and retain information, poor judgment, poor mood, delayed reaction times and increased error rates, decreased vigilance, and reduced short-term memory (Division of Sleep Medicine [DSM], n.d.; Shattuck et al., 2018). The short-term and intermediate-term consequences of not obtaining enough sleep pose a significant risk to the individual and the crew due to the increased risk for serious accidents or injury (Shattuck et al., 2018). The Division of Sleep Medicine at Harvard University states that the effects of chronic sleep deprivation, or long-term sleep loss, is associated with a multitude of health problems like obesity, diabetes, cardiovascular disease, and shortened lifespan (DSM, n.d.). Additional intermediate and long-term effects of poor sleep habits are illustrated in Figure 7.

Table 2. Risk Factors Contributing to Sleep Deprivation and Disruption. Adapted from Medic et al. (2017).

Category	Risk Factors
Lifestyle	• Consuming excessive amounts of caffeine • Drinking alcohol • Drug abuse • Shift work • Attending university • Jet lag
Environmental	• Excessive noise (e.g., industrial wind turbines) • Excessive light
Psychosocial	• Anxiety, worry, and rumination • Parents of young children • Caregivers to a family member with a chronic, life-threatening, or terminal illness
Sleep disorder	• Insomnia • Obstructive sleep apnea • Restless leg syndrome • Narcolepsy • Circadian rhythm disorders
Medical conditions	• Pain • Restrictive lung disease • Chronic kidney disease • Diabetes • Neurodegenerative disease • Psychiatric disorders • Use of certain medications

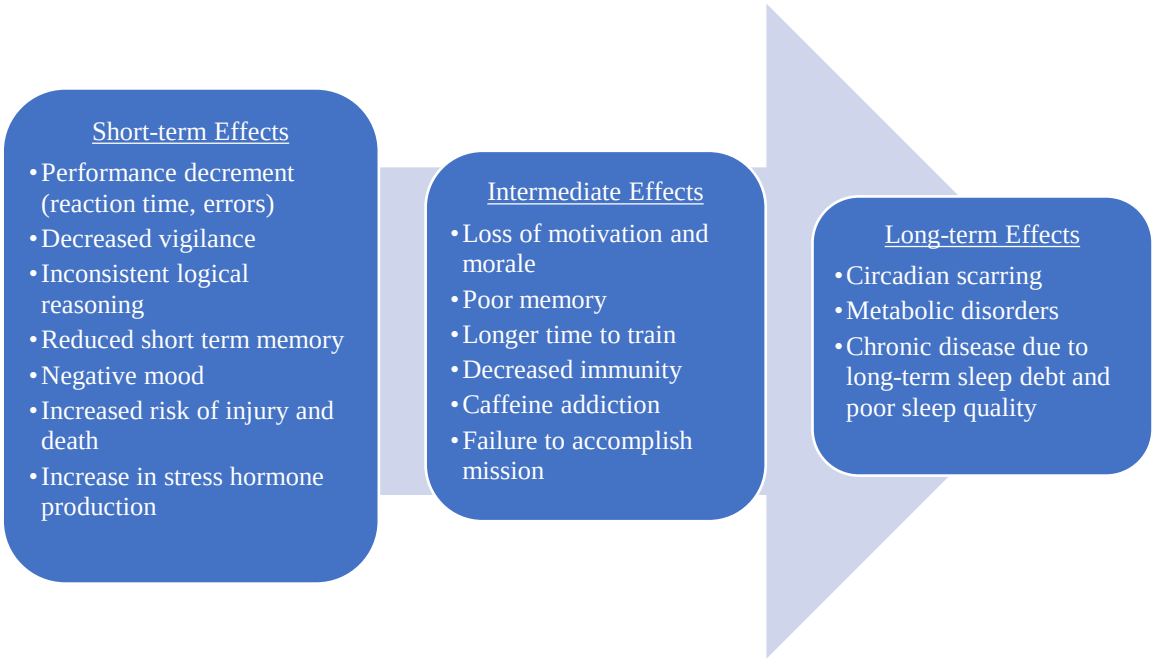
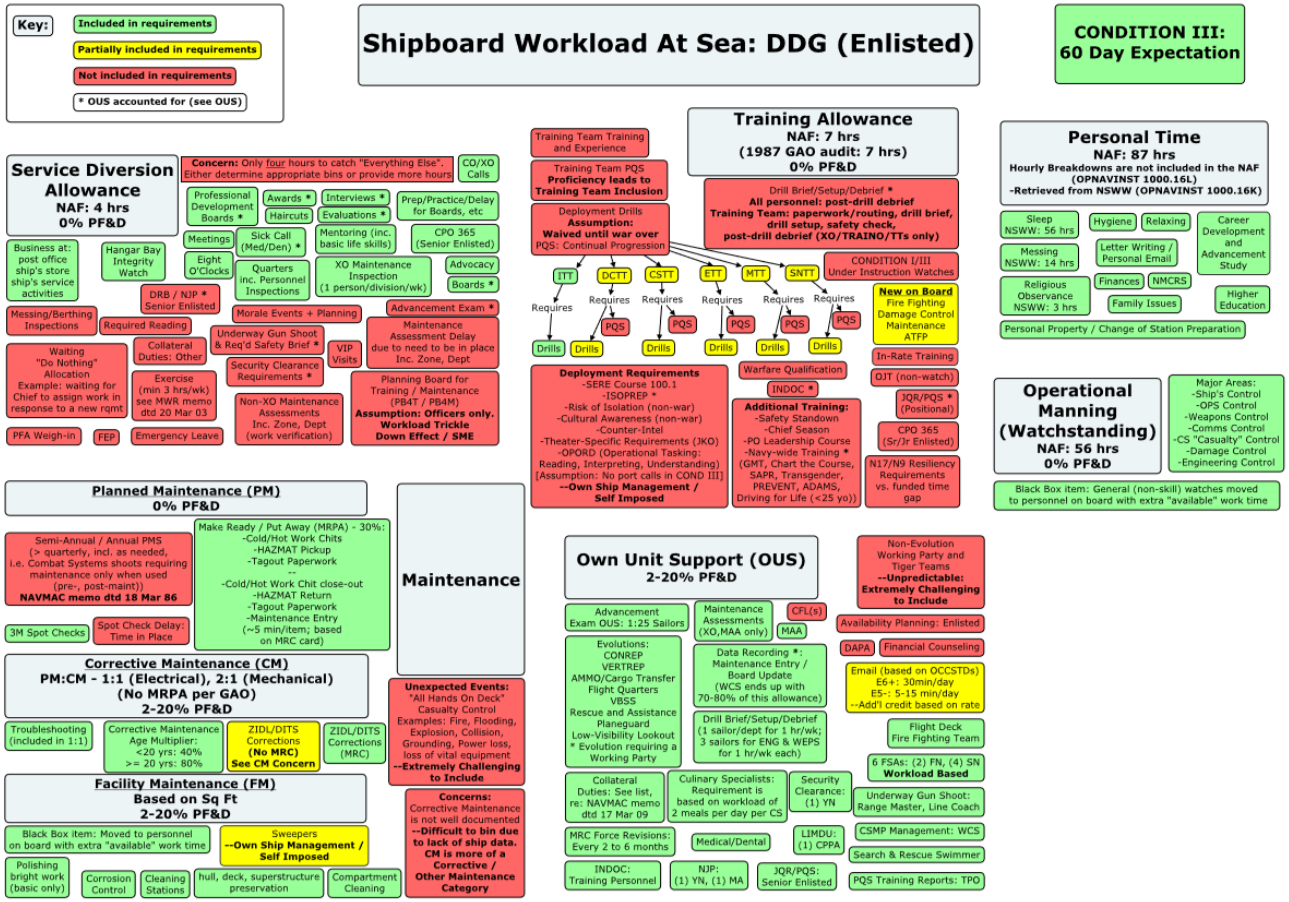


Figure 7. Consequences of Poor Sleep Practices. Adapted from Shattuck, Matsangas, and Dahlman (2018).

A 2018 NPS thesis by Christine Fletcher highlighted the disparity between the shipboard requirements that were accounted for in fleet manpower documents and how Sailors were forced to adapt to manning shortfalls by working longer hours (Fletcher, 2018). Figure 8 is Fletcher's At-Sea Shipboard Workload Model which graphically shows the various requirements for enlisted personnel that are accounted for (green), partially included (yellow), and unaccounted for (red) in the fleet manpower documents. While the majority of requirements are accounted for in the Personal Time, Operational Manning, and Own Unit Support categories, there are many items under Training Allowance, Service Diversion, and Maintenance categories which are not currently accounted for when calculating manning levels (Figure 8).



The items in green denote requirements which are included within the Fleet Manpower Requirements Determination (FMRD) model. Yellow indicates requirements that are partially included; red indicates requirements that are not included within the FMRD.

Figure 8. Enlisted Personnel Workload Demands during Condition III Steaming. Source: Fletcher (2018).

Impaired perception, judgment paired with reduced efficiency, and sleep deprivation lead to increased rates of errors and accidents (DSM, n.d.). Several analysts estimate that the 2017 collisions involving the USS *Fitzgerald* and USS *John S. McCain* may ultimately cost U.S. taxpayers over $500 million (LaGrone, 2017) and $220 million (Werner, 2017) in repairs, respectively. The deaths of seven Sailors on the USS *Fitzgerald* and ten on the USS *John S. McCain*, respectively, were sobering reminders of the heavy toll sleep loss can take. To counteract the effects of sleep-induced performance impairment, people often implement a variety of techniques like napping, exposing themselves to bright lights, and consuming stimulants like coffee or energy drinks (Kerno, 2014). While these may result in temporary increases in alertness, human performance, and efficiency, employing fatigue countermeasures is not a sustainable practice; the only long-term way to alleviate the effects of fatigue due to sleep deprivation is to get adequate sleep (Darwent et al., 2015).

B. FATIGUE IN THE MILITARY ENVIRONMENT

The fatigue resulting from inadequate sleep, circadian rhythm interruption, and acute or chronic mental strain presents a considerable risk to personal and group safety, mission success, and national security (Miller & Eddy, 2008; Good et al., 2019). Fatigue is defined by the International Maritime Organization (IMO) as "the degradation of human performance, the slowing down of physical and mental reflexes and/or the impairment of the ability to make rational judgments" (International Maritime Organization [IMO], 1993, p. 3). Fatigue is an overarching term which can include physical and mental causes. Physical fatigue can be attributed to sleep deprivation or sustained periods of physical activity while mental stress, emotional overtiredness, or elevated workloads can contribute to elevated levels of mental fatigue (Jepsen et al., 2015). Inadequate or insufficient sleep is a major determinant of fatigue which can impair physical performance, such as speed and strength, and mental performance, such as delayed reaction times and decision making (Jepsen et al., 2015). Irregular sleep patterns due to shiftwork, excessive workloads, and disturbed or shortened sleep periods contribute to prolonged wakefulness (Miller & Eddy, 2008; Miller et al., 2007). Prolonged wakefulness is typically defined as more than 16 hours

between two sleep periods which can result in acute and chronic mental fatigue (Miller & Eddy, 2008). The consequences of work-related fatigue can range from minor mishaps to devastating disasters. Workers in the maritime industry report increased levels of fatigue and sleepiness due to the shiftwork nature of their watches, increased workloads, rotating work schedules, and less than ideal sleeping conditions (Jepsen et al., 2015).

Many studies have associated military service and lifestyles with several fatigue-causing factors such as prolonged wakefulness and acute and chronic sleep loss (Shattuck & Matsangas, 2016). After the deadly collision between the USS *John McCain* and tanker *Alnic MC* on August 21, 2017, the National Transportation Safety Board (NTSB) released a report in 2019 which attributed the watch team's acute fatigue as a causal factor of the collision (National Transportation Safety Board [NTSB], 2019). The acute fatigue experienced by the lee helmsman, conning officer, Boatswain's Mate of the Watch (BMOW), Junior Officer of the Deck (JOOD), and Officer of the Deck (OOD), each of whom had received fewer than five hours of sleep the previous night, impaired the watch team's ability to properly and effectively execute the required actions to avoid the collision (NTSB, 2019; DON, 2017b). The accident also occurred between the hours of 0200 and 0600, which coincides with the circadian low point, a time when the body is usually more fatigued and suffers from decreased levels of alertness (Goel et al., 2013; Miller & Eddy, 2008; Miller et al., 2007; Mysliwiec et al., 2016).

Naval operations are inherently dangerous and require vigilant Sailors who can assess and mitigate risk to accomplish mission tasking. A fatigued Sailor reduces mission readiness, impacts team effectiveness and performance, and introduces unnecessary risk to in port and at-sea operations. Sleep is foundational to optimal human performance and resiliency and inadequate sleep results in degraded physical and cognitive performance, increased fatigue levels, poor morale, reduced individual and team resilience, and a myriad of other negative outcomes (Good et al., 2019; Young-McCaughan et al., 2018; Shattuck et al., 2018).

C. MARITIME WORK AND REST ACTIVITY REGULATIONS

The general trend of increased shipping intensity has historically resulted in rising crew workloads for ships and continues to do so today (Simkuva et al., 2016). Despite the rising levels of work, the commercial maritime industry has not experienced an associated uptick in its work force to compensate for the increased workloads. The increased operational risk associated with longer working hours led to the creation of regulations such as the International Safety Management (ISM) Code and the International Ship and Port Facility Security (ISPS) code. These regulations laid bare the prevalence of systematic violations in the enforcement of work and rest hour policies (Simkuva et al., 2016). With the global shipping industry being responsible for transporting as much as 90% of world trade, maritime shipping traffic growth is not expected to abate any time soon (Kinsey, 2020). The subsequent increase in seafarer workloads, especially relevant for ships that carry dangerous goods, considerably diminish maritime safety due to increased fatigue levels (Wadsworth et al., 2008; Jepsen et al., 2015).

In order to mitigate the risk from fatigued seafarers, work and rest activity hours were regulated in the shipping industry under the provisions of the International Convention of Standards of Training, Certification, and Watchkeeping for Seafarers (STCW) from 2010 (IMO, n.d.) and the Maritime Labour Convention (MLC) from 2006. The regulations outlined in Table 4 explicitly stated minimum and maximum limits for work and rest periods for ship's crews and created reporting requirements for regulation violations. Table 4 also includes relevant maritime work and rest hour guidelines from the United States Code (United States Code [USC], 2016), Navy Availability Factor (NAF) (OPNAVINST 1000.16L, 2015), Navy Standard Work Week (NSWW) (OPNAVINST 1000.16K, 2007), and the *Comprehensive Fatigue and Endurance Management Policy* (COMNAVSURFPAC/COMNAVSURFLANT INST 3120.2, 2017). The civilian maritime industry has commercially available tools capable of tracking compliance with these work and rest policies such as CREWEXPRESS by SHIPIP Ltd., ISF Watchkeeper by the IT Energy and the International Shipping Federation, and Navigator Port modules by DNV GL. Presently, the U.S. Navy does not have an analogous tool onboard ships

capable of tracking work and rest activity hours where users can assess the work/rest levels of their Sailors.

Table 3. Maritime Work and Rest Time Regulations. Adapted from Simkuva, Purins, Mihailova, and Mihailovs (2016) and Shattuck and Matsangas (2017).

Standard	**Work/Rest in any**			**Rest period amount and duration**
	24-hour period	**3-day period**	**7-day period**	
MLC	Work ≤ 14 hours Rest ≥ 10 hours		Work ≤ 72 hours Rest ≥ 77 hours	Not more than 2 rest periods, one of which shall be at least 6 hours Interval between rest periods of less than 14 hours
STCW	Rest ≥ 10 hours		Rest ≥ 77 hours	Not more than 2 rest periods Interval between rest periods of less than 14 hours
USC		Work ≤ 36 hours		
NAF			Work ≤ 81 hours	
NSWW			Rest ≥ 56 hours	
DON	Work ≤ 12 hours or 8 continuous hours Rest ≥ 7 hours			Rest must be one uninterrupted 7-hour period or broken up as separate 5-hour and 2-hour uninterrupted blocks

One of the NTSB's recommendations based on their findings from the 2017 collision between the USS *John S. McCain* and *Tanker Alnic* was for the U.S. Navy to adopt comparable work and rest standards from the STCW (NTSB, 2019). While civilian and military mariners operate in similar environments, careful consideration should be applied when defining and adopting work and rest hour limits. Over a decade's worth of research involving 35 U.S. Navy ships and nearly 1,700 Sailors by NPS's Crew Endurance

Team show that USN Sailors are often subjected to unrelentingly high workloads, constantly shifting work schedules, and different types of stressors when compared to their civilian counterparts (Shattuck & Matsangas, 2020).

A retrospective analysis comparing the work and rest activity patterns of 184 servicemembers from the USS *Nimitz* with the seafarers' work/rest activity regulations listed in Table 4 found that USN Sailors routinely worked past established limits (Figure 9) and obtained insufficient amounts of rest (Figure 10) (Shattuck & Matsangas, 2017). Figure 9 shows that USN Sailors exceed seafarer work time limits by approximately 25% during 24-hour periods, 50% during any 3-day period, and 80% during any 7-day work period. Furthermore, the results highlight the impact of rotating non-circadian watch schedules (i.e., 5/10) on work and rest activity hours. Sailors under the 5/10 work schedule were subject to longer work hours, both daily and per 7-day period, and more limited sleep/rest opportunities when compared to Sailors with static watch times (i.e., 3/9) (Shattuck & Matsangas, 2017).

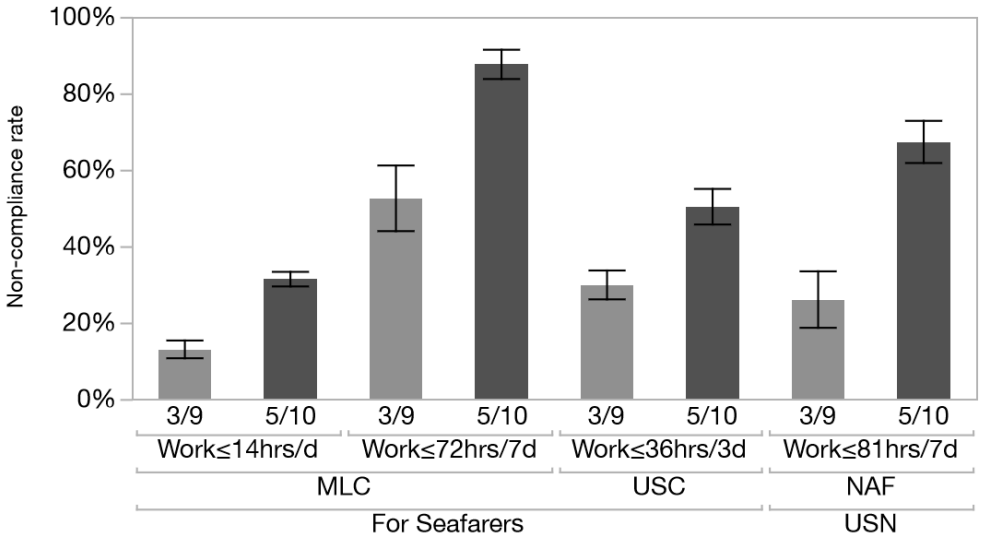


Figure 9. Rate of Excessive Maritime Work Hour Limits Comparison by Varying Criterion. Source: Shattuck and Matsangas (2017).

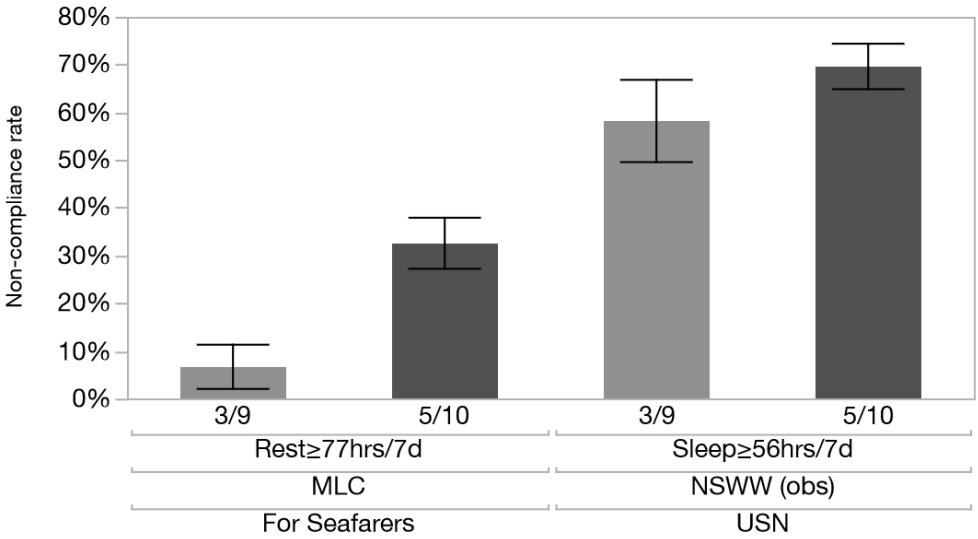


Figure 10. Rate of Insufficient Rest/Sleep Hour Limits Comparison by Varying Criterion. Source: Shattuck and Matsangas (2017).

The USN's adoption of circadian-based watchbills has been associated with increased alertness, reduced daytime sleepiness, improved sleep quality and mood, and increased psychomotor vigilance performance (Shattuck & Matsangas, 2019). An assessment of the utility of circadian-based schedules for surface combatants found that there were a multitude of benefits associated with circadian-based watchbills and routines (Shattuck & Matsangas, 2019). Most of the participants reported feeling better rested as the main benefit, but they also experienced improved overall performance in the form of increased situational awareness, increased productivity, and improved performance/endurance (Figure 11). The study also evaluated the combined effect of occupational stressors on the participants by analyzing the aggregate metrics collected from several assessments. The aggregate metrics are sorted into figure of merits (FOM) defined as FOM_3 and FOM_4, consisting of the Epworth Sleepiness Scale (ESS), Insomnia Severity Index (ISI), and Pittsburgh Sleep Quality Index (PSQI) and the ESS, ISI, PSQI, and Profile of Mood States (POMS), respectively. Their analysis revealed that the type of watchbill (e.g., fixed or rotating) and the number of sections (e.g., 2, 3, or 4) were statistically significant predictors for the FOM_3 and FOM_4 scores (all $p < 0.02$).

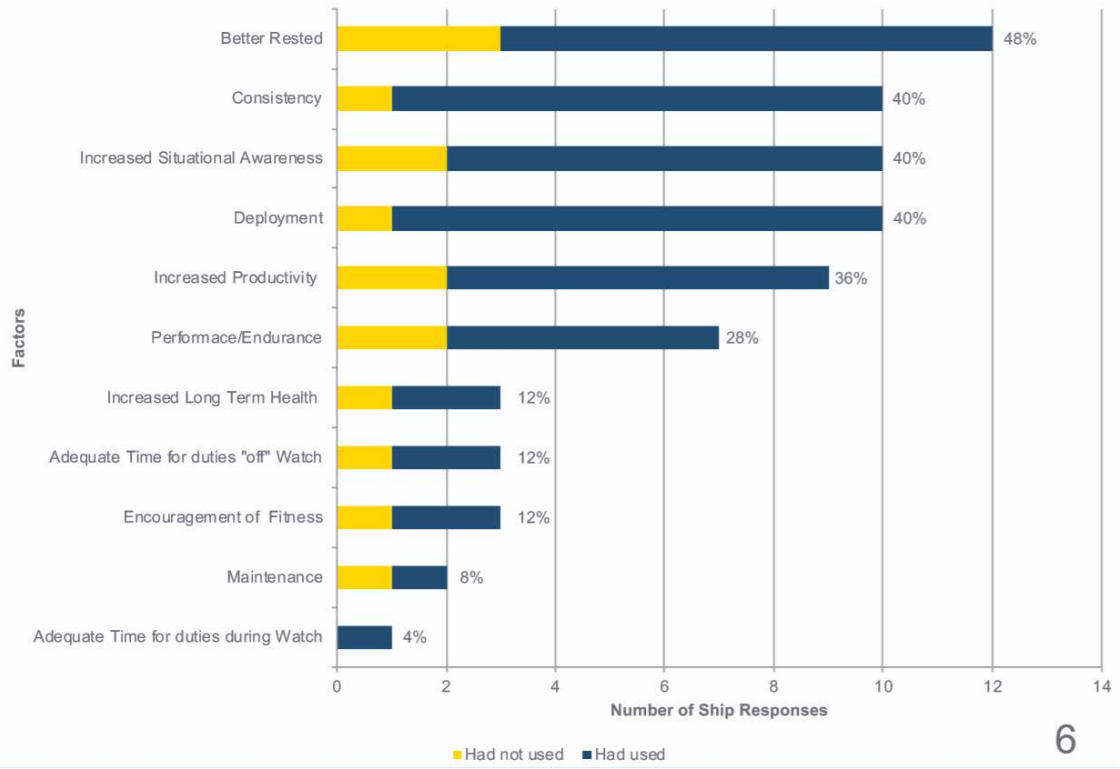


Figure 11. Benefits of the Implementation of Circadian-based Watchbills and Routines onboard USN Vessels. Source: Shattuck and Matsangas (2019).

Despite the reported benefits of fixed watch schedules and more watch sections, the lack of qualified personnel, lack of time for events such as meetings, drills, or training, and scheduling conflicts act as barriers for the implementation of circadian-based schedules (Shattuck & Matsangas, 2019). Another important note is that even when circadian watch rotations were implemented, they did not always result in Sailors obtaining more sleep when compared to Sailors on non-circadian watch schedules. The same circadian-based schedule utility study found that while the sleep duration between circadian versus non-circadian watchbills were not dissimilar, the non-circadian watchstanders were unable to sufficiently meet the normal sleep requirements of "timing, duration, and quality" (Shattuck & Matsangas, 2019, p. 45). Moreover, several Crew Endurance Team studies identified that excessive workloads and increased tasking requirements greatly contributed to higher levels of Sailor fatigue. The Team's studies found that USN Sailors worked 12-hours/day with roughly 25% of them working 13-hour days and 10% working 14-hour days

(Shattuck & Matsangas, 2020). The increased workloads and requirements translate to over 50% of USN Sailors working more than 84 hours per week and approximately 10% working 98 hours or more per week.

While existing regulations on seafarers' work and rest limits allow for an assessment of known fatigue factors, they do not directly address the sources for fatigue at sea. Currently, USN manning models do not entirely account for the time involved in meeting tasking requirements which result in insufficient manning levels and contribute to the excessive work hours (Fletcher, 2018). Adopting STCW, MLC, or other crew rest requirements without tackling the root causes of fatigue will not remedy the U.S. Navy's crew endurance and fatigue management issues. Until these root causes can be addressed more directly, more effort should be placed on finding ways to optimize the work and rest patterns of USN Sailors (Shattuck & Matsangas, 2017).

D. FATIGUE RISK MODELS AND SCHEDULING TOOLS

The following section outlines selected sleep, fatigue, and human performance biomathematical models and scheduling tools which have been tailored for use in the military environment. These tools can provide warfighters and decision makers with valuable insight into individual and crew readiness levels which may affect current and future military operations. A more comprehensive list of biomathematical models is available in Appendix A from Mallis and colleagues (2004) which provides brief model descriptions, prediction goals, implemented capabilities, required inputs, and primary outputs.

1. Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE) Model

The Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE) model was developed by Hursh and his colleagues (2003) at Walter Reed Army Institute of Research over 25 years ago. The model has been used extensively by commercial and military entities like the U.S. Department of Transportation (DOT), Federal Aviation Administration (FAA), Federal Railroad Administration (FRA), and the Department of Defense (DOD). SAFTE is a three-process model which integrates the following information: (1) circadian rhythms, (2) cognitive performance recovery and decay rates

associated with sleep and wakefulness, respectively, and (3) cognitive performance effects associated with sleep inertia to create a model of predicted human cognitive effectiveness (Hursh, 2003). The SAFTE model's general design includes the sleep regulation and the performance modulation components (Figure 12). The sleep regulation component is influenced by the hours of sleep and wakefulness, existing sleep debt, the circadian process, and sleep fragmentation (Figure 12). The performance modulation component is dependent upon the current balance of the sleep reservoir, a byproduct of the sleep regulation component, circadian oscillations, and sleep inertia which outputs a measure of cognitive effectiveness (Air Force Research Laboratory [AFRL], 2003).

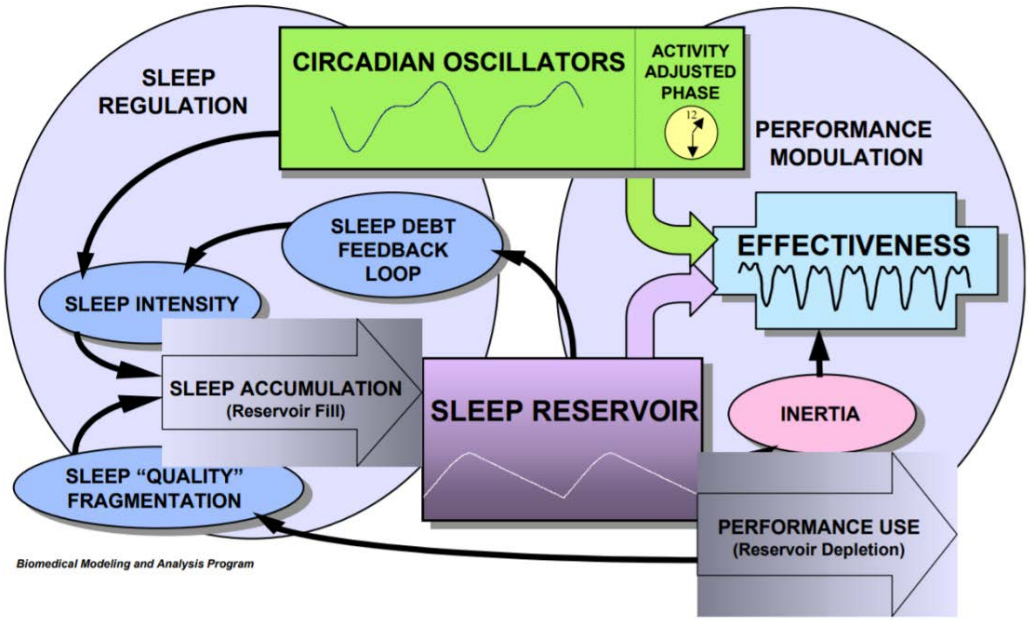


Figure 12. Schematic of the SAFTE Model. Source: Air Force Research Laboratory (2003).

While more laboratory and field validation studies are required to assess the adequacy of the SAFTE model's application within the maritime operational environment, the model does offer some essential features and advantages (Table 5) which allow for performance predictions with varying work schedules and sleep deprivation levels. Notably, the model does not account for the effects of sleep fragmentation, circadian

variations, jet lag due to time zone shifts, shiftwork, around the clock performance, and sub-optimal sleep schedules – all of which are commonplace onboard U.S. warships. Further refinement of the model within the maritime domain could result in more accurate predictive values of Sailor performance.

Table 4. SAFTE Model Key Features and Advantages. Adapted from the AFRL (2003).

Key Features	Advantages
Model is homeostatic. Gradual decreases in sleep debt decrease sleep intensity.	Predicts the normal decline in sleep intensity during the sleep period.
Progressive increases in sleep debt produced by extended periods of less-than-optimal levels of sleep lead to increased sleep intensity.	Predicts the normal equilibrium of performance under less-than-optimal schedules of sleep.
Model delays sleep accumulation at the start of each sleep period.	Predicts the detrimental effects of sleep fragmentation and multiple interruptions in sleep.
Model incorporates a multi-oscillator circadian process.	Predicts the asymmetrical cycle of performance around the clock.
Circadian process and Sleep-Wake Cycle are additive to predict variations in performance.	Predicts the mid-afternoon dip in performance, as well as the more predominant nadir in performance that occurs in the early morning.
Model modulates the intensity of sleep according to the time of day.	Predicts circadian variations in sleep quality.
Model includes a factor to account for the initial lag in performance upon awakening.	Predicts limits on performance under schedules that arrange daytime sleep.
Model incorporates adjustment to new time zones or shift schedules.	Predicts sleep inertia that is proportional to sleep debt.
	Predicts temporary “jet lag” effects and adjustment to shift work.

2. Circadian Rhythm and Shiftwork

The inclination to sleep is a primal requirement modulated by a homeostatic process (Borbély, 1982; Shattuck et al., 2018). The sleep and wakefulness process cycles in a roughly 24.5 to 25-hour sinusoidal pattern (Borbély, 1982; Shattuck et al., 2018). The

human biological clock, or circadian rhythm, regulates many important biological functions like sleep and wake patterns, cellular activities, immune system functions, and dietary decisions (Potter et al., 2016, Achermann, 2003; Van Dongen & Dinges, 2000). Studies have shown that the different phases of the circadian clock can be influenced by exposure to environmental light (Figueiro et al., 2017) and shifting mealtimes (Wehrens et al., 2017).

Table 5. Sources and Primary Mechanisms of Circadian Rhythm Disruption. Adapted from Potter et al. (2016).

Source	**Mechanism**				
		Behavioral		**Biological**	
	Environmental LD Cycle Disruption	**Feeding/ Fasting Cycle Disruption**	**Rest/ Activity Cycle Disruption**	**Genetic Disruption (e.g., Clock Gene Mutations)**	**Physiological Disruption (e.g., Retinal Dysfunction)**
Work schedules (e.g., shift work, social jetlag, early school start times)	✔	✔	✔	✖	✖
Jetlag	✔	✔	✔	✖	✖
Unusual photoperiods (e.g., polar regions)	✔	✖	✖	✖	✖
Circadian rhythm sleep/wake disorders (e.g., non-24-hour sleep/wake disorder)	✔	✖	✖	✔	✔
Senescence	✖	✖	✖	✖	✔
Disease states (e.g., Alzheimer's, Smith-Magenis syndrome)	✖	✖	✖	✔	✔

The nature of naval maritime operations often requires Sailors to engage in shiftwork (i.e., work outside of the typical daytime working hours of 8 a.m. to 5 p.m.). This phenomenon often results in disruptions to the normal circadian rhythm, or circadian desynchrony. Meanwhile, circadian misalignment can occur when an individual sleeps during the biological "day" instead of "night" (Shattuck et al., 2018). Sailors working

onboard ships often experience circadian desynchronization and misalignment due to limited sleep opportunities, long workdays, and exposure to artificial or natural light during circadian inappropriate times (Miller & Eddy, 2008; Mysliwiec et al., 2016). Table 2 details additional sources which contribute to disrupted circadian rhythms.

3. Fatigue Avoidance Scheduling Tool (FAST)

The Fatigue Avoidance Scheduling Tool (FAST) is a Windows-based program that is based upon the SAFTE Model. Planners and schedulers can use the FAST program to approximate the effects of a variety of schedules on human performance. Work and sleep activity data can be entered in graphic or text-based formats. The user can create several work schedules through this interface where work periods are shown as red bands and sleep periods are depicted as blue bands (Figure 13). The average predicted effectiveness for a given work period may be extracted and printed as shown in the table in Figure 14. The information from FAST can then be applied to hypothetical, future work schedules to pinpoint potential performance problems and to enhance operational planning and scheduling (Hursh et al., 2004). Moreover, it can be used to examine retrospective data such as sleep patterns of individuals involved in mishaps.

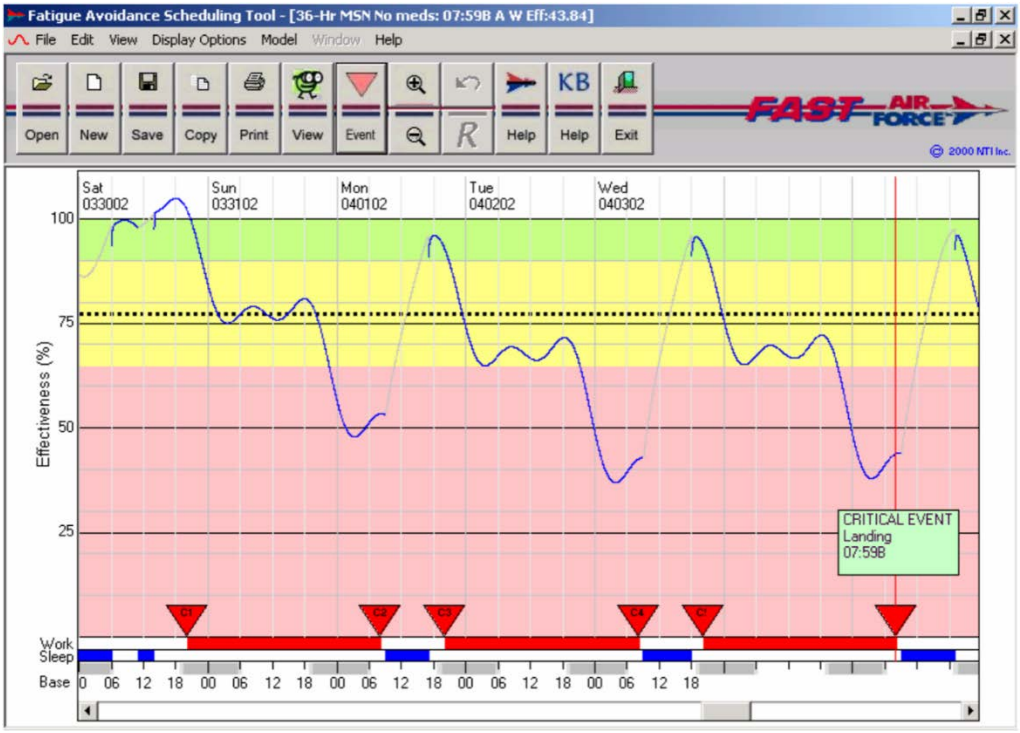


Figure 13. Sample of FAST Work Schedule. Source: AFRL (2003).

Awake			Work		
Start Day - Hr	Duration (Minutes)	Mean Effectiveness	Start Day - Hr	Duration (Minutes)	Mean Effectiveness
0 - 06:00	300	98.97	0 - 20:00	1079	81.14
0 - 14:00	2580	76.42	1 - 14:00	1080	63.97
2 - 17:00	2400	64.78	2 - 20:00	1079	71.23
4 - 18:00	2340	64.58	3 - 14:00	1080	54.51
6 - 19:00	1741	72.23	4 - 20:00	1079	72.00
			5 - 14:00	1080	54.92

Figure 14. Sample of FAST Work Schedule Output. Source: AFRL (2003).

Previous studies on alternate schedules onboard warships assessed the relationship between watch rotations and associated levels of fatigue and performance (Yokeley, 2012; Roberts, 2012; Young, 2013; Kerno, 2014; Shattuck & Matsangas, 2014). An illustrative comparison between a 3/9 versus a 5/10 watch rotation on FAST is provided in Figure 15 which depicts improved predicted effectiveness and blood alcohol equivalence percentages associated with the 3/9 watch rotation. The percent effectiveness is displayed on the left

and the blood alcohol equivalence percentage is displayed on the right from Figure 15. One of the outcomes from the previous fatigue and work/rest cycle theses eventually resulted in the adoption of circadian rhythm-based watch rotations through the implementation of the *CFEMP* in 2017 (DON, 2017a).

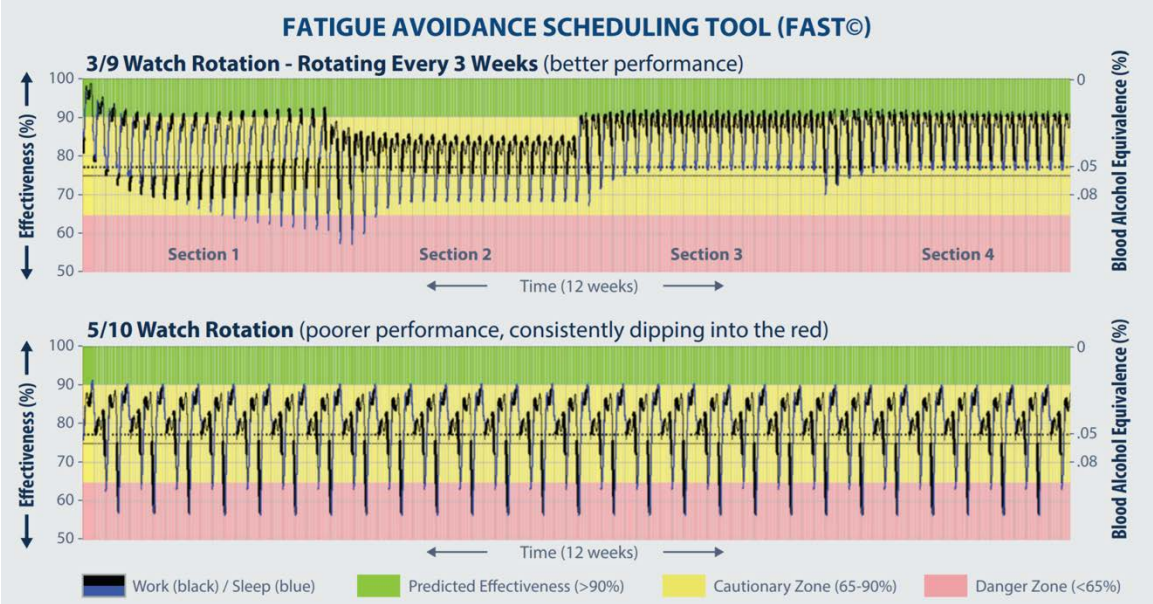


Figure 15. FAST Output Based on 3/9 and 5/10 Watch Rotations.
Source: *Crew Endurance Handbook* (2017).

A previous study of the work/rest patterns of Sailors onboard the USS *Rentz* (FFG-46) compared data from daily activity logs and wrist activity monitors to NSWW hours and found that the hours worked by many participants were above NSWW limits (Green, 2009). Figure 16 is a sample of one participant's FAST data from the study. Participant 5318 scored an overall effectiveness of 68.76% for the duration of the study and in one instance, their predictive effectiveness score dipped to 26% (Figure 16). As Participant 5318's sleep time decreased, the associated predicted effectiveness score also decreased from 90% to 48% during a five-day underway period (Green, 2009). Of interest are the red flags towards the bottom of Figure 14 which display the following alerts (1) Percent Sleep, (2) Chronic Debt, (3) Hours Awake, and (4) Time of Day which contributed to Participant 5318's low predicted effectiveness score at 1:33 a.m. on May 19, 2009.

Figure 16. Participant 5318's FAST Analysis Result. Source: Green (2009).

FAST shares many of the limitations mentioned in the SAFTE section since it is based on that model. While the FAST interface and application have undergone several updates to improve its accuracy, capability, and usability, there is still room for improvement. Some improvements include added features to "allow users to adjust sleep environments, display shifts in time zones, and analyze the effects of sleep aides on performance" (Brown, 2012, p. 14). Currently, FAST users do not have the ability to adjust for variations in working environments, specifically maritime environments, which may result in inaccurate predicted effectiveness values. According to Heus and colleagues (1998), there are varying levels of energy expenditure associated with the muscular effort required to maintain one's balance while working on a pitching or rolling surface compared to working on a stable surface. While the motion effect will vary due to the stability of a

ship platform and weather conditions, more work is required to account for how motion affects fatigue levels onboard ships.

In Lieutenant Brown's 2012 thesis, she used FAST to assess the performance of 21 volunteers during in port and at-sea conditions with varying sea state levels. One of her findings was that increased motion on maritime platforms contributes to a reduction in sleep quality and higher levels of perceived fatigue (Brown, 2012), which supported outcomes from previous studies (Calhoun, 2006; Sullivan, 2009). Lieutenant Brown also evaluated FAST for application within the maritime workplace and found that it inadequately predicted performance by overestimating the effects of poor sleep quality on performance during the study (Brown, 2012). One of Lieutenant Brown's recommendations was to further refine the SAFTE model by exploring how the maritime domain affects sleep reservoir replenishment and its components to adequately account for the long-term disjointed sleep typically seen in the operational maritime environment (Brown, 2012).

4. FlyAwake

In 2009, Lieutenant Beshany conducted a comparative analysis of U.S. Navy flight schedules using FAST and a related software tool, FlyAwake. FlyAwake is a software application developed by the U.S. Air Force that reverse-engineered the SAFTE model. FlyAwake calculates predicted effectiveness based on user inputs, such as crewmembers' sleep and duty cycles, much like FAST since they are both based on the SAFTE model (Beshany, 2009). Some advantages of using FlyAwake vice FAST were the reduced workload requirements for schedulers since the program was tailored for use with the military aviation community in mind. FlyAwake had an updated graphical user interface (GUI), pre-populated data-specific fields such as missions and duties based on the squadron's Type/Model/Series (T/M/S) of aircraft, and default settings for "mission brief, launch, recovery, and debrief times" (Beshany, 2009, p. 22). A screenshot of the FlyAwake's work schedule builder is available in Figure 17.

Figure 17. FlyAwake Work Schedule Builder Screenshot. Source: Beshany (2009).

One of the objectives from Lieutenant Beshany's study was to provide a statistically valid proof of concept for the integration of FlyAwake's fatigue prediction functionality into the existing flight scheduling tool, U.S. Navy Sierra Hotel Aviation Readiness Program (SHARP). Based on the historical flight schedules from Helicopter Antisubmarine Squadron Light Four Two's (HSL-42) SHARP database, Lieutenant Beshany was able to compare the outputs of FlyAwake and FAST and concluded that FlyAwake provided comparable fatigue mitigation recommendations (Figure 18) to schedulers (Beshany, 2009). In 2009, Commander, Naval Air Forces (CNAF) directed the creators of SHARP and FlyAwake, Inova Systems and MacroSystems, respectively, to integrate the functionality of FlyAwake with SHARP and to disseminate the product to select squadrons for usability testing by October 2009 (Beshany, 2009). The results from this integration and testing are currently unknown. As of 2020, the FlyAwake functionality within SHARP is not widely used or available. Incorporation of the fatigue prediction functionality of FlyAwake with the flight scheduling functionality of SHARP may enhance the Naval Aviation community's ability to create rest optimized work schedules for their aircrews.

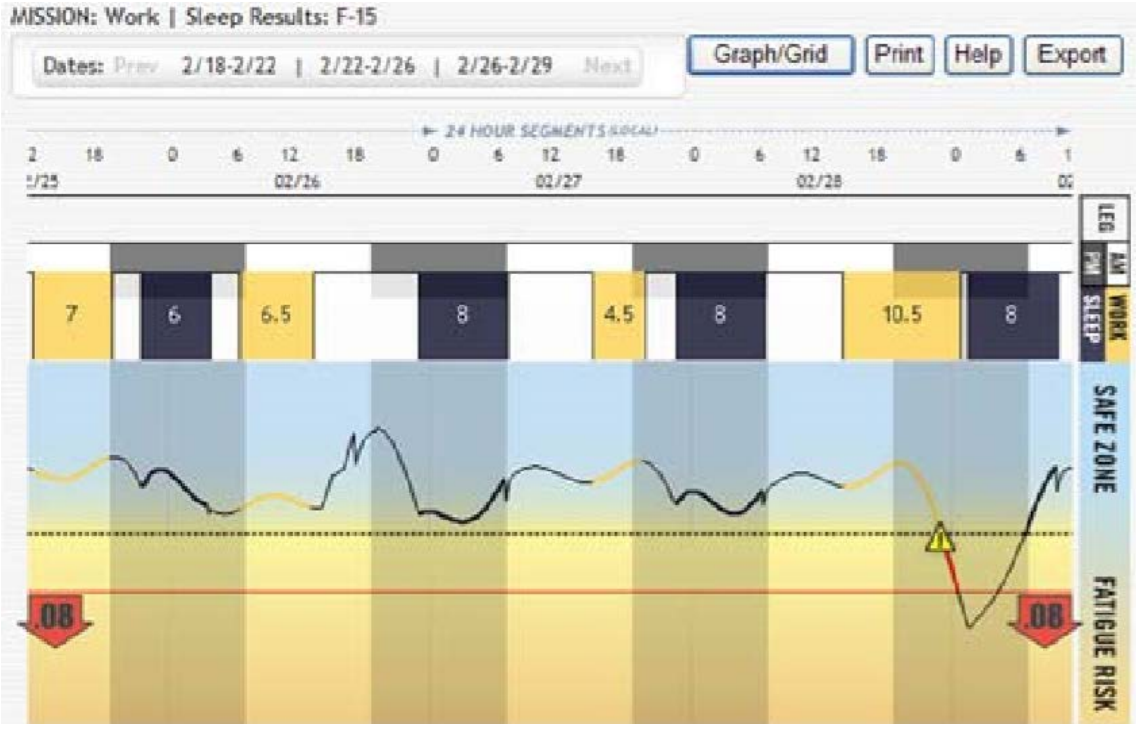


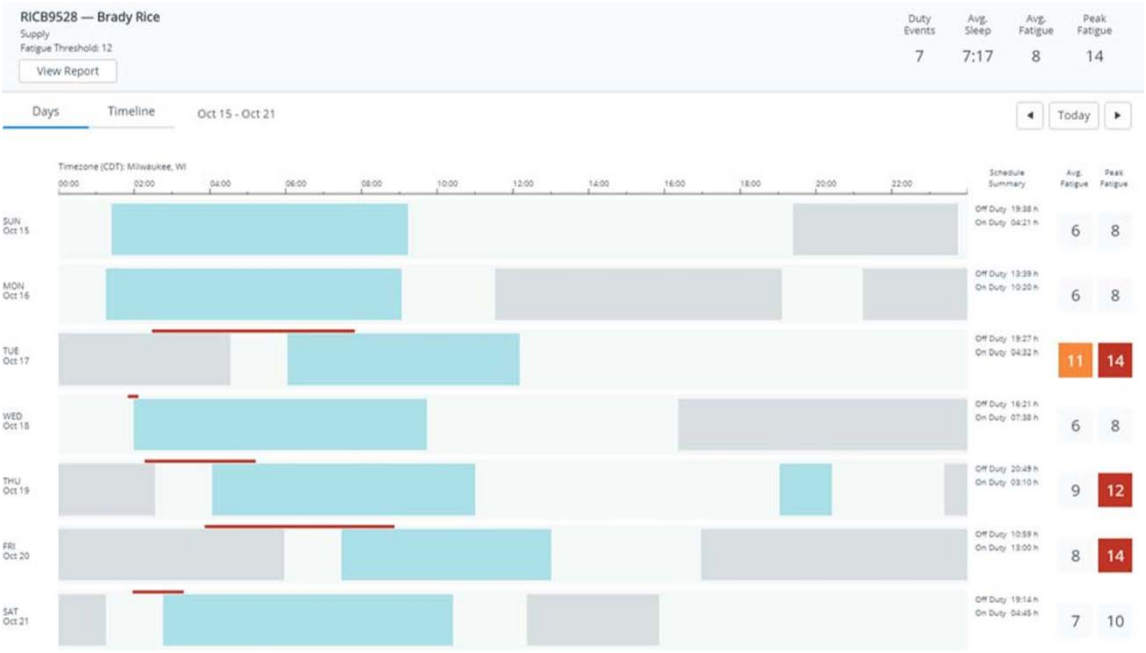
Figure 18. FlyAwake Graphical Output Screenshot. Source: Beshany (2009).

5. Optimized Watchbill and Logistics Fatigue Meter (OWL FM)

The Optimized Watchbill and Logistics Fatigue Meter (OWL FM) application was designed to support watchbill scheduling and watchbill fatigue assessments with a dashboard that supports fatigue analysis (Mollicone & Bruneau, 2018). The calculated fatigue scores are from a biomathematical model described by McCauley and colleagues (2009) which incorporates information about an individual's approximated sleep history and an offset to account for time zone shifts (Mollicone & Bruneau, 2018). The fatigue model was also calibrated with validated data from a variety of operational and laboratory studies to cover a wide range of situations a person may experience in a submarine environment. The following parameters are incorporated into the model's fatigue score calculation: total or partial sleep deprivation, presence of naps, shift work, night work, and partial sleep deprivation episodes followed by sleep recovery periods (Mollicone & Bruneau, 2018).

Funded by the Office of Naval Research and with the assistance of the Naval Submarine Medical Research Laboratory (NSMRL), Pulsar Informatics created this tool to detect and prevent high fatigue risk situations and provide near real time fatigue monitoring throughout an operational day (Mollicone & Bruneau, 2018). The calculated fatigue scores for the unit are linked to performance lapses on the Psychomotor Vigilance Test (PVT) which measures behavioral alertness during a 10-minute reaction time task (Lim & Dinges, 2008). As a reference, eight hours of sleep per night is associated with a predicted daytime average of 4.6 PVT lapses; however, after a 24-hour awake period, the number of PVT lapses jumps to 16.5. These lapses are an important objective measure of performance because they have been correlated to higher operational error rates in a variety of safety sensitive environments like the transportation and railroad industry (Mollicone et al., 2019; Hursh et al., 2011).

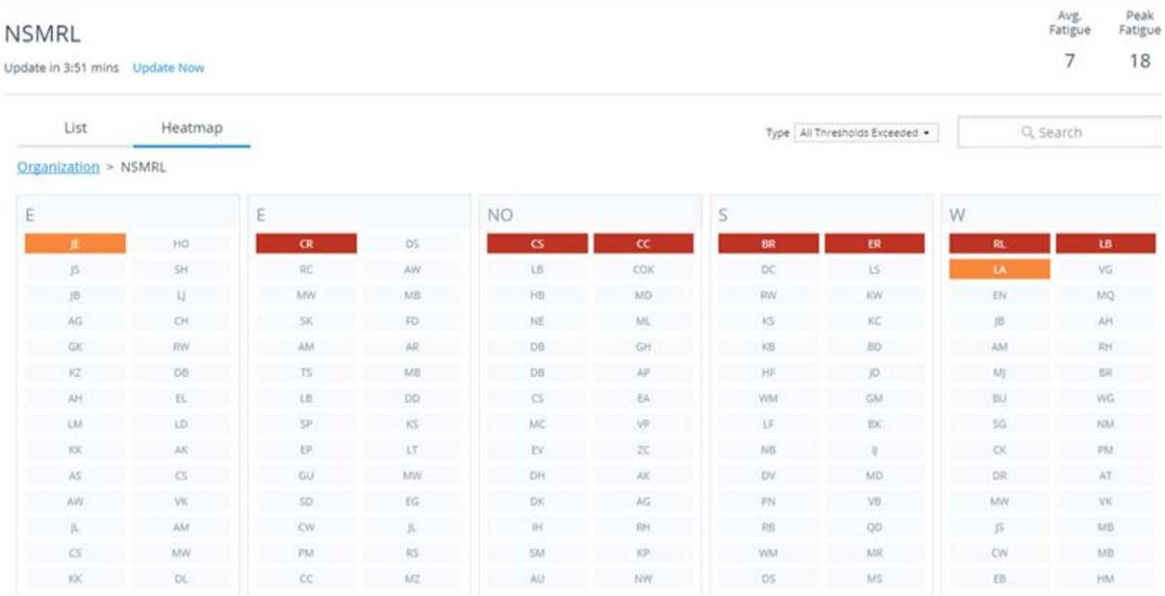
OWL FM reportedly provides predicted fatigue scores for individuals based on their duty periods, depicted as gray bars, and sleep estimates, depicted as blue bars (Figure 19). Throughout the application's dashboard, relevant information like a crewmember's average number of duty events, average sleep hours, average fatigue levels, and average fatigue scores are clearly displayed on the top right-hand corner for easy viewing (Figure 19). The application also allows users to perform fatigue monitoring and trend analysis as illustrated in Figures 20 and 21 which provides schedulers with critical feedback to identify and mitigate fatigue risk through proactive scheduling. Additional images of the OWL FM dashboard are included in the figures in Appendix C. The results from this integration and testing are currently unknown. These dashboard views make it easy for users to spot dangerous fatigue trends at the unit or individual level to implement fatigue mitigation actions. Since the system maintains historical data for an individual, the warning thresholds can be adjusted to a specific person's work and rest patterns instead of using group averages. The retention of historical data could be an extremely useful function for future analysis since the effect of fatigue factors and the amount of required sleep can vary between individuals.



Crew member duty periods are represented by gray bars and the corresponding sleep period estimates are represented by blue bars. The fatigue scores are listed on the right-hand side.

Figure 19. Crew Member Duty Periods and Sleep Estimates with Corresponding Fatigue Scores. Source: Mollicone and Bruneau (2018).

The OWL FM application allows users to focus on specific times when a person may have exceeded an absolute threshold or when their fatigue score deviates above their average personal range. The preliminary values for an absolute threshold and fatigue score deviation may be chosen based on benchmarks such as the number of PVT lapses (e.g., highlight when the number of PVT lapses are greater than 12) or a particular sleep deprivation situation (e.g., if a person experiences fatigue comparable to 24 hours of total sleep deprivation). Thresholds may also be adjusted after the initial period of use, and periodically thereafter, based on the observed fatigue score distribution (Mollicone & Bruneau, 2018).



Crew members exhibiting elevated fatigue levels are highlighted in orange and the members exhibiting excessive fatigue levels are highlighted in red.

Figure 20. Heat Map of Crew Member Fatigue Levels Grouped by Organizational Level. Source: Mollicone and Bruneau (2018).

Duty Fatigue

Average	Name	Duty Events	Peak
12	Veum, Dewitt	27	24
11	Aufderhar, Ethan	27	20
11	Bergnaum, Luciano	19	24
11	Effertz, Jaylen	26	19
11	Windler, Allie	24	21
11	Wunsch, Marquis	25	22
10	Bosco, Darrell	21	21
10	Dach, Dawn	21	17
10	Dicki, Freddy	22	19
10	Durgan, Marquise	23	19

Figure 21. List of Crew Members Sorted by Fatigue Level. Source: Mollicone and Bruneau (2018).

Software applications like FAST, FlyAwake, and OWL FM have been used in various military environments to estimate the fatigue risk associated with an individual's work and sleep schedule. While these tools offer users valuable fatigue management insight, extensive study is still required to validate the proffered performance measures against the actual performance of Sailors within the military maritime domain. Of particular interest is how to tailor the algorithms for these applications to appropriately account for the effects of sleep fragmentation, circadian variations, time zone shifts, shiftwork, around the clock performance, and sub-optimal sleep schedules and quality – all of which are commonplace onboard U.S. warships (Shattuck et al., 2014; Shattuck & Matsangas, 2016).

Existing applications and models are not specifically tailored for use in the military maritime environment. Accounting for unique occurrences like shipboard motion causing decreased sleep quality and increased levels of perceived fatigue (Brown, 2012; Grow & Sullivan, 2009) and the use of alternative watch schedules (Shattuck & Matsangas, 2014; Young, 2013; Roberts, 2012; Yokeley, 2012) would reduce the instances of over-estimation or under-estimation of fatigue or readiness levels. Further research into how sleep, fatigue, and performance may differ based on a Sailor's organizational level and watch rotation (Kerno, 2014) may also result in more useful and accurate predictive values of Sailor performance in military maritime operational settings.

E. SHIPBOARD WATCHBILLS AND PERSONNEL ASSIGNMENT CONSIDERATIONS

The following section will go over the watch organization onboard U.S. Navy warships, watchbills, data repositories used for watchbill creation, and personnel scheduling considerations.

1. U.S. Navy Watch Organization and Watchbills

Chapter 4 of the Standard Organization and Regulations of the U.S. Navy (SORM) instruction outlines the watch organization and composition based on the range of operations that are characteristic of naval warfare. A watch is defined as "any period of time during which a Sailor is assigned specific, detailed responsibilities on a recurring

basis"; furthermore, ships must set watches for both in port and underway conditions (DON, 2017c, p. 4-1, para. 2). The instruction also outlines the specific watch stations which must be manned in port and underway, the basic function of the watchstander, associated duties, responsibilities, and authority, and organizational relationships with other watchstanders. Standard U.S. Navy watches may be structured as follows: 0000–0400 (Mid Watch), 0400–0800 (Morning Watch), 0800–1200 (Forenoon Watch), 1200–1600 (Afternoon Watch), 1600–1800 (First dog Watch), 1800–2000 (Second dog Watch), and 2200–0000 (Evening Watch) (DON, 2017c, p. 4-7). While ships may follow different watch rotation structures, the requirement to man certain watch stations for 24-hour operational coverage is an important requirement for creating watchbills and is partially dictated by the ship's readiness condition (Table 6).

Table 6. Navy Readiness Conditions. Adapted from Fletcher (2018).

Condition	Name	Description
I	Battle Readiness or General Quarters	All battle stations are fully manned in preparation for combat situations or emergencies. The crew is expected to be able to maintain this posture for 24 continuous hours.
II	Modified Battle Readiness	A modified Condition I readiness state set to meet increased battle readiness requirements for a warfare area or areas. The crew is expected to be able to maintain this posture for 10 days.
III	Wartime, Increased Tension, and Forward-Deployed Cruising Readiness	Typical posture for deployed ships where watches are manned to defend against pop-up threats. The crew is expected to sustain this posture for 60 days or fewer.
IV	Peacetime Training Cruising Readiness	Lowest underway readiness posture associated with reduced watch station manning requirements. The crew must be prepared to step through the higher readiness conditions as required.
V	In Port Readiness	Capable of meeting any in-port requirement or emergency.

2. Watch Organization and Personnel Scheduling Challenges

There are several factors and constraints schedulers must consider when making a watchbill. A more comprehensive list is available in the concept map located in Appendix B. Previous messages from Naval Surface Forces Commanders encouraged the adoption of alternative watch schedules and the promotion of better exercise, nutrition, and sleep practices to address crew endurance issues (Naval Surface Forces [NSF], 2013; NSF, 2016). While these recommendations were encouraged, not all commands were able to fully incorporate them into their organization. The policy constraint and how it interacts with the other factors and constraints is of interest in the watchbill and personnel scheduling problem (Figure 22) because it establishes another requirement with which schedulers and COs must comply. One key development since the *Comprehensive Review* of 2017 was the release of Commander, Naval Surface Force, U.S. Pacific Fleet (COMNAVSURFPAC) and Commander, Naval Surface Force Atlantic's (COMNAVSURFLANT) *Comprehensive Fatigue and Endurance Management Policy* (or CFEMP) on November 30, 2017. This policy marked a major cultural shift for naval surface forces and a stronger commitment to addressing crew endurance issues which have plagued the Navy for decades. With the desired end state of ensuring that "Sailors are adequately rested for safe, professional shipboard operations to deliver enhanced warfighting effectiveness," the policy established crew rest requirements, workday limits, crew endurance training, and fatigue mitigation steps for the surface navy (DON, 2017a, p. 1, para. 3).

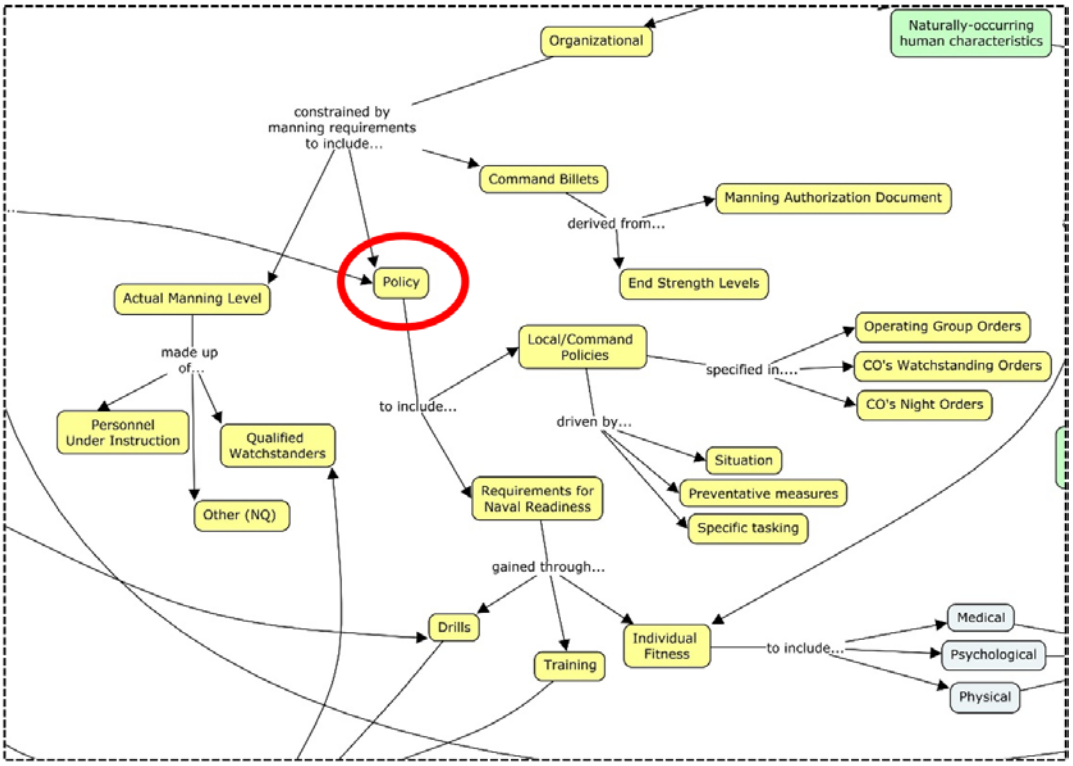


Figure 22. Partial Concept Map of Commanding Officer Scheduling Considerations and Constraints. Source: Brown (n.d.)

Currently, ship COs are required to make go/no-go decisions based on the following fatigue management policy (DON, 2017b):

> (1) Under ordinary circumstances underway, Sailors should receive a minimum of 7 hours of sleep in a 24-hour day; either by one uninterrupted 7-hour period or an uninterrupted 5-hour period with an uninterrupted 2-hour nap. Each of these notional watch rotations and shipboard routines presented in [the *Naval Postgraduate School Crew Endurance Handbook* v1.1, 1 Oct 2017], meet these guidelines.
>
> (2) [The U.S. Coast Guard Crew Endurance Management Practices, Jan 2003] recommends that Sailor workdays not exceed 12 hours in a 24-hour period or 8 continuous hours of work. Per [the Naval Air Training and Operating Procedures Standardization (NATOPS) General Flight and Operating Instructions Manual, CNAF M-3710.7, 15 Jul 2017], as the time continuously awake exceeds 16 hours, performance begins to drop. After 18 hours, performance efficiency rapidly declines to 75% of effectiveness or less, and accident rates increase for almost every activity. (p. 2)

At present, no standardized method exists for commanding officers to account for a Sailor's hours to ensure compliance with this instruction. The Individual Risk Management Tool (IRMT) included as an enclosure to the fatigue management policy must be included as a "part of operational risk management in both routine operations, as well as special evolutions briefings" (DON, 2017a, p. 3, para. 2). This process requires an accounting of the "proficiency, currency, and fatigue level of key watchstanders" as well as the status of key equipment and the weather in preparation for conducting operational evolutions (DON, 2017a, p. 3, para. 2).

The categories for the IRMT are as follows: watch/rest, experience, weather, and equipment. The human-related values of the "watch to rest ratio" and "experience," as outlined in Figures 23 and 24, are directly related to a Sailor's schedule. A Sailor's watch to rest ratio is based on their sleep and watch activity hours while their experience rating comes from hours spent on watch or participating in training. The values from each category make up the Individual Risk Management (IRM) score which is associated with the following risk ratings: 8 is critical, 8–10 is serious, 11–13 is moderate, 13–14 is minor, and 15–16 is negligible. After the rating process is complete, the final score influences whether the CO makes a go/no-go decision for an operational evolution like an underway replenishment (DON, 2017a). A completed sample IRMT is available in Appendix D. There are some overlapping values which allow for subjective risk assessments when COs balance other operational and mission tasking considerations.

Watch to Rest Ratio:

4: No watch leading into event (or during scheduled watch), 7 hours of sleep in last 24 hours

3: 7 hours of sleep in last 24 hours, stood a full watch before event

2: Between 5 and 7 hours of sleep in last 24 hours

1: Less than 5 hours of sleep in last 24 hours

Figure 23. Watch to Rest Ratio (left) Rating Scale from the Individual Risk Management Tool. Source: DON (2017a).

Experience:

4: 11 or more details in last 3 mos

3: 5-10 details in last 3 mos

2: 5 or less details in last 3 mos or UI

1: First time as qual'd watschstander

Figure 24. Watch Experience (right) Rating Scale from the Individual Risk Management Tool. Source: DON (2017a).

Without an objective way to assess the watch-to-rest ratio rating from Figures 23 and 24, the CO and schedulers are left to accept watchstanders' self-reported sleep estimates which may not be accurate. The fatigue models previously presented also determined that there are more factors that influence fatigue outside of how much sleep a person received in the past 24 hours. The surface navy requires a more holistic and standardized way to model fatigue for their Sailors to reduce the operational risk associated with fatigue and sleep deprivation.

3. Data Repositories for Scheduling Considerations

The growing manning shortfall, at 9,000 unfilled ship billets, poses a large problem for future force readiness and continues to be a major scheduling consideration (Larter,

2020). The large gap of unfilled sea-going billets, up from 2,750 from 2019 (Larter, 2020), have significant downstream effects such as limiting the number of available watch standers and workers onboard USN ships.

a. Navy Tactical Command Support System (NTCSS)

According to the Assistant Secretary of the Navy for Research, Development & Acquisition webpage, the Naval Tactical Command Support System (NTCSS) is an "information system for the management of supply, maintenance, and personnel administration for ships, submarines, aviation squadrons, and intermediate maintenance activities" (para. 3). Table 7 contains a brief description and status of the various NTCSS applications. Of interest are the Organizational Maintenance Management System – Next Generation (OMMS-NG) and the Relational Administration Data Management (RADM) applications which contain information about how Sailors are employed. The OMMS-NG application is used to "plan, schedule, report, and track maintenance actions [and] interfaces with shore activities to provide them with configuration, maintenance, and logistics information they require to support the fleet" (Arbulu, 2007, pp. 46). Although the system does not provide a sequenced accounting for individual manhours, it does record information such as the number of maintenance hours required to perform corrective maintenance and severity of the impact of space and system degradations which are captured under Job Sequence Numbers (JSNs). This information contributes to the aggregate metrics regarding workhours from maintenance, but it is associated with spaces, systems, divisions, and work centers which make fatigue tracking and risk management for individuals challenging.

Table 7. NTCSS Applications and Descriptions. Adapted from GAO (2005).

NTCSS Applications	Description	Status
Relational Supply (R-Supply)	Supports supply chain management, inventory management, and financial management processes. Provides Navy personnel with access to the supply support functions they perform most often—ordering, receiving, and issuing necessary supplies and materials; maintaining financial records; and reconciling supply, inventory, and financial records with the Navy's shore infrastructure	Operational, as of September 1998, on large force-level ships, smaller unit-level ships, and at air stations and marine aviation logistics squadrons.
Organizational Maintenance Management System – Next Generation (OMMS-NG)	Assists shipboard personnel in planning, scheduling, reporting, and tracking maintenance and related logistics support actions. Maintains online lists of maintenance actions to be performed, parts required to maintain shipboard equipment, and parts carried onboard ship to support maintenance actions. Interfaces with Relational Supply to requisition parts that are not onboard.	Operational, as of September 1998, primarily on large force-level ships and smaller unit-level ships.
Relational Administration Data Management (RADM)	Automates the management of personnel awards and decorations, work assignments, and berthing assignments.	Operational, as of April 2000, on large force-level ships, smaller unit-level ships, and at air stations and marine aviation logistics squadrons.
Optimized Intermediate Maintenance Activities	Provides online intermediate-level aviation maintenance, configuration, and logistics management support. Interfaces with other major integrated logistics support systems within the Naval aviation community.	Operational, as of April 2000, at force-level ships and at air stations and marine aviation logistics squadrons.

The RADM application serves as the afloat personnel management system and was designed to automate several functions such as personnel awards and decorations management, work assignments, and berthing assignments. Users can perform various functions including, but not limited to, creating muster reports, updating training records, tracking qualification data, and building watchbills. A Sailor's qualification data, or the completion of Personnel Qualification Standards (PQSs) and Job Qualification Requirements (JQRs), directly inform the personnel scheduling process. While RADM retains a historical record of watchbills which associate individual Sailors with their assigned watches, it is common practice to overwrite these watchbills which results in the loss of previous versions. Unless the scheduler has historical copies of the watchbills, another system in place to track a Sailor's watch, or an impeccable memory, this information is typically not retained or accounted for when the time comes to draft the next watchbill.

The muster section within RADM allows schedulers to mark whether a Sailor is present or accounted for that will affect the scheduler's ability to assign a Sailor a watch. A Sailor's watch status can only be recorded for ship's company or for personnel attached to the ship (e.g., individual augmentees, ship riders, temporarily assigned individuals, aircrew detachments, etc.). If a Sailor is on leave, liberty, Sick in Quarters (SIQ), or on Temporary Additional Duty (TAD) status, the start and end time must be entered. When overlapping times cause a logical conflict in the system, the user will receive a notification to either modify the start and end times or confirm their muster accounting choice before they can proceed with scheduling. These alerts are designed to prevent schedulers from inadvertently assigning watches to non-available personnel; however, the process is not infallible. If the alerts are disregarded or the incorrect accountability information is entered, a non-available Sailor may accidentally be scheduled for watch.

The training tab within RADM captures the type and time related to certain training modules and sessions for Sailors. Training data from RADM interfaces with the Fleet Training Management Planning System (FLTMPS) when the afloat and the ashore servers update (Arbulu, 2007). The training data does not provide an hourly accounting of when an individual participated in training and may not provide training duration in certain cases.

The qualifications section of the application can track progress made on PQSs and JQRs, provide tentative goals for completion, and retain the associated qualification statuses and data. One advantage of the RADM application is that it contains software logic which will not allow a scheduler to assign a Sailor for watch unless the Sailor is designated as Qualified (Q), Under Instruction (U/I), or Interim Qualified (I). This prevents the inadvertent assignment of someone who is not qualified to stand the watch.

The personnel assignment process can be labor intensive, especially when one must create a watchbill and perform the watch station and PQS/JQR associations from scratch. The tentative qualification dates associated with assigning Sailors PQSs and JQRs do not automatically translate to any future planning considerations within the application for watchbill making purposes. Division officers and warfare area leads tasked with creating quarterly Watch Team Replacement Plans (WTRPs) must transfer the existing information from this database manually to show qualification progression for their personnel. While the start dates for qualification deadlines are adjustable in the system, the duration of the qualification timeline is fixed. This rigid structure fails to account for numerous, often concurrent, PQS assignments and increased workloads. Additionally, the GUI can be difficult to work with and the application itself is subject to long lag times, freezing, overwriting existing files, or failing to save watchbill changes.

Anecdotal reports claim that NTCSS, to include RADM, will be phased out soon, meaning that it is subject to expiration unless it is renewed. A Government Accountability Report (GAO) from 2005 called for the reassessment of future investment into NTCSS due to the Navy's mismanagement of the program. The GAO recommended increased scrutiny into the program to determine if it was a "prudent use of limited resources" due to the lack of economic justification for re-investment, inability to make the program follow the "well-defined DOD or Navy enterprise architecture," absence of key measurement, reporting, budgeting and oversight activities, and inadequate requirements management and testing activities (GAO, 2005).

b. SKED 3.2

SKED 3.2 is a Maintenance and Material Management (3M) scheduling tool utilized onboard ships to manage organizational level maintenance through the completion of Planned Maintenance System (PMS) checks (Sponseller, 2019). The PMS schedules can fall under the following categories: cycle, quarterly, and weekly. The schedules are then populated with maintenance based on the periodicity codes listed on the Maintenance Requirement Cards (MRCs) (Naval Sea Systems Command, 2015). A list of periodicity codes is provided in Table 8.

Table 8. Periodicity Codes Associated with the Planned Maintenance System. Adapted from NAVSEAINST 4790.8C (2015).

Calendar Periodicity Codes	
Periodicity	**Date Range**
D – Daily	None
2D – Every 2 days	None
3D – Every 3 days	None
W - Weekly	None
2W – Every 2 weeks	9-19 days
3W – Every 3 weeks	14-28 days
M - Monthly	21-41 days
2M – Every 2 months	41-83 days
Q - Quarterly	61-121 days
4M – Every 4 months	83-165 days
S – Semi-annually	121-243 days
8M – Every 8 months	165-331 days
9M – Every 9 months	± 90 days from scheduled date
A - Annually	± 90 days from scheduled date
xM – Every x months where x = # of months	± 90 days from scheduled date
Non-Calendar Periodicity Codes	
R – Situational Requirement	
U – Unscheduled Maintenance	
AP – Assessment Procedure	
Inactive Equipment Maintenance (IEM) Codes	
LU – Lay-Up	
PM – Periodic Maintenance	
SU – Start-Up	
OT = Operational Test	

The Work Center Supervisor (WCS) can create a maintenance schedule in SKED 3.2 for specified periods, which is then approved by the divisional and departmental chain of command. The scheduler, or the WCS, can assign qualified personnel on specific days to complete the required scheduled maintenance checks. This system accounts for the manhours a Sailor spends on performing organizational level maintenance, but it does not have an hourly accounting of their time and it does not take credit for corrective maintenance associated with unplanned equipment failure. Moreover, this method may not accurately account for a Sailor's maintenance workload if they are assigned to complete a check that requires more than one maintenance person since the maintenance hours involved are subsumed by the more senior or experienced maintenance person. The 3M manual requires that the more senior or more knowledgeable maintenance person take credit for the check.

c. Plan of the Day (POD) and Plan of the Week (POW)

The Plan of the Day (POD) and Plan of the Week (POW) provide an overview of the day's or week's events which affect a Sailor's schedule. Events like cleaning stations and sweepers are often all-hands events while certain events like training, working parties, and meetings may only affect a handful of people. The information contained within these documents is usually not associated with individual Sailors unless it is for a high visibility item like checking-in/out with members of the triad composed of the Commanding Officer (CO), Executive Officer (XO), and Command Master Chief (CMC). Some scheduled events from these sources require a Sailor to change their existing work/rest schedule for various planned (e.g., freshwater wash down) and unplanned evolutions (e.g., shifted underway replenishment). A Sailor may have to adapt to this scheduling information by switching watches or procuring a watch relief, which may result in sleep loss or a disadvantageous shift in their circadian rhythm.

In summary, vigilant warfighters are necessary to carry out essential mission tasking and to safeguard the nation's interests. Excessive wakefulness, limited sleep/rest opportunities (Shattuck et al., 2018), and ever-increasing requirements and workloads (Fletcher, 2018) place an undue burden on Sailors which diminishes their performance and

threatens mission effectiveness. The U.S. Navy must continue leveraging knowledge about human performance risk factors into their everyday operations to improve crew endurance, warfighter performance, operational effectiveness, and safety. Left unchecked, the confluence of lapses in judgment, reduced vigilance, impaired reaction times, and degraded decision-making increase operational risk and pose a critical safety risk to Sailors and crews throughout the fleet. An alert watchstander could mean the difference in avoiding a collision, properly executing casualty control actions, or identifying and neutralizing an incoming threat. In an environment where seconds count and attention to detail matters, investing in Sailors to ensure they are resilient and ready for tasking could pay dividends in preventing loss of life or damage to the ship.

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III. APPROACH IN PROTOTYPE DEVELOPMENT

While the 2017 *CFEMP* established work and rest hour guidelines and mandated circadian-based watchbills (DON, 2017a), the U.S. Navy lacks a standardized and holistic way to manage Sailors' work and rest patterns. The absence of a systematic way to collect this data presents a large knowledge gap and a missed opportunity to optimize work schedules, improve crew resource management, and gain insight on fatigue risk indicators. Fatigue risk indicators such as prolonged wakefulness and insufficient sleep are associated with increased human performance risks which can lead to major accidents during naval operations. To improve crew endurance, warfighter performance, and operational effectiveness and safety, the U.S. Navy must invest in fatigue management tools and methods tailored to the military maritime environment. The following chapter presents a conceptual design overview, development rationale and information, and a functionality assessment for the SMART prototype. This chapter also describes the data created, analytical approach, and assumptions of the model underlying the decision aid.

A. PROTOTYPE CONCEPTUAL DESIGN

The main objective of this thesis is to create a scheduling decision aid prototype in MS Excel capable of tracking work and rest activity data for USN crewmembers. The output of the prototype provides a data-driven way to assess work/rest schedules, enhance crew resource management, and mitigate human performance risk related to fatigue. Figure 25 contains an overview of the inputs, constraints and limitations, and outputs of the SMART prototype. The main inputs are the activity information categorized as watch (W), work (A), maintenance (M), and sleep/rest (S) hours, in blue, for crew members (Figure 25). The main outputs are the graphical displays and reports, in orange, which provide schedulers and decision makers with human performance risk insights, in green (Figure 25).

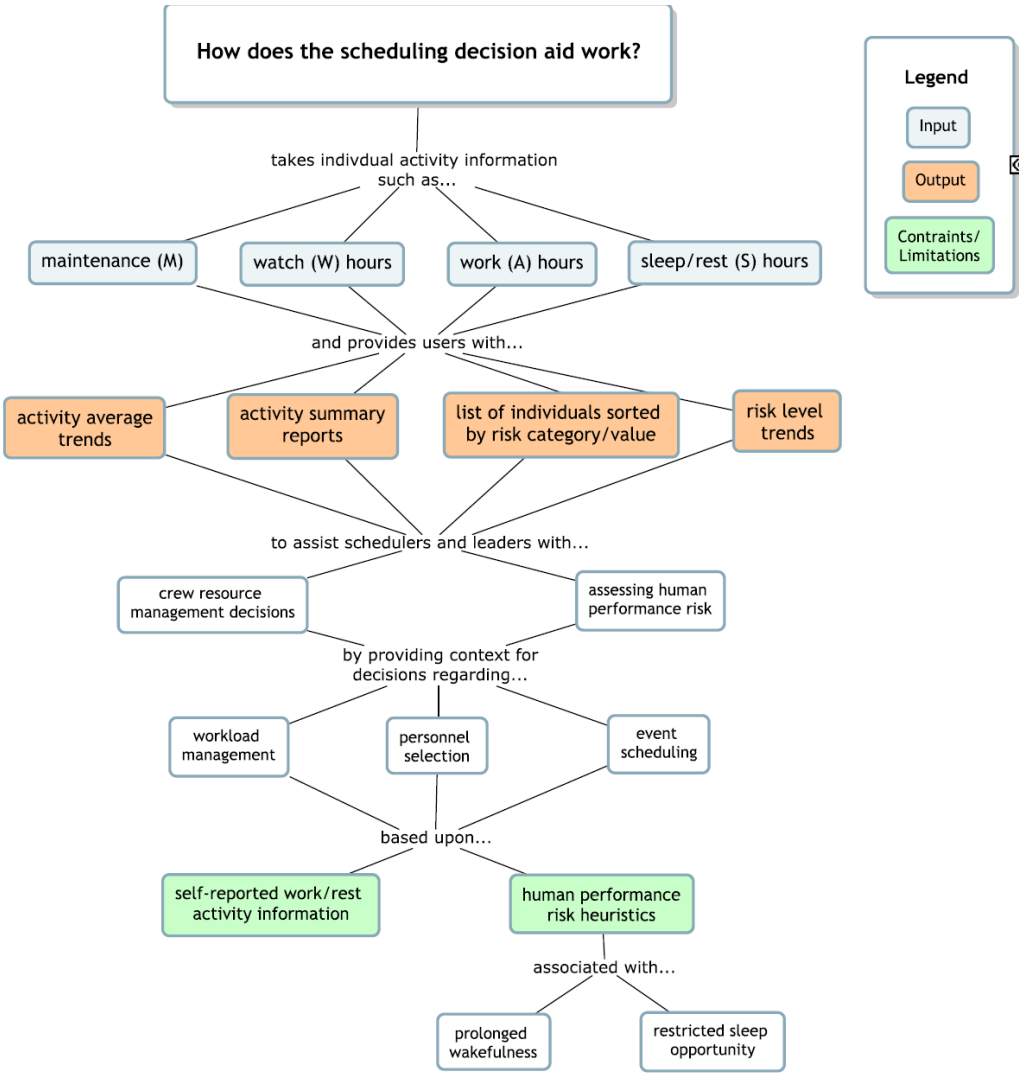
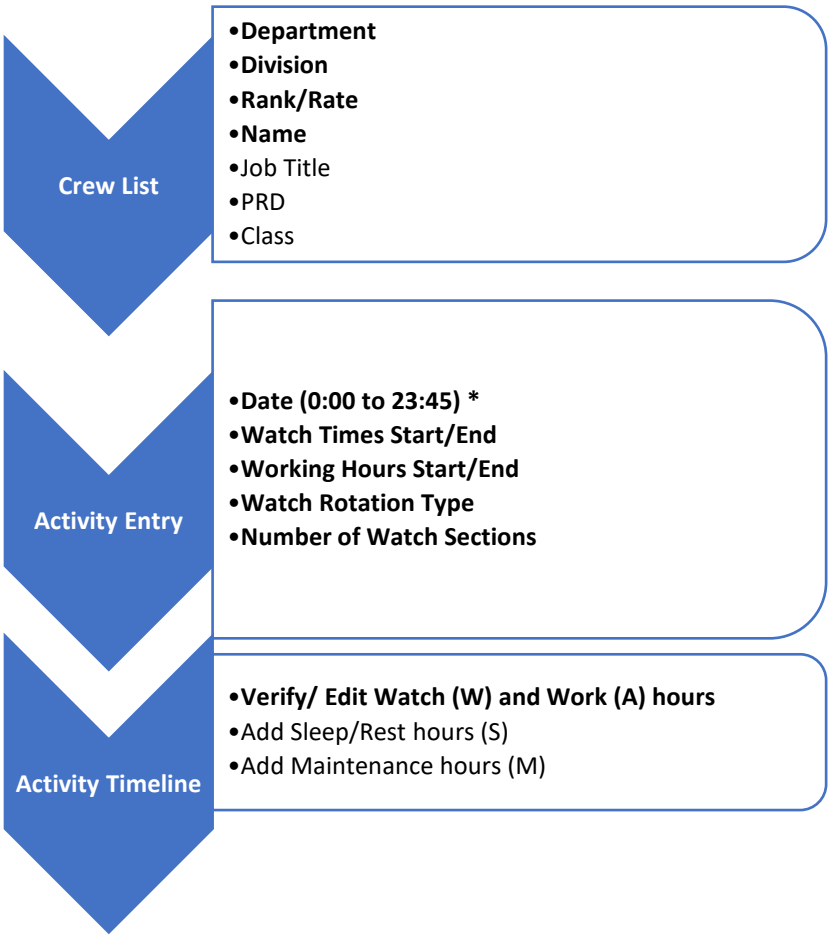


Figure 25. SMART Prototype Concept Map

The SMART prototype contains two databases, one for personnel and one for work/rest activity. Figure 26 outlines the data entry process which begins with the entry of the crew member names and their organizational associations (e.g., Department, Division) in the Crew List tab. The Activity Entry tab is automatically populated with the personnel data from the Crew List tab which enables users to enter the individuals' watch and work times within a given day. Additional days for the same individual are added in the same tab. The activity data from the Activity Entry tab automatically populates the respective 15-minute time blocks in the Activity Timeline tab. Users can verify and revise the watch and working hours in the Activity Timeline tab. Additionally, users can enter sleep/rest and

maintenance activity in the Activity Timeline tab. The Activity Timeline also allows the user to filter the data to display the activity distribution by organizational level, date, or select crew members. Of note, the day ends at 23:45 to keep the 15-minute tracking pattern.



Bold text indicates required user inputs and regular text indicates optional data entry fields.

Figure 26. Diagram of Data Entry Process

After the data entry is completed, the SMART prototype automatically calculates descriptive statistics based on the human performance risk metrics listed in the Activity Thresholds tab. Descriptive statistics such as average working hours and average sleep/rest hours are in the Activity Summary tab. This information enables data-driven crew resource

management decisions and forms the foundation for the various dashboards within the prototype.

B. PROTOTYPE DEVELOPMENT

This section contains development notes, database attribute details, and data associations for the prototype. To accomplish the main objective of this thesis, SMART must have the following attributes:

1. Data Structure

    a. Contains a list of crew members and their associated occupational information (e.g., organizational affiliation) to produce graphical outputs and enable targeted (i.e., individual or organizational level) crew resource management actions.

    b. Enables additions, deletions, or modifications to the crew list to accommodate changes resulting from personnel transfers or crew augments.

    c. Records multiple 24-hour periods of work and rest activity data for each crew member for systematic data collection and processing to enable trend analysis.

2. Data Processing and Handling

    a. Automatically carries over the information from the personnel and activity databases for processing to reduce the user's data entry time.

    b. Delineates required and optional data fields to reduce the user's data entry time and administrative burden.

    c. Accounts for data gaps or missing entries.

    d. Automatically calculates summary statistics for work (e.g., watch, work, and maintenance) and rest activity data at different organizational levels (e.g., individual, division, department, and command) to produce graphical outputs and reports.

3. Data Outputs

   a. Work/rest activity summary reports sorted by organizational level for trend analysis.

   b. Average activity levels sorted by organizational level to assist with crew resource management (e.g., personnel selection and work schedule management)

   c. Lists the critical and serious risk crew members to provide users with human performance risk insight. The information is designed to assist with personnel selection.

1. Prototype Organizational Structure

The SMART workbook contains several tabs. The Overview tab in the workbook contains summary information (e.g., name, purpose and available functions, and user notes) for the available tabs. Each tab name in the directory is directly linked to the associated tab for ease of navigation. The tabs visible to the user are marked in blue, and the hidden, developer tabs are marked in red (Table 9). The developer tabs within the prototype contain pivot tables that are linked with the outputs displayed in the three dashboards (Table 9). The pivot tables were hidden to reduce the display of redundant information and reduce the likelihood of formatting changes or errors to the dashboard outputs. More detailed information regarding the technical aspects of the prototype (e.g., formatting structure, formulas, etc.), operator instructions, and troubleshooting steps are available in the user manual supplemental published on Calhoun, the NPS institutional archive.

Table 9. Organizational Structure of the SMART Prototype

Tabs visible to the user are shown in blue, and hidden developer tabs are show in red.

Tab	Function(s)
Overview	Provides a navigational pane and overview of the available functions.
Crew List	Contains a list of all personnel along with their associated Department, Division, and Rank/Rate. This information will feed into the functionality of other tabs in the prototype.
Activity Entry	Allows users to enter an activity (e.g., watch and work) hours.
Activity Timeline	Allows users to verify and edit watch and work activity information. The user can also enter maintenance and sleep/rest activity.
Activity Summary	Contains summarized information for activity hours. Allows users to enter activity thresholds for assessment of human performance risk.
Threshold Values	Displays the activity threshold limits, associated risk assessment values, and concern level ratings. The user can modify the activity threshold limits in this tab.
Average Activity Dashboard	Provides graphical displays for activity averages (e.g., total work, watch, sleep/rest, and maintenance).
Risk Level List Dashboard	Provides a list of all personnel by risk level category (e.g., minor, moderate, serious, or critical).
Risk Level Charts Dashboard	Provides graphical displays sorted by risk level category (e.g., minor, moderate, serious, or critical).
Activity Averages by Organizational Level	Contains the pivot tables for the activity averages graphics sorted by Department and Division utilized in the Average Activity Dashboard tab.
Activity Averages Trend	Contains the pivot tables for the activity averages trend graphic utilized in the Average Activity Dashboard tab.
Risk Charts	Contains the pivot tables for the risk level graphics utilized in the Risk Charts Dashboard tab.
Validation	Provides drop down item selections to aid in data validation.
Demographics	Provides demographic graphics from the Crew List tab.

2. Crew List Tab

The personnel database is contained in the Crew List tab and is formatted as a table to facilitate future development and ease of summary statistic tabulation. Table 10 details the field names, data types, and data descriptions for the entry fields in the Crew List tab. The Department, Division, and Class entry fields are data-validated and the selection options are tailored for a Cruiser or Destroyer ship type organizational structure.

Table 10. Crew List Tab Field Names and Attributes

Bold field names are required SMART prototype inputs.

Field Name	Data Type	Data Description
Department	Text	Department abbreviation
Division	Text	Division abbreviation
Rank/Rate	Text	Rank (Officer)/ Rate (Enlisted) abbreviation
Name	Text	First and last name
Job Title	Text	Primary billet title
Class	Text	Officer or Enlisted classification
Projected Rotation Date (PRD)	Date/Time	Local date/time (minimum of month and year)

3. Activity Database

The Activity Database is comprised of the Activity Entry, Activity Timeline, and Activity Summary tabs. The method for collecting activity information for the SMART prototype was inspired by several sources. Previous NPS theses on U.S. Navy Sailor work and rest activity patterns utilized activity logs alongside wrist-worn actigraphy, surveys, and questionnaire data. Civilian mariners use several commercially available software applications to track work/rest activity.

The Activity Entry, Activity Timeline, and Activity Summary tabs were designed to automatically populate with Department, Division, Rank/Rate, and Name data points from the Crew List tab. This function was designed to reduce the administrative burden on the user by eliminating the need to enter redundant information. The Activity Entry tab was designed to transfer data typically contained in a watchbill in a centralized location (Table 11). The watches were separated into two blocks because watchstanders commonly stand two watches during a 24-hour period. Working hours were meant to capture the individual's normal working hours (e.g., 0600 to 1600). Additional watch or work hours can be manually added under the Activity Timeline tab as required. While users can utilize additional or alternative activity codes like "T" for training, they will not be tabulated in the Activity Summary table without additional programming changes. Additionally, the outputs will not reflect activities outside of the pre-programmed activity codes.

Table 11. Activity Entry Tab Field Names and Attributes

Field Name	Data Type	Data Description
Date	Date/Time	Formatted as MM/DD/YYYY
Watch Rotation Type	Text	Fixed or Rotating
Number of Watch Sections	Numeric	Total number of watch sections for the individual's watch station
Watch 1 Start	Time	Formatted as 00:00:00 AM in military time
Watch 1 End	Time	Formatted as 00:00:00 AM in military time
Watch 2 Start	Time	Formatted as 00:00:00 AM in military time
Watch 2 End	Time	Formatted as 00:00:00 AM in military time
Working Hours Start	Time	Formatted as 00:00:00 AM in military time
Working Hours End	Time	Formatted as 00:00:00 AM in military time

After the required inputs are entered in the Activity Entry tab, the watch (W) and work (A) activity blocks are automatically filled in the Activity Timeline tab. The collection form for the Activity Timeline is formatted in 15-minute time increments to account for staggered watch relief schemes common to most USN ships. There is a hierarchical structure for watch and work activities. In cases where working hours overlap with watch times, watch will take precedence because that is the Sailor's main priority. For example, if a Sailor has watch from 0600 to 0900 and normally works from 0600 to 1600, the 0600 to 0900 blocks will contain a "W" and the 0915 to 1600 blocks will contain an "A." The user can verify that the work/rest activity data is correct under the Activity Timeline tab and manually modify the information to account for watch/work changes. Users can also add Sleep/Rest and Maintenance activity data to the same tab.

Once the Activity Timeline tab is populated with work/rest activity data, the summary metrics are automatically calculated and displayed in the Activity Summary tab (Table 12). The Activity Summary tab populates the pivot tables and charts in the SMART prototype's dashboards.

Table 12. Activity Summary Tab Field Names and Attributes

Field Name	Data Type	Data Source	Data Description
Watch (hours/day)	Numeric	Activity Timeline tab	Cumulative watch time from 00:00 to 23:45 in 15-minute increments
Sleep/Rest (hours/day)	Numeric	Activity Timeline tab	Cumulative sleep/rest time from 00:00 to 23:45 in 15-minute increments
Work (hours/day)	Numeric	Activity Timeline tab	Cumulative work time from 00:00 to 23:45 in 15-minute increments
Maintenance (hours/day)	Numeric	Activity Timeline tab	Cumulative maintenance time from 00:00 to 23:45 in 15-minute increments
Total Work Time (hours/day)	Numeric	Activity Summary tab	Sum of watch, work, and maintenance hours
Sleep/Rest Score	Numeric	Activity Summary tab	Integer values from 0 to 3
Work Period Score	Numeric	Activity Summary tab	Integer values from 0 to 3
Watch Rotation Score	Numeric	Activity Summary tab	Integer values from 0 to 1
Watch Section Number Score	Numeric	Activity Summary tab	Integer values from 0 to 2
Risk Value	Numeric	Activity Summary tab	Sum of the activity (sleep/rest, work, watch rotation, watch section number, and maintenance) scores
Risk Rating	Text	Activity Summary tab	Critical, Serious, Moderate, or Minor/Negligible ratings based on the risk value

4. Dashboard Display and Reports

The dashboard displays and reports are the outputs for the SMART prototype. SMART contains three dashboards separated in the Average Activity, Risk List, and Risk Charts tabs. Table 13 contains the field names and attributes for the dashboard displays and reports from the prototype. The Activity Summary tab and associated dashboards are designed to update as the Activity Entry or Activity Timeline tabs are changed. The

dynamic dashboard interfaces were designed to allow the user to quickly filter through the summarized data.

Table 13. Dashboard Displays and Reports Field Name and Attributes

Graphic Title	Graphic Type	Data Source	Notes
Activity Averages Trends	Line Chart	Activity Summary tab	Displays average activity hours (e.g., work and sleep/rest) trends by date. The user can filter the results by Date, Department, Division, and Name.
Activity Averages by Department	Column Charts	Activity Summary tab	Displays charts for total work, sleep/rest, watch, and maintenance averages by Department. The user can filter the results by Date and Department.
Activity Averages by Division	Column Charts	Activity Summary	Displays charts for total work, sleep/rest, watch, and maintenance averages by division. The user can filter the results by Date, Department, and Division.
Risk List Table	Pivot Table	Activity Summary tab	Displays a list of all individuals who fall under a specified risk rating or risk value. The user can filter the results by Date, Risk Rating, Risk Value, Department, Division, and Name.
Risk Level Trends	Line Chart	Activity Summary tab	Displays the number of individuals per risk rating category by date. The user can filter the results by Date, Department, Division, Risk Rating, and Name.
Risk Rating Counts by Department	Column Charts	Activity Summary tab	Displays charts for the number of individuals at each risk level category by department. The user can filter the results by Date, Department, Division, and Risk Rating.
Risk Rating Counts by Division	Column Charts	Activity Summary tab	Displays charts for the number of individuals at each risk level category by division. The user can filter the results by Date, Department, Division, and Risk Rating.

C. DESIGN ASSUMPTIONS

The following assumptions were used in the development of the SMART prototype:

- Sleep/rest activity times only indicate opportunities for sleep or rest.
- The ship utilized an approved watchbill with circadian (i.e., fixed) and non-circadian (i.e., rotating) rhythm-based watch rotations while underway.
- Departures from the notional schedule mimicked planned and unplanned events which will shift a Sailor's work/rest hours.
- Sailors will not deviate from their scheduled watch times.
- Daily routines events such as cleaning stations, training, messing and berthing inspections, mealtimes, etc., will be captured under the period designated as Working Hours.
- Sailors were already qualified or PQS-assigned to stand their applicable watch stations and to perform their required maintenance or work tasks.
- The scheduling events modeled reflect those of a typical warship's schedule and will roughly translate to the experience of other units.

D. FUNCTIONALITY ASSESSMENT

The functionality of the SMART prototype will be assessed by how well it can perform the following functions:

- Account for and calculate activity hours correctly.
- Enable identification of individuals beyond specified activity thresholds.
- Determine the magnitude of departure from established activity time limits.

- Provide dynamic graphical displays to enable schedulers to filter the work and rest activity data.
- Enable trend analysis of activity data to showcase patterns for individuals or different organizational levels.

E. CRITERIA FOR RISK ASSESSMENT

The risk assessment criteria for the test scenarios were based on the Basic Risk Assessment Matrix (Table 14). In Table 14, probability refers to the frequency of occurrence over time. Severity is related to the effect of hazard. Risk assessment levels are categorized as Extremely High (EH) = 1, High (H) = 2, Medium (M) = 3, or Low (L) = 4. The *Operational Risk Management* instruction outlines the operational risk management (ORM) decision making process and explains the time versus non-time critical risk management processes (OPNAVINST 3500.39D, 2018). These criteria were chosen because of the Department of the Navy's familiarity with the matrix and risk assessment process.

Table 14. Basic Risk Assessment Matrix. Adapted from OPNAVINST 3500.39D (2018).

Risk Assessment Matrix		**Probability**				
		Frequent (A)	**Likely (B)**	**Occasional (C)**	**Seldom (D)**	**Unlikely (E)**
Severity	Catastrophic (I)	EH (1)	EH (1)	H (2)	H (2)	M (3)
	Critical (II)	EH (1)	H (2)	H (2)	M (3)	L (4)
	Moderate (III)	H (2)	M (3)	M (3)	L (4)	L (4)
	Negligible (IV)	M (3)	L (4)	L (4)	L (4)	L (4)

For example, the risk (i.e., likelihood) of the ship running aground or colliding with another vessel during a high-risk Sea and Anchor (S & A) evolution is increased when a watchstander is sleep-deprived. Similarly, a watchstander who is less alert may hurt themselves or cause damage to localized equipment if, for example, they inadvertently activate a fire suppression system or improperly shut down a running engine. Both situations require an assessment of risk and appropriate mitigating actions to lower the

assessed risk to an acceptable level. Risk mitigation may be accomplished by stationing safety observers in strategic locations, employing props during drills and training events, or assessing watchstander readiness (e.g., fatigue, illness, or injury) prior to assuming the watch especially during high-risk evolutions.

The framework behind the work/rest activity data risk score assignment is comparable to the method by which the Individual Risk Management (IRM) code is assigned. The overall work/rest activity data risk score, referred to as the Concern Level in the prototype, is the sum of risk assessment values for various categories. Metrics from the service members' activity data are collected and roughly categorized based on the activity thresholds outlined in the *CFEMP (2017)* and the IRM Tool (Appendix D). Activity limits were selected after combining elements from the policy and the IRMT. The combination allowed for less ambiguity compared to strictly adopting the IRMT Watch to Rest Ratio limits. Moreover, the combination accommodated stratified risk assessment ratings compared to strictly adopting the *CFEMP* limits. The metrics, criteria, and risk assessment values are outlined in Table 15. The activity thresholds were based on existing DON guidelines which directly apply to U.S. Navy warships. Moreover, the human performance risk metrics associated with insufficient sleep and excessive workloads are supported by years of crew endurance and fatigue research and are known contributors to degraded Sailor productivity and warfighting capacity.

Table 15. Criterion and Risk Assessment Value

Risk Metrics	**Criterion (in a 24-hour period)**	**Risk Assessment Value**
Sleep/Rest Period Length	Sleep/Rest hours ≤ 3	3
	3 < Sleep/Rest hours ≤ 5	2
	5 < Sleep/Rest hours < 7	1
	Sleep/Rest hours ≥ 7	0
Total Work Period Length	Work hours ≤ 8	0
	8 < Work hours ≤ 12	1
	12 < Work hours < 16	2
	Work hours ≥ 16	3
Watch Rotation Type	Fixed	0
	Rotating	1

Risk Metrics	Criterion (in a 24-hour period)	Risk Assessment Value
Number of Watch Sections	Watch Sections ≤ 2	2
	Watch Sections = 3	1
	Watch Sections ≥ 4	0

The final risk level values/ratings outlined in Table 16 are based on the sum of the sleep/rest period length, total work period length, watch rotation type, and number of watch sections risk assessment values. During a 24-hour period, if a Sailor had a 6-hour sleep/rest period, a 14-hour work period, a fixed watch, and a four section watch rotation, the Sailor would receive risk assessment values of 1, 2, 0, and 0, respectively (Table 15). As a result, the Sailor would receive a Risk Level score of 3 or Moderate (Table 16). Low Concern Levels values are ideal and indicate little to no additional risk due to human performance; high numbers indicate higher human performance risk associated with the work/rest activity data from the individual. The activity threshold and risk assessment values are adjustable in the prototype to account for policy changes or to accommodate a ship's unique operational schedule. Sailors onboard a ship operating in Condition III underway steaming configuration will have a different work/rest activity pattern compared to Sailors operating under Condition I or General Quarters. The difference in operational schedules and tasking would translate to a different risk tolerance and warrant adjustments to the Risk Level ratings.

Table 16. Risk Level Values and Ratings

Values	Rating
8 +	Critical
5 - 7	Serious
2 - 4	Moderate
0 - 1	Minor/Negligible

F. ANALYTICAL APPROACH

Notional crew and work/rest activity data were used to test whether the SMART prototype functioned properly. The following section describes the test case data generated,

SMART prototype functions tested, scenario descriptions, and criteria used to evaluate the SMART prototype.

1. Data Description

The SMART prototype was populated with a crew complement based on a notional guided missile destroyer (DDG) platform. Table 17 contains a summary of the departments, divisions, and rates associated with the hypothetical individuals and was adapted from Table 9 of Lieutenant Garbacz's 2019 thesis. Officers are not listed in Table 17 because they span the departments and divisions.

Table 17. Department, Division or Work Center, and Rates Summary

Department	Division	Rates
Combat Systems (CS)	CC	IT
	CE	ET & IC
	CF	FCA
Engineering (ENG)	EA	MM
	EE	EM
	ER	DC, HT, & FN
	MP	GSE, GSM, & GS
Executive/Navigation (EXEC/NAV)	EX	MA, NC, PS, RP, & YN
	HM	HM
	NN	QM
Operations (OPS)	OD	BM & SN
	OI	OS
Plans and Tactics (PT)	CA	STG
	OT	CTT, CTR, & IS
Supply (SUP)	S1	LS
	S2	CS
	S3	SH
Weapons (WEPS)	CG	GM
	CM	FC

One hundred sixty-eight hours of activity data spanning seven days was used to model the work and sleep/rest activities of Sailors onboard the theoretical ship. The generated test case watch activity data was based on historical watchbills from a DDG. The

seven-day timeframe has two days in port followed by five days underway and formed the framework for the functional analysis of the prototype (Table 18). Human performance risk related to insufficient sleep opportunity and long workdays was assessed using the Basic Risk Assessment Matrix (Table 14). Risk mitigating actions were not included during the initial Risk Assessment Codes (RAC) calculations when they were associated with the evolutions of interest listed in Table 18.

Table 18. Activity Time Period and Evolutions of Interest

Day (Date)	Ship Status	Evolutions of Interest	Risk Assessment Code
1 (September 8, 2020)	In port	Duty Section	Low
2 (September 9, 2020)	Underway	Sea and Anchor Seamanship Drill	Extremely High High
3 (September 10, 2020)	Underway	All Hands Training Normal Watches	Low Moderate
4 (September 11, 2020)	Underway	All Hands Training Normal Watches	Low Moderate
5 (September 12, 2020)	Underway	All Hands Training Normal Watches	Low Moderate
6 (September 13, 2020)	Underway	All Hands Training Normal Watches	Low Moderate
7 (September 14, 2020)	In port	Sea and Anchor Seamanship Drill Duty Section	Extremely High High Low

2. SMART Functions

The user can complete the following main tasks using the SMART prototype:

- Add/Delete/Modify personnel database entries in the Crew List tab.
- Add/Modify watch and work activity hours in the Activity Entry tab.
- Modify watch and work activity hours in the Activity Timeline tab.
- Add/Modify sleep/rest activity data in the Activity Entry tab.

- Adjust activity threshold values in the Individual Summary tab.

After the main tasks are completed, the prototype calculates summary data, assigns risk assessment values, and categorizes the information. The summary results are displayed on the appropriate dashboard where the user can then perform the following actions:

- Assess the overall human performance risk status of the crew at three organizational levels.
- Assess individual human performance risk.

3. Prototype Response to Specified Scenarios

Typically, a scheduler assigns personnel for watches, special evolutions, or work details devoid of previous or sometimes even current work/rest activity information. The SMART prototype was assessed based on how it detects human performance risk during two scenarios. The first scenario involved a human performance risk assessment for S & A watchstanders. The second scenario involved an assessment of departmental, divisional, and individual performance risk during routine underway (Condition III) operating conditions. The Sailors were split into best, mixed, and worst-case groups, with 98 individuals for each group, based on how their work/rest activity data was populated (Table 19). The wide range of values covered by the mixed-case group was intended to model the effect of unplanned tasking, additional work responsibilities, and general unpredictability inherent in everyday naval operations. Additionally, the values for work and sleep/rest hours were varied each day for the mixed-case group to reflect the variability in an individual's schedule.

Table 19. Heuristic Value Assignments by Case

Note: Total work hours include work and maintenance hours.

Heuristic	Best Case	Mixed Case	Worst Case
Total Work Hours	≤ 8	16 ≤ __ ≤ 8	≥ 16
Sleep/Rest Hours	≥ 7	7 ≤ __ ≤ 3	≤ 3
Watch Rotation Type	Fixed	Fixed or Rotating	Rotating
Number of Watch Sections	≥ 4	4 ≤ __ ≤ 2	≤ 2

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IV. RESULTS

This chapter contains descriptive statistics of the notional data, functional assessment, initial prototype results, sensitivity comparison, and results for specified scenarios.

A. DESCRIPTIVE STATISTICS OF THE NOTIONAL DATA

The ship's crew was based on a notional DDG's crew complement. The crew members, composed of 294 unique individuals, were interspersed between seven departments (Figure 27) and 19 divisions (Figure 28). Although the number of individuals by department and division vary, there is a consistent pattern of a high enlisted personnel to officer ratio which is typical of a warship's crew composition (Figures 27 and 28). The abbreviated departments and divisions for the following figures were based on the organizational structure introduced in Table 17. The department designations are as follows: Combat Systems (CS), Engineering (ENG), Operations (OPS), Supply (SUP), Executive/Navigation (EXEC/NAV), Weapons (WEPS), and Planning and Tactics (PT).

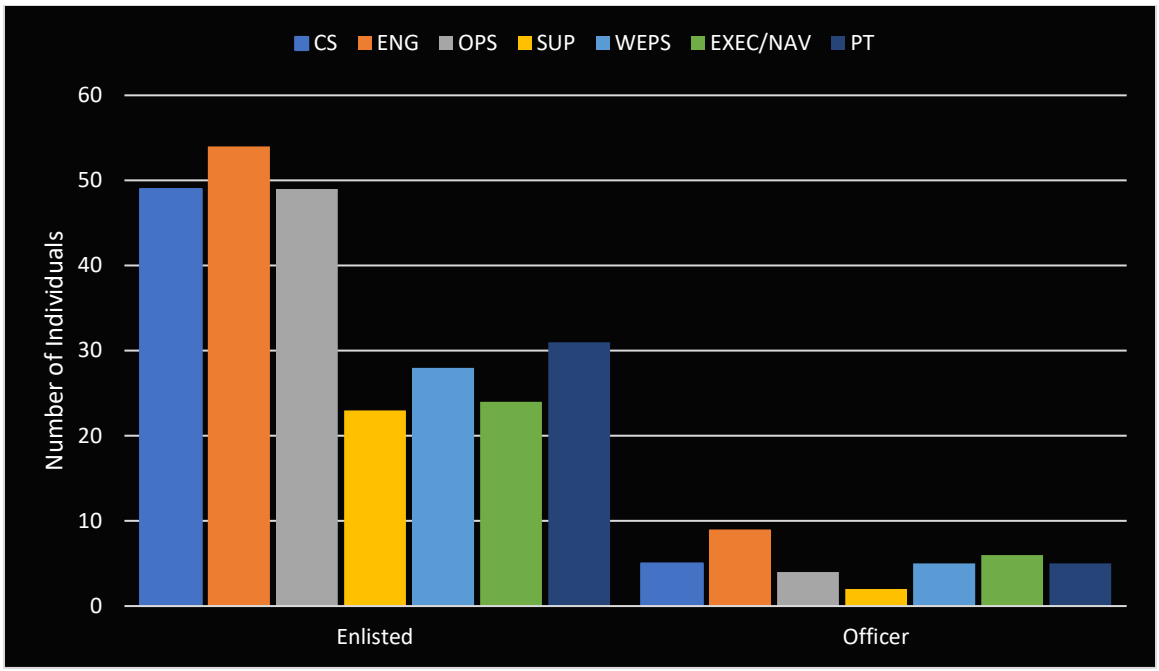


Figure 27. Distribution of Officers and Enlisted Personnel by Department

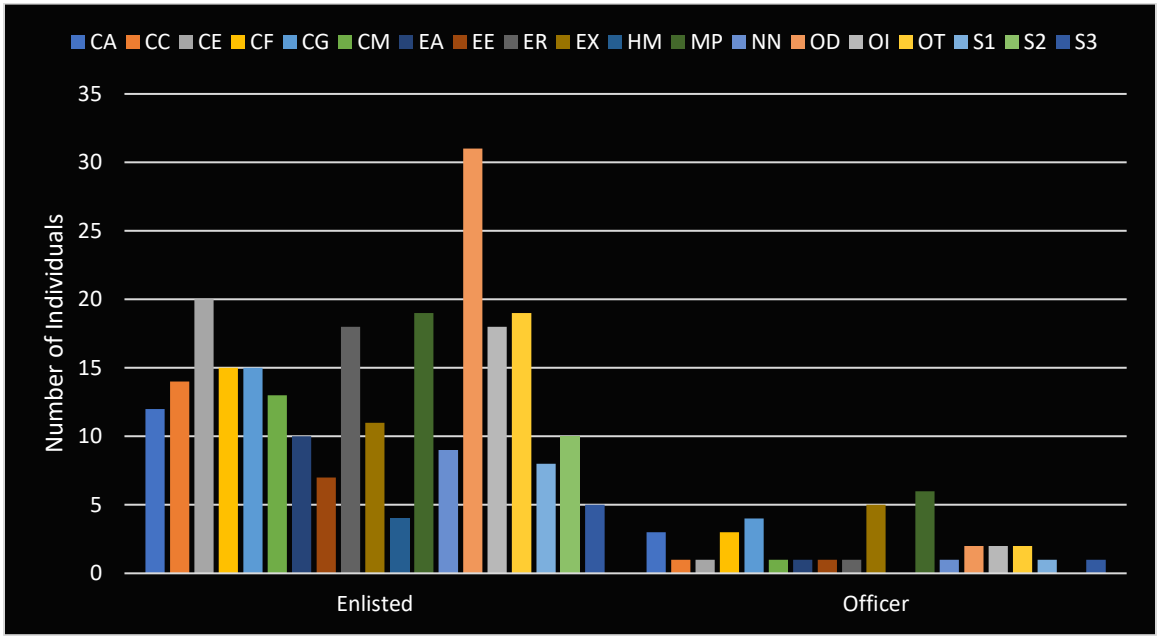


Figure 28. Distribution of Officers and Enlisted Personnel by Division

B. FUNCTIONALITY ASSESSMENT

Based on the notional data, the SMART prototype was able to properly quantify and categorize the human performance risk for all crew members. The prototype's functionality was assessed based on a simple yes or no scale based on the evaluation factors listed in the Functionality Assessment subsection (pp. 63–64). Although there are still areas for improvement, the SMART prototype met all the functional criteria previously listed (Table 20).

At its current state, SMART does not provide recommendations for limiting human performance risk or staying within recommended activity thresholds. However, it provides users with several benefits. First, the user can record and process activity information in a holistic way. Previously, there was no widely available approach to account for man-hours, outside of maintenance tracking, at an individual or organizational level. Second, the outputs provide users with insight into the crew's workloads, enabling proactive scheduling and more effective crew resource management decision making. Lastly, the human performance risk heuristics provide visibility on a formerly untapped data source, allowing for intuitive and targeted risk mitigation actions. Future development of the tool could include additional data points such as a work center organizational level, qualifications listing, watch station assignment and location associations, and additional activity types.

Table 20. SMART Functionality Assessment

Code	Evaluation Factor	Y/N	Notes
A	**Accuracy** (SMART is able to…)		
A1	calculate activity times correctly	Y	The day ends at 2345 vice 2359.
A2	quantify risk values correctly	Y	
A3	categorize risk correctly	Y	
F/C	**Flexibility/Customization** (users are able to…)		
FC1	add other activity categories	Y	Developer (hidden) option and requires more experience with Excel to minimize errors.
FC2	account for watches or work periods that span two days	Y	Watches spanning two days must be split between two 24-hour periods. For example, a 2200–0200 watch should be accounted for as 2200–2345 for the first

Code	Evaluation Factor	Y/N	Notes
			day and 0000–0200 for the second day.
F	**Functionality** (SMART is able to…)		
F1	record and retain personnel data	Y	
F2	record and retain activity data	Y	
F3	identify individuals by risk value	Y	
F4	identify individuals by risk category	Y	
F5	determine the magnitude of departure from recommended activity time limits	Y	Visual markers associated with the risk levels are displayed on the charts.
F6	perform activity time trend analysis by organizational level	Y	
F7	perform activity time trend analysis for individuals	Y	
D	**Display** (SMART utilizes…)		
D1	dynamic graphic displays	Y	
D2	intuitive filter selections	Y	

C. INITIAL PROTOTYPE RESULTS

Instead of conducting a direct comparison between the watch time and watch station assignments from the available historical watchbills, the activity assignments were varied based on the heuristic value thresholds by case as outlined in Table 19. This slight modification to the activity data entry process occurred due to the assignment of multiple watches or the presence of conflicting watch times for several personnel. For example, an individual was assigned all-day watches (e.g., Duty Admin, Reaction Force Member, and Investigator from 0630 to 0630) and a static watch (e.g., Entry Control Point Sentry from 1700 to 2200). This made it difficult to ascertain when they performed work-related activities outside of their static watch assignment. The changes were still in keeping with typical watch assignment practices and had minimal impact on the utility of the protype. The mixed case group thresholds were randomly varied to span the range between the best- and worst-case limits. Due to the small sample size, the activity values were not distributed in a normal fashion and were randomly varied throughout the notional study period.

Figures 29 through 35 are screenshots of the initial outputs from the prototype after the notional data was entered. The red, orange, yellow, and green dashed lines visually reinforce the corresponding activity thresholds as listed in Table 15. Each color follows the risk rating color scheme outlined in Table 16: red (critical), orange (serious), yellow (moderate), and green (minor/negligible). The total work time, as indicated by the purple squares, are the summation of watch, maintenance, and work activity categories (Figure 29). The user can see how total work hours for the entire study period hover around 12 hours which is associated with a moderate human performance risk rating (Figure 29). The watch and work hours remain relatively consistent, while the changes in maintenance hours significantly contribute to changing total work time trends (Figure 29). A large spike in maintenance hours, as seen on September 13th, is a point of interest. The increase in maintenance hours could be attributed to a variety of causes such as equipment failure, failure to balance workloads evenly throughout the work week, or maintenance requirements associated with the prior to entering port checklist. Whatever the reason, it may be prudent to investigate the cause of the sharp increase to reduce the likelihood of it occurring again. Crew members averaged between five to seven hours of sleep with minor

fluctuations during the study period, which is associated with serious to moderate human performance risk, respectively (Figure 30). The lack of sleep is not overly surprising since typical workdays were around 12 hours (Figure 29).

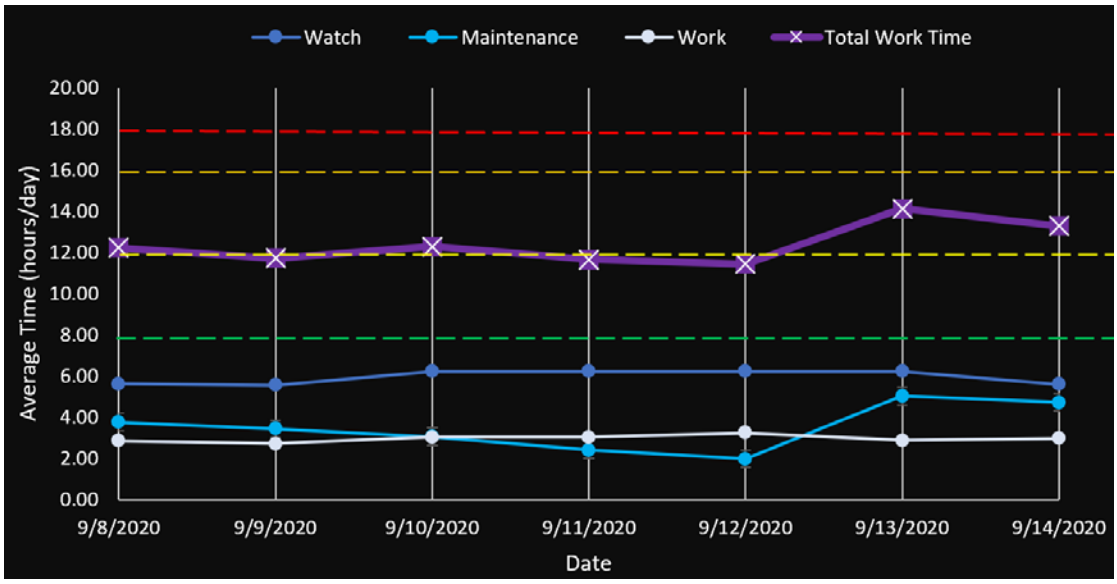


Figure 29. Initial Average Work Activity Trends

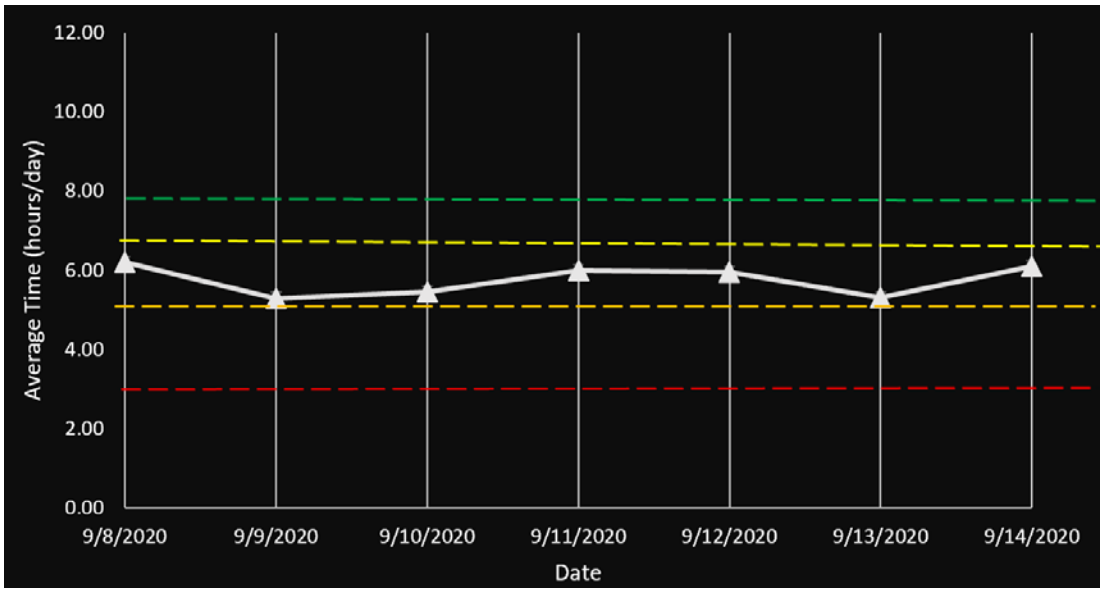
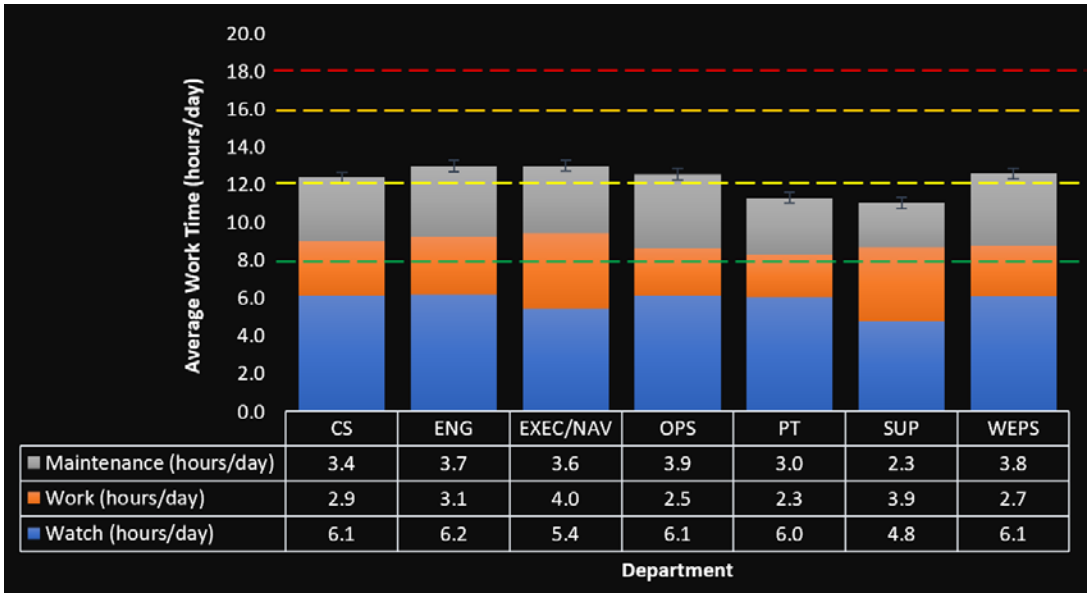


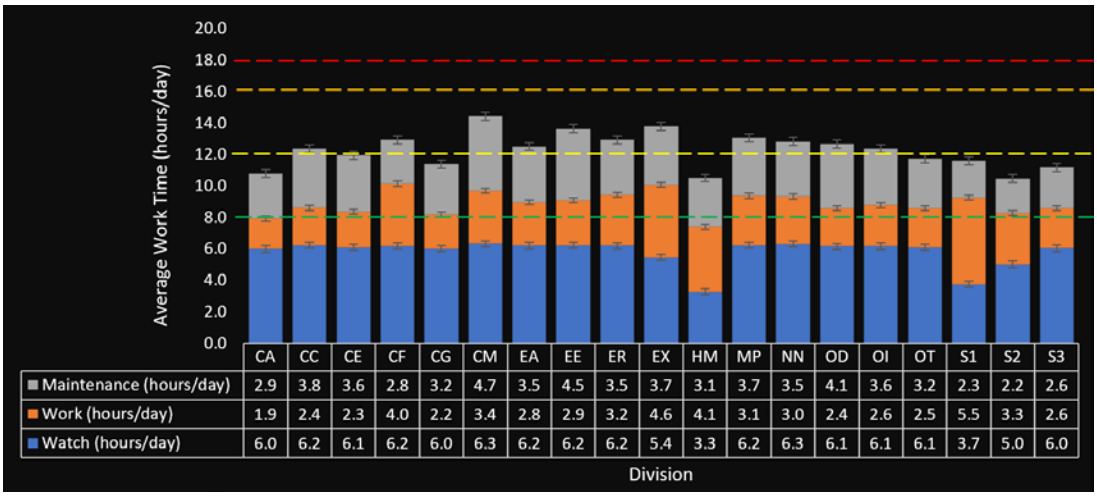
Figure 30. Initial Average Sleep/Rest Activity Trends

Figures 31 and 32 detail the average work activities by department and division. The error bars displayed on Figures 31 and 32 were based on the following standard error formula: Standard Error = Standard Deviation(Sampling Range) / Square Root(Count(Sampling Range)). The prototype was able to discern differences in the distribution of work activity averages between departments (Figure 31) and divisions (Figure 32). This functionality indicates the ability to measure how a Sailor's organizational affiliation can influence how much and what type of work they will perform. The SMART prototype allows for the quantification and comparison of workloads at varying organizational levels, adding credence to the "choose your rate, choose your fate" sentiment.



	CS	ENG	EXEC/NAV	OPS	PT	SUP	WEPS
Maintenance (hours/day)	3.4	3.7	3.6	3.9	3.0	2.3	3.8
Work (hours/day)	2.9	3.1	4.0	2.5	2.3	3.9	2.7
Watch (hours/day)	6.1	6.2	5.4	6.1	6.0	4.8	6.1

Figure 31. Initial Average Work Activity Times by Department



	CA	CC	CE	CF	CG	CM	EA	EE	ER	EX	HM	MP	NN	OD	OI	OT	S1	S2	S3
Maintenance (hours/day)	2.9	3.8	3.6	2.8	3.2	4.7	3.5	4.5	3.5	3.7	3.1	3.7	3.5	4.1	3.6	3.2	2.3	2.2	2.6
Work (hours/day)	1.9	2.4	2.3	4.0	2.2	3.4	2.8	2.9	3.2	4.6	4.1	3.1	3.0	2.4	2.6	2.5	5.5	3.3	2.6
Watch (hours/day)	6.0	6.2	6.1	6.2	6.0	6.3	6.2	6.2	6.2	5.4	3.3	6.2	6.3	6.1	6.1	6.1	3.7	5.0	6.0

Figure 32. Initial Average Work Activity Times by Division

The average sleep/rest times look relatively constant across departments with the supply and planning and tactics departments averaging the most sleep at 6.6 hours and 6.3 hours, respectively (Figure 33). Unfortunately, all departments and divisions fell below the National Sleep Foundation's recommended threshold of eight hours of sleep (Figures 33 and 34). Although the numbers do not speak to the quality of sleep or whether the individual was sleeping or just allotted time to sleep/rest, the data-driven graphics emphasize the chronic problem of inadequate sleep. The capability to sort activity information by organizational level provides leaders with the ability to pinpoint departments or divisions suffering from high workloads and insufficient sleep/rest time. This insight allows leaders to implement targeted crew resource management mitigations such as increasing training opportunities to produce more qualified personnel or requesting permanent or temporary personnel augmentation to reduce the strain of excessive workloads.

Figure 33. Initial Average Sleep/Rest Time by Department

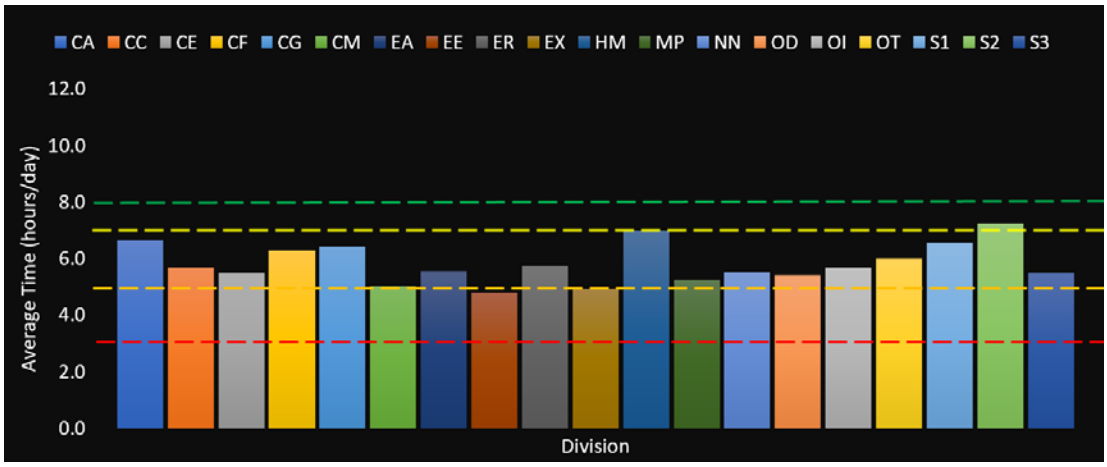
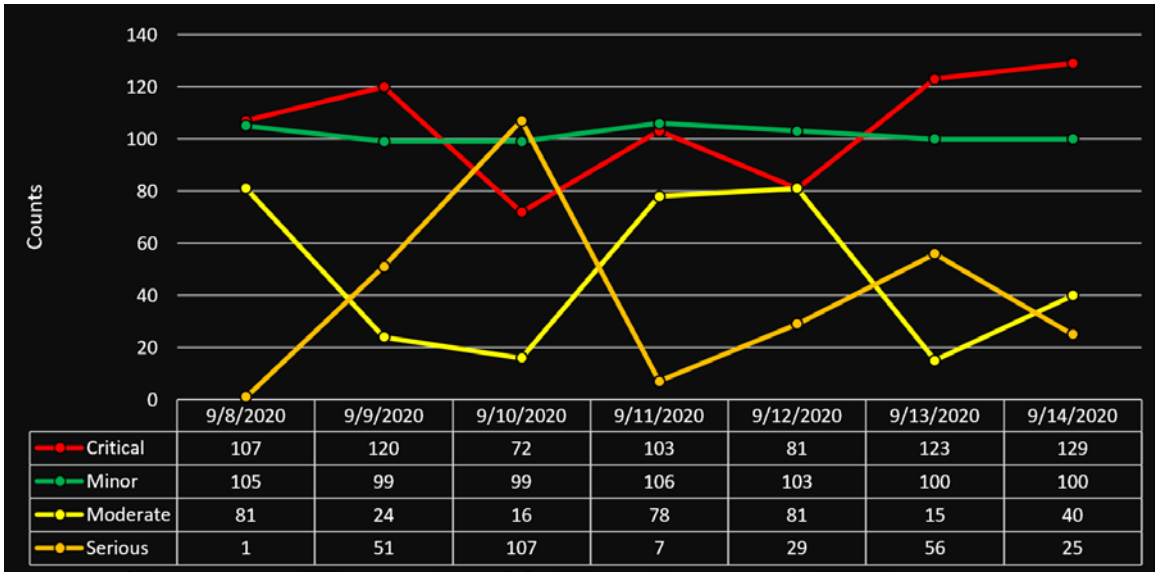


Figure 34. Initial Average Sleep/Rest Time by Division

The human performance risk, mainly in the moderate (yellow) and serious (orange) categories, associated with the crew's activity data greatly fluctuates throughout the study period (Figure 35). All best-case scenario individuals (n = 98) fall under the minor risk (green) category, while any additional minor risk individuals were from the mixed-case scenario group. Although an individual's shift from one risk category to another is not explicitly shown, users can gain a sense of magnitude and degree of change in human performance risk over time (Figure 35). It is concerning to observe the increasing number of critical risk individuals, especially towards the end of the study period which coincides

with a high-risk Sea and Anchor evolution (Figure 35). Figures 36 and 37 show the number of critical and serious risk individuals by organizational level. The majority of the critical risk individuals, 177, and serious risk individuals, 70, are from the Engineering Department followed by the Operations Department with 143 critical and 52 serious risk individuals (Figures 36 and 37). This insight facilitates greater understanding about the human performance risk trends throughout the study period. Moreover, the categorization and quantification of risk enables leaders to implement targeted human performance risk reduction actions.



	9/8/2020	9/9/2020	9/10/2020	9/11/2020	9/12/2020	9/13/2020	9/14/2020
Critical	107	120	72	103	81	123	129
Minor	105	99	99	106	103	100	100
Moderate	81	24	16	78	81	15	40
Serious	1	51	107	7	29	56	25

Figure 35. Initial Risk Level Trends

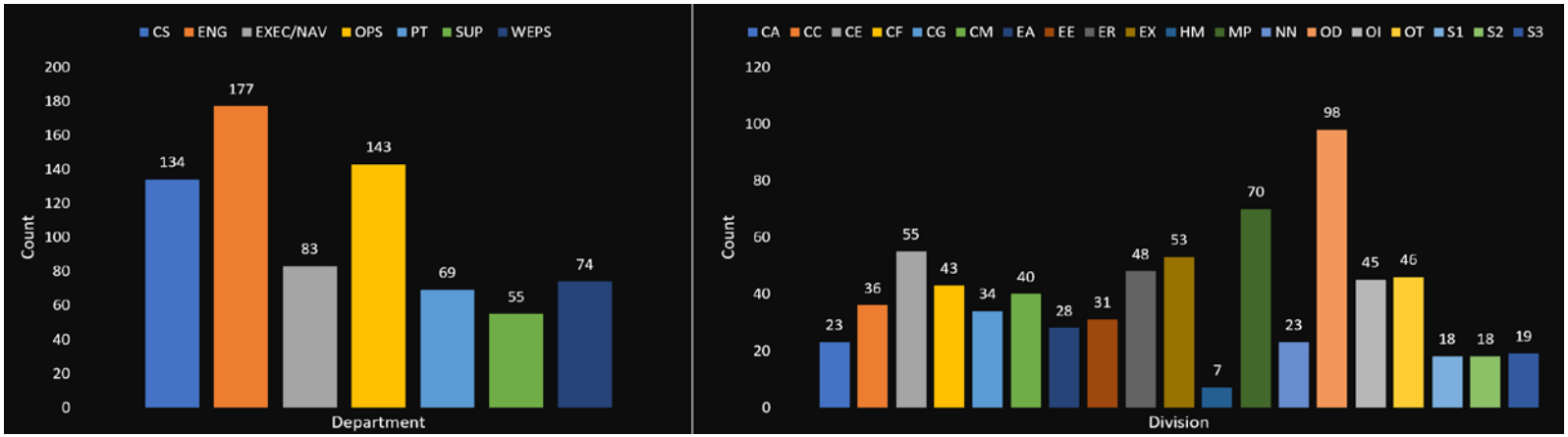


Figure 36. Number of Critical Risk Individuals by Department (left) and Division (right)

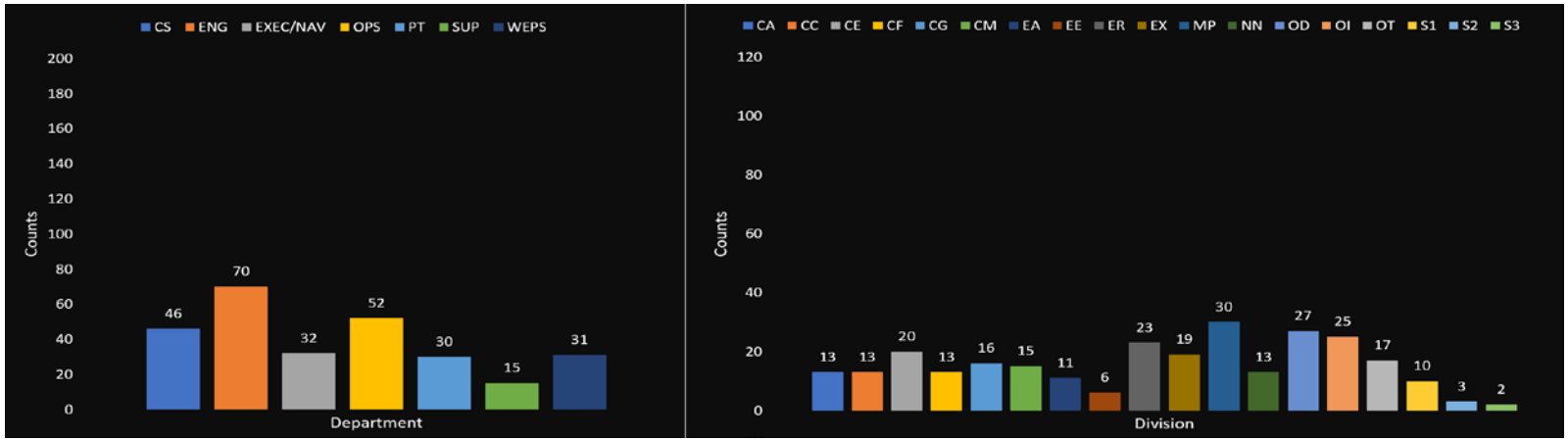


Figure 37. Number of Serious Risk Individuals by Department (left) and Division (right)

D. SENSITIVITY COMPARISON

The SMART prototype's initial results demonstrated its ability to process and display activity trends and human performance risk metrics. While the tool provides helpful information for assessing risk and managing crew resources, it is not without its limitations. The prototype's ability to illustrate the differences in magnitude for the best-case and worst-case individuals requires some refinement. This subsection showcases several instances where the prototype was not particularly sensitive to individuals operating in the extremes. These examples provide an overview of the starkly different prototype results based on an individual's case group classification.

Sailors in the best-case group received adequate sleep/rest opportunities (≥ 7 hours/day), low to moderate total work hours (≤ 8 hours/day), were in non-rotating watches, and stood watches with at least four watch sections. Sailors in the worst-case group received little to no sleep/rest opportunities (≤ 3 hours/day), high total work hours (≥ 16 hours/day), were in rotating watches, and stood watches with no more than three watch sections. Sailors in the mixed case group received a range of sleep/rest opportunities (0 - 12.25 hours/day) and total work hours (7.5 - 21 hours/day), were assigned fixed and rotating watches, and were in various sized watch sections (1 – 5 sections). The prototype only categorizes people based on their risk value score or risk rating category; it does not separate individuals into best, worst, and mixed case groups. Partitioning individuals into these case groups was an artificially induced event meant to test the sensitivity of the prototype.

The average work activity trend comparisons show that the best-case group deflated the average work time increases from the mixed and worst-case groups. (Figure 38). There were no total work time instances which exceeded the 16-hour recommended threshold compared to three instances each for the mixed (September 10, 13, and 14) and worst-case (September 8, 13, and 14) groups (Figure 38). Unless the user filtered their results appropriately, they may not see these troubling spikes in total work times. The comparisons also indicate that the fluctuations in maintenance hours were substantial contributors to increasing total work times for the mixed and worst-case groups, which is reflected by the

initial output (Figure 38). Figure 38 also shows that the pattern of relatively static amounts of watch hours throughout the data collection period holds true for all case groups and is reflected by the initial output.

The SMART prototype was also not particularly sensitive to the extremely high and extremely low levels of sleep/rest opportunities between the best and worst-case groups, respectively (Figure 29). One of the most concerning observations was that the worst-case group averaged three or fewer hours of sleep/rest time during the entire data collection period (Figure 29). Despite the shocking trend of all those individuals operating in the red, there were no instances where the average dipped below five hours in the initial output (Figure 29). The eight or more hours of sleep/rest time from the best-case group dampened the prototype's ability to reflect the increased risk the worst-case group was experiencing. Interestingly, the activity average oscillations observed within the mixed-case group output are reflected in the initial output as seen in the dips on September 9, 10, and 13 (Figure 29).

The SMART prototype's average metric may provide misleading results, especially in cases where comparatively equal proportions of the crew are operating on extremes of the activity spectrum. Perhaps a minimum and maximum trend analysis would provide more context to the average results currently displayed and could be incorporated into the next version of the prototype. This sensitivity limitation demonstrates that great care should always be taken when interpreting these results. Fortunately, users have the ability to analyze the summarized results in the Activity Summary tab to provide additional context to the average activity outputs. While individuals operating in the serious or critical risk categories may not be readily apparent in the activity trends outputs, they are easily identifiable in the Risk List and Risk Charts tabs. Users are not only able to track the number of people at each risk category (Figure 40), but they are also able to filter that information based on organizational level (e.g., department, division, or individual) and identify specific individuals based on their risk value or risk category rating. Additional initial versus case comparison figures are available in Appendix E for reference.

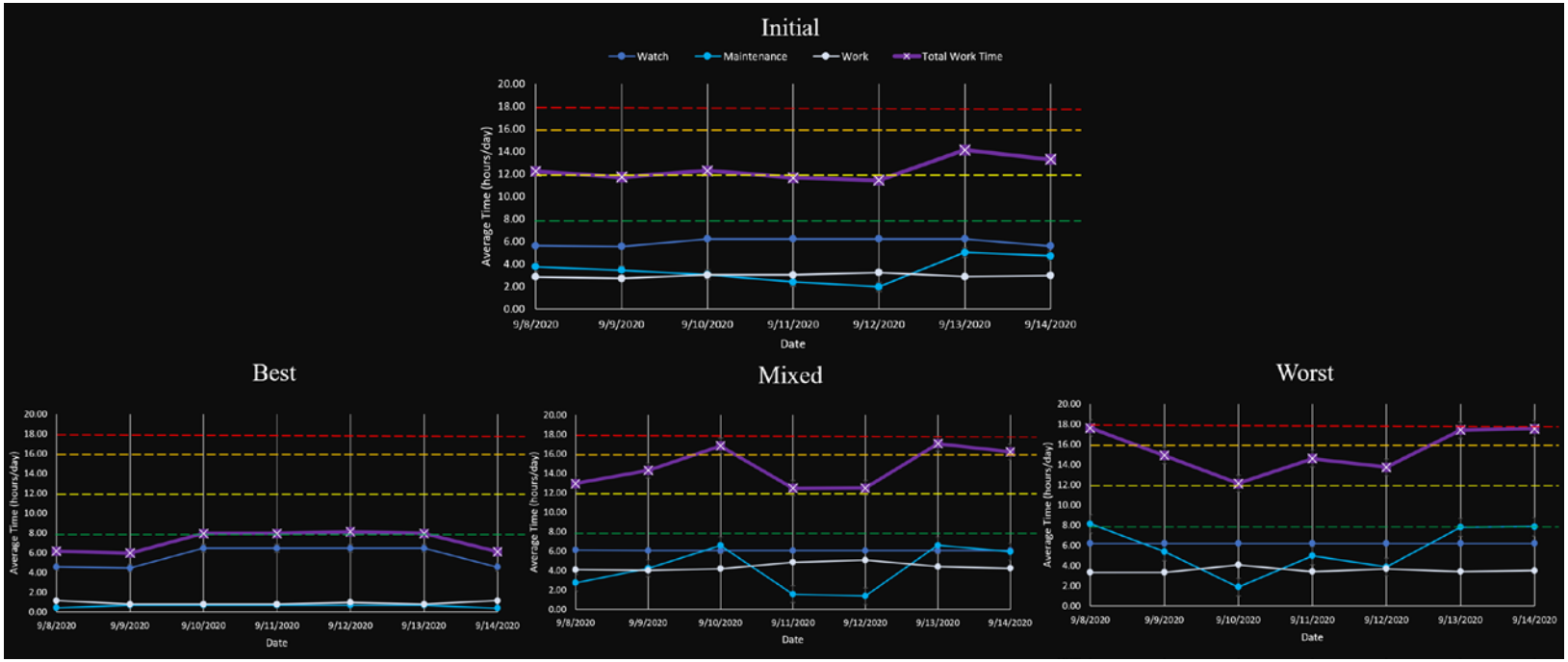


Figure 38. Initial versus Case Comparisons for Average Work Activity Trends

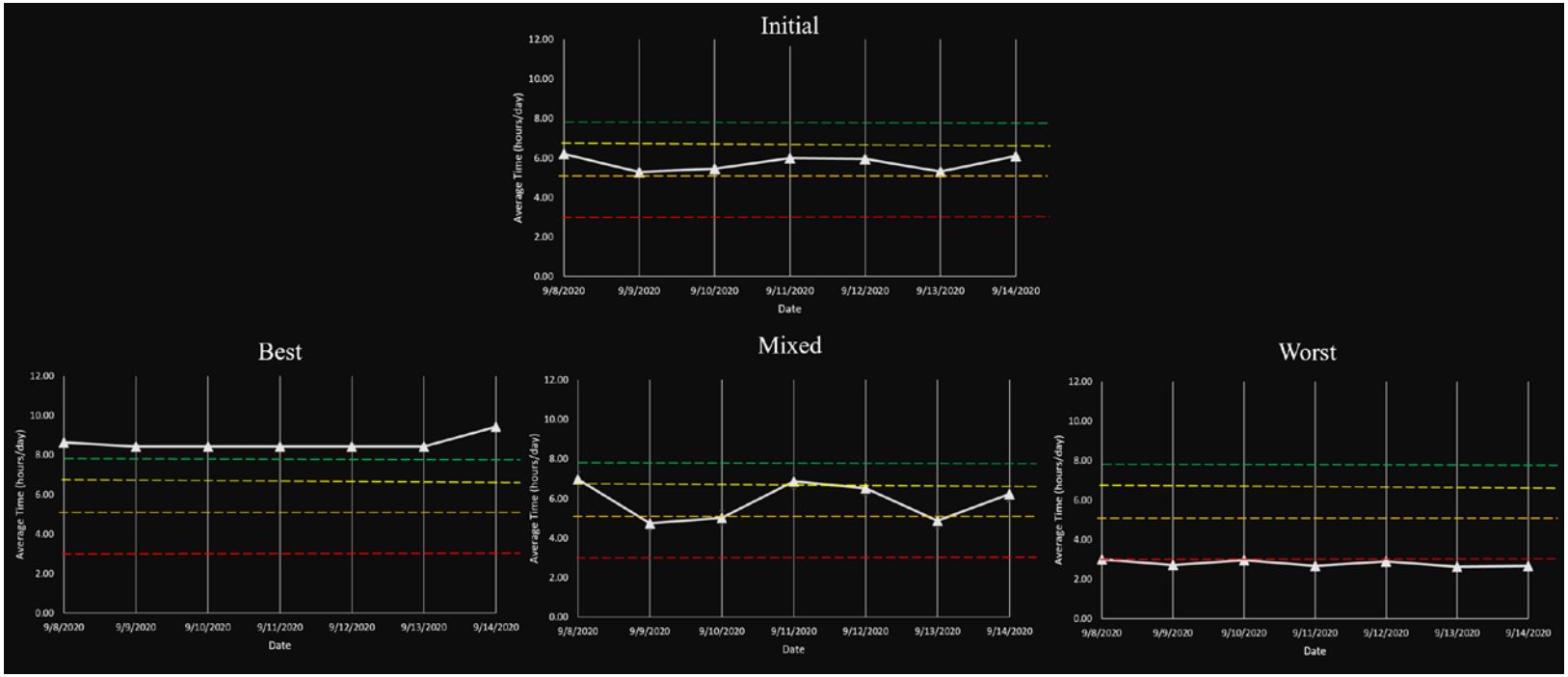


Figure 39. Initial versus Case Comparisons for Average Sleep/Rest Activity Trends

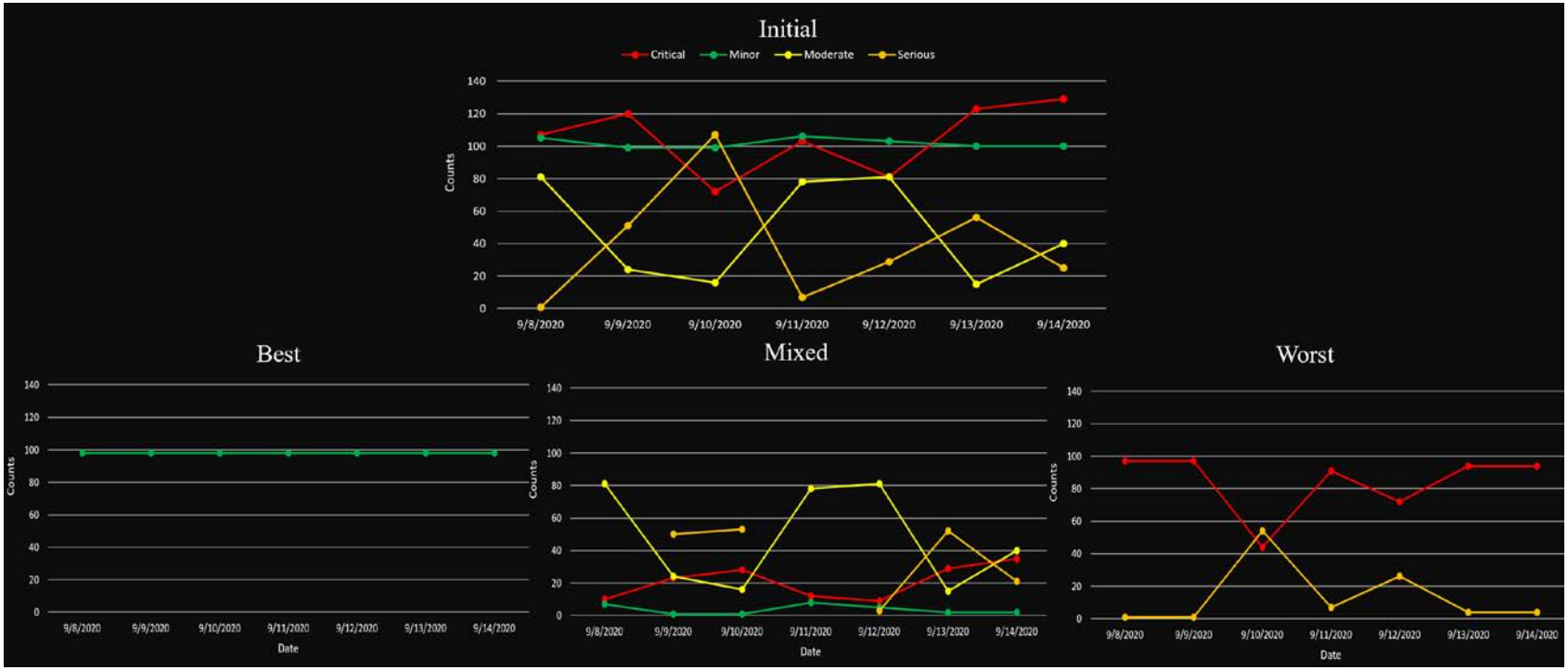


Figure 40. Initial versus Case Comparisons for Risk Trends

E. OUTPUT TO SPECIFIED SCENARIOS

1. Sea and Anchor Watchbill Human Performance Risk Assessment

The Sea and Anchor (S & A) watchbill assessment involves the review of several prototype outputs and scheduling considerations. For the prototype evaluation purposes, the user will be the Operations Officer (OPSO), a department head, looking to assess the human performance risk within a proposed inbound S & A watchbill scheduled for September 14th. OPSO would select the period of interest, September 8–13, and Operations Department (Figure 41). September 14th was excluded because the data has yet to be populated for the purposes of this scenario. The OD and OI divisions will be automatically selected since they belong to the Operations Department (Figure 41).

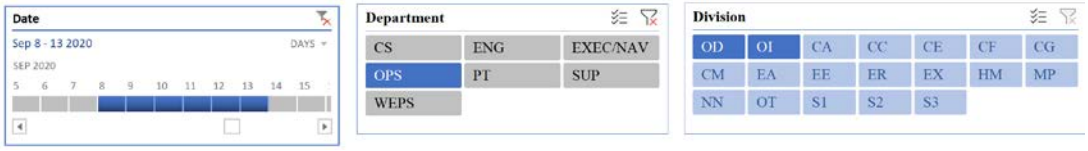
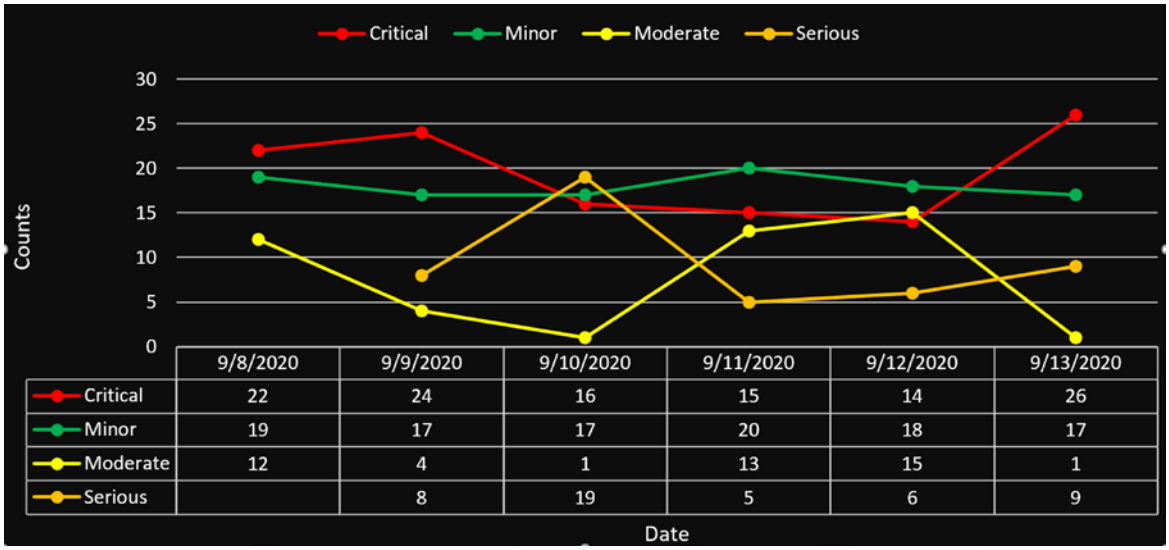


Figure 41. Operations Department Filter Selections for Sea and Anchor Watchbill Evaluation

The resulting outputs, Figures 42 through 44, can provide the user with several insights to base their watchbill evaluation upon. Figure 42 shows that there are 26 critical, 9 serious, 1 moderate, and 17 minor risk departmental personnel listed under September 13th, one day prior to the high-risk S & A evolution. OPS can find the names of all critical risk individuals to compare against the departmental personnel listed on the proposed watchbill to assess how many personnel may require intervention (Figure 43). The moderate (yellow) and serious (orange) human performance risk associated with the department's activity data fluctuated greatly throughout the data collection period (Figure 42). While the numbers of minor (green) risk individuals remained comparatively steady, the number of critical (red) risk individuals spike on September 13th (Figure 42). This is an especially concerning trend for the OPSO to note since many of his or her Sailors are involved in this evolution. Members from the OD division are particularly susceptible to

more serious physical injuries due to their proximity to heavy equipment or tensioned lines during the S & A evolution.

Based on that risk information displayed by the prototype, OPSO can implement several interventions to mitigate human performance risk for his or her personnel. Three possible interventions would be to adjust the Sailor's schedule to include more time for rest prior to the following day's evolution, assign another safety observer at that particular watch station location, or to substitute the critical risk watch stander with another qualified lower-risk individual. The latter intervention is facilitated by the minor risk filtered list prototype output from the Risk List dashboard, which shows 17 potential candidates for substitution (Figure 44). The Operations Department filtered average activity trends (Figures 55 and 56) were not directly relevant to this assessment but are available in Appendix E for reference.



	9/8/2020	9/9/2020	9/10/2020	9/11/2020	9/12/2020	9/13/2020
Critical	22	24	16	15	14	26
Minor	19	17	17	20	18	17
Moderate	12	4	1	13	15	1
Serious		8	19	5	6	9

Figure 42. Operations Department Filtered Risk Level Trends from September 8–13, 2020

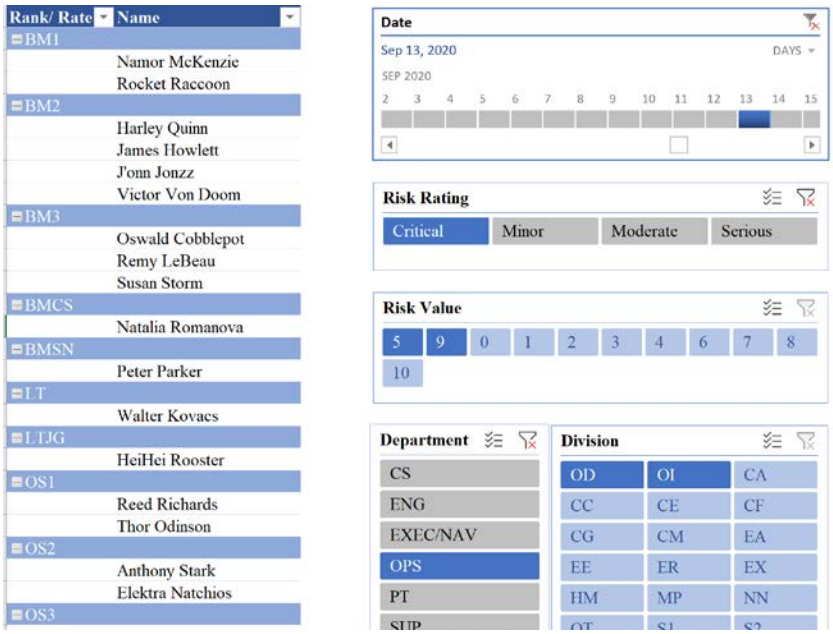


Figure 43. Critical Risk Listing of Operations Department Individuals from September 13

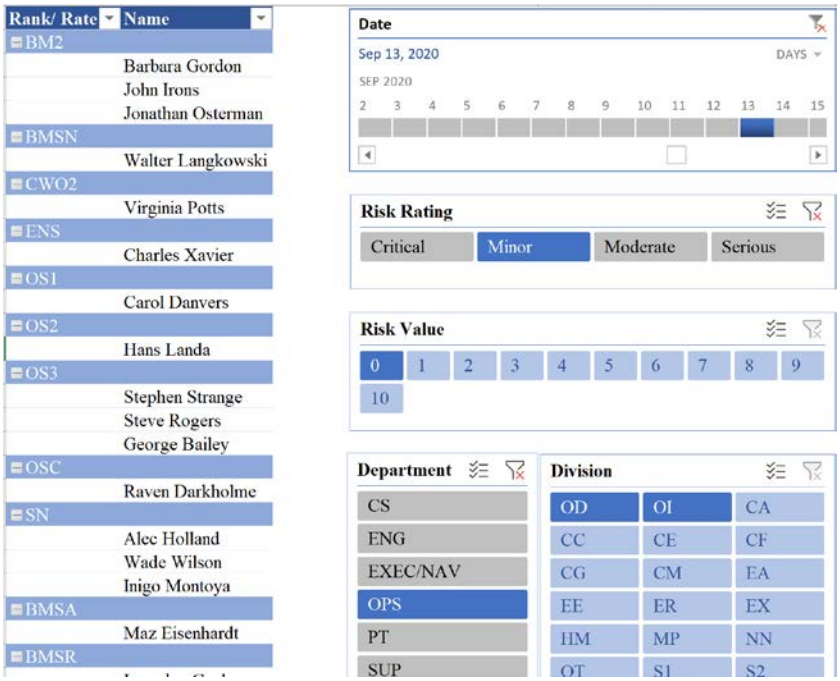


Figure 44. Minor/Negligible Risk Listing of Operations Department Individuals from September 13

2. Divisional Activity and Human Performance Risk Assessments

For the next example, the users will be the divisional leadership of the CM division. The Strike Officer (STRIKE) leads the CM division which is comprised of Fire Control Technicians (FCs). FCs operate and maintain the Tactical Tomahawk Weapons Systems integral to supporting Strike Warfare (STW) missions. The divisional leadership's goals are to perform an activity time review and human performance risk assessment for their entire division spanning the whole study period (Table 21). First, the users would select the period of interest, September 8–14, 2020, and the CM division from the available filters. The resulting outputs, Figures 45 through 49 can provide the users with useful information to base their assessments on.

Table 21. Weapons Department CM Division Members

Rank/Rate	Name	Job Title	Type
ENS	Mildred Burke	STRIKE	Officer
FCC	Sara Del Rey	LCPO	Enlisted
FC1	Jake Roberts	LPO	Enlisted
FC1	John Cena	WCS	Enlisted
FC2	Akira Hokuto		Enlisted
FC2	Mickie Foley		Enlisted
FC2	Shawn Michaels		Enlisted
FC3	Chris Jericho		Enlisted
FC1	Judy Grable		Enlisted
FC1	Kurt Angle		Enlisted
FC2	Randy Savage		Enlisted
FC1	Ima Sailor		Enlisted
FC2	Davy Jones		Enlisted
FC3	Ono Goose		Enlisted

Figure 45 shows that the division averaged 12 hours of total work with a noticeable spike in maintenance hours on September 13th. This increase may be associated with a faulty system requiring repair or greater than normal periodic maintenance requirements. A Work Center Supervisor (WCS) can utilize the information from Figures 45 and 46 to better inform their maintenance planning schedules in the future by distributing maintenance hours more evenly throughout the work week. A comparison of work activity

averages shows that the CM division completes more maintenance and work hours when compared to another Weapons Department division (Figure 46). This observation may be useful in determining the proportion of divisional personnel that should be allocated for work details or for the assignment of additional tasking.

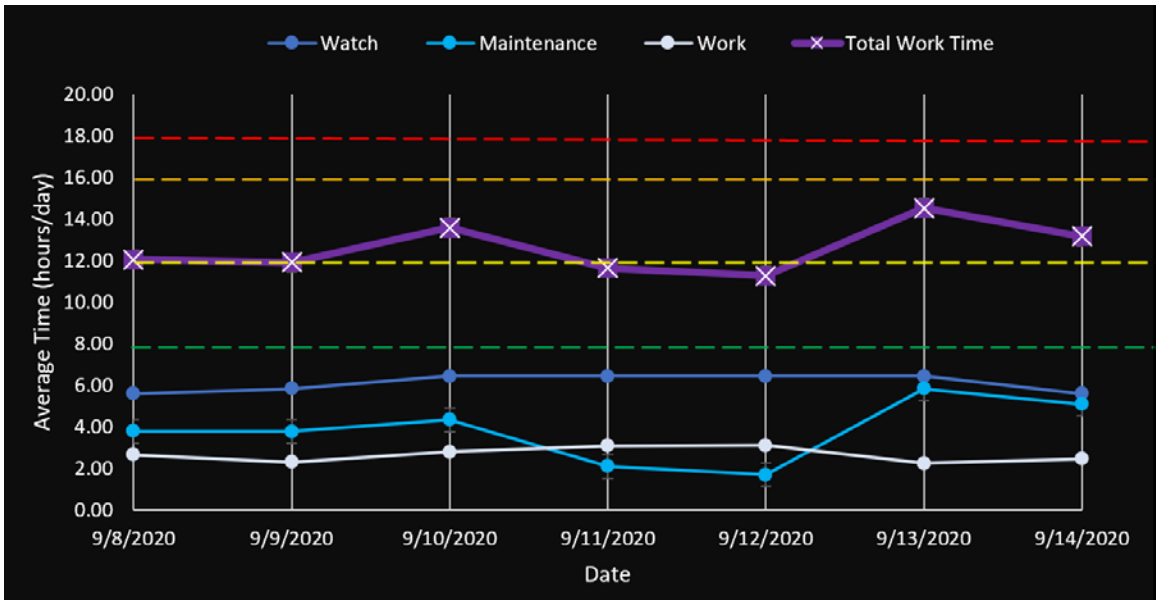


Figure 45. CM Division Filtered Risk Work Activity Trends from September 8–14, 2020

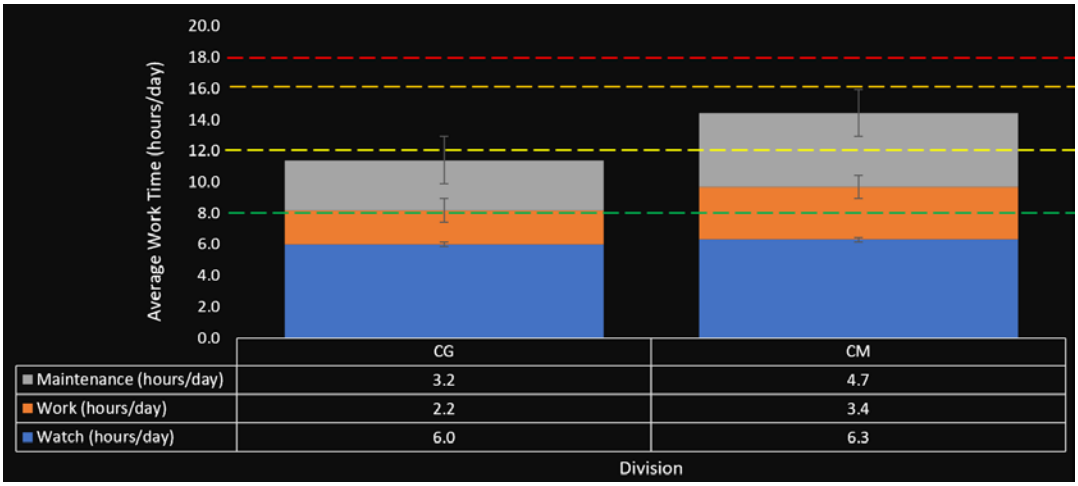


Figure 46. Weapons Department Filtered Average Work Activity Times

The CM division appears to be getting consistent amounts of sleep/rest opportunities but is still operating below the recommended NSF standard of eight hours (Figure 47). Additionally, the CM division is consistently getting less sleep/rest opportunities, approximately one hour less, when compared to CG division (Figure 48). Research has shown that operating at sustained levels of sleep debt has detrimental effects on human performance and increases human performance risk (Shattuck et al., 2014; Shattuck & Matsangas, 2016; Belenky et al., 2003). A significant proportion of the division was assessed as operating at critical to moderate risk, with large fluctuations in risk levels, throughout the data collection period (Figure 49). Divisional leadership can use this information to implement steps to increase sleep/rest opportunities for their Sailors to mitigate for these human performance risks.

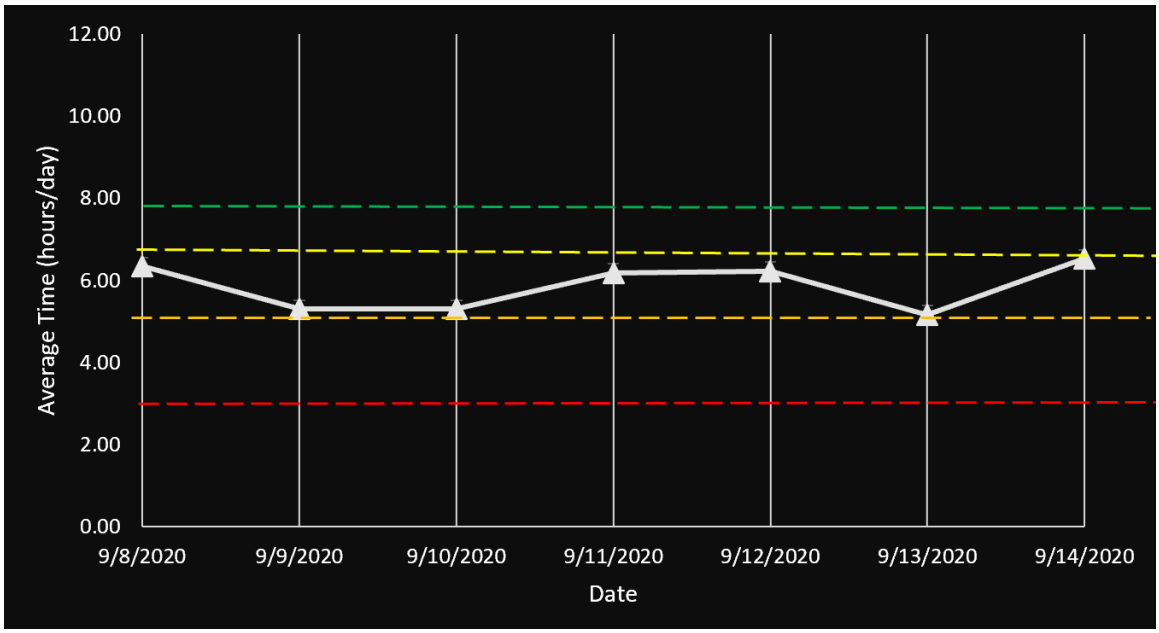


Figure 47. CM Division Filtered Risk Work Activity Trends from September 8–14, 2020

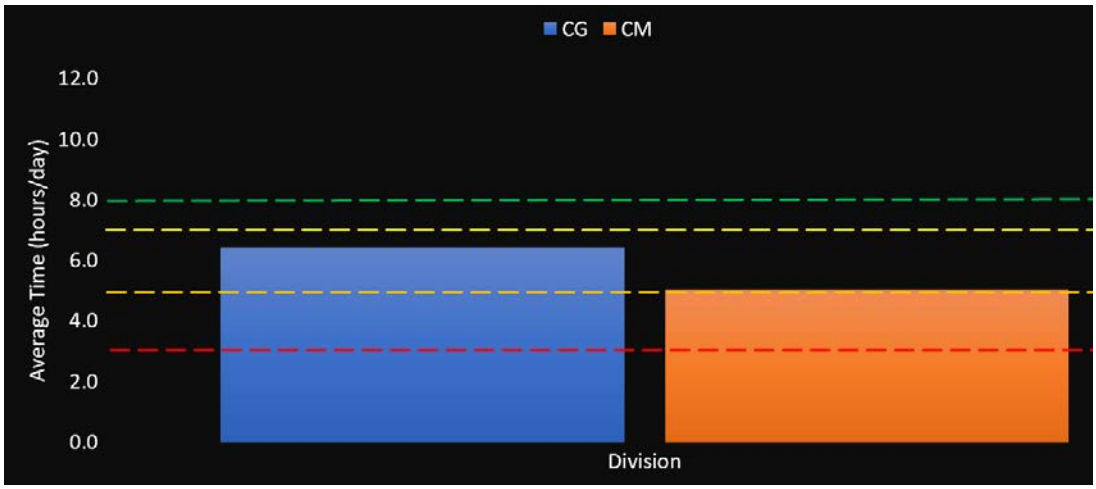
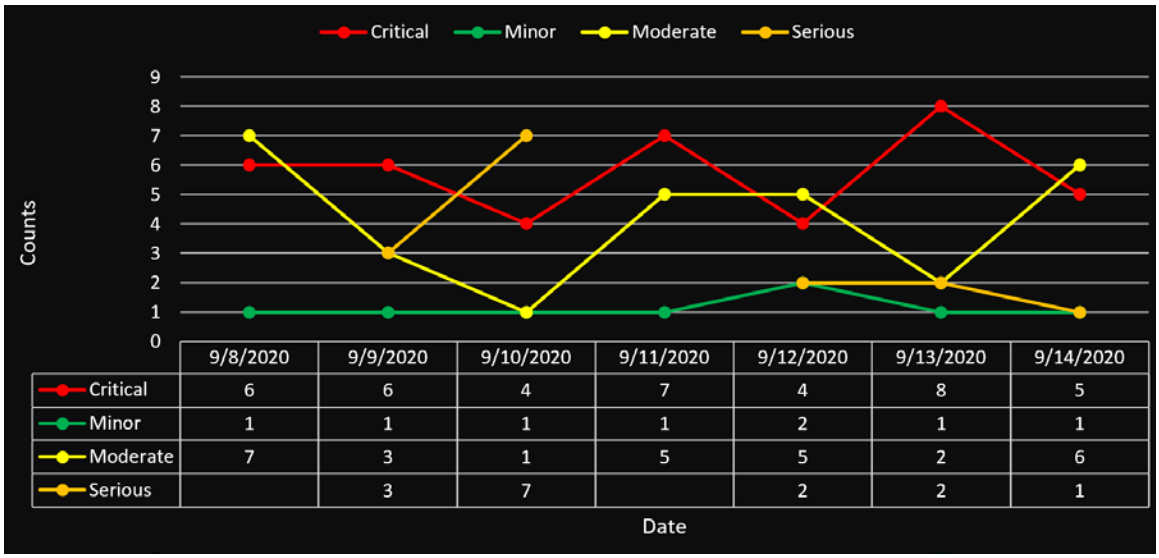


Figure 48. Weapons Department Filtered Average Sleep/Rest Activity Times



	9/8/2020	9/9/2020	9/10/2020	9/11/2020	9/12/2020	9/13/2020	9/14/2020
Critical	6	6	4	7	4	8	5
Minor	1	1	1	1	2	1	1
Moderate	7	3	1	5	5	2	6
Serious		3	7		2	2	1

Figure 49. CM Division Filtered Risk Level Trends

3. Critical Billet Holder and Individual Tracking

The next scenario is a human performance risk and readiness evaluation of a Search and Rescue (SAR) swimmer, a critical billet holder. Ships are required to have "properly equipped Search and Rescue Swimmers" (DON, 2011, p. 2). Failing to meet the requirement of having two SAR swimmers onboard is considered a redline, defined as a "personnel or equipment standard that must be met before a ship can safely get or remain

underway" (DON, 2011, p. 2). While decision makers considered factors such as the currency of the SAR swimmer's qualification and their demonstrated proficiency, they did not have a way of assessing human performance risk based on their historical activity data.

First, the user filters their selection for a specific individual, such as the fictional character of Harley Quinn (Figure 50). The dynamic nature of the prototype's filter selections automatically shows the individual's organizational affiliation, Operations Department in OD division (Figure 50). The Sailor's work and sleep/rest activity averages wildly fluctuate throughout the data collection period (Figures 50). The work activity averages ranged from 11 to 18-hour total workdays where the Sailor worked three, 18-hour days during the week (Figure 50). While the Sailor averaged six hours of sleep/rest opportunity for the week, it was largely inconsistent and prone to substantial downturns or upticks (Figure 50). The erratic activity patterns elevated the Sailor's human performance risk scores to critical on September 9th and 13th; both days coincided with high total work hours and low sleep/rest hours (Figure 50). There could have been substantial risk involved if the SAR swimmer were deployed for a rescue mission during those two days. Risks could include injury to the SAR swimmer, potential loss of a critical billet holder, or the failure to safely rescue someone. With the information presented by the SMART prototype, users would be made aware of those potential risks. Decision makers could then make data-driven and risk-informed decisions like deploying the other rescue swimmer if needed.

For the last example, a Chief Petty Officer wants to nominate Ima Sailor for an award while collecting inputs for their Sailor's evaluation report. Activity summaries for Ima Sailor show that she worked an average of 15.36 hours during the week and worked three 18-hour days (Figure 52). Those three days may have coincided with emergent repairs for a critical system or her taking on extra maintenance responsibilities which would be positive points. The review also revealed Ima Sailor's chronic pattern of inadequate sleep, three or fewer hours per day (Figure 52) and consistent operation in the critical risk zone (Figure 53). Now that the Chief is aware of that information, he or she can work with their Sailor to ensure adequate rest opportunities and find ways to reduce their workload.

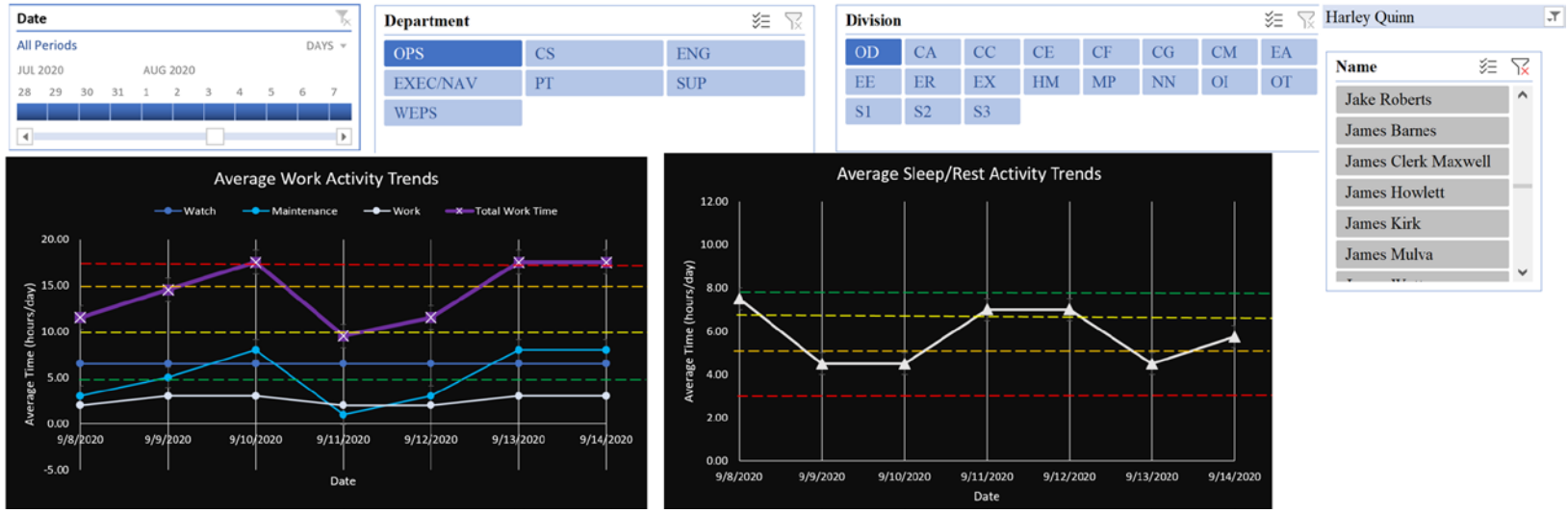


Figure 50. Average Activity Dashboard for the Search and Rescue Swimmer

0	9/8/2020	9/9/2020	9/10/2020	9/11/2020	9/12/2020	9/13/2020	9/14/2020
Critical		1				1	
Minor	1			1	1		
Moderate							1
Serious			1				

Date

Figure 51. Risk Rating Trends for Search and Rescue Swimmer

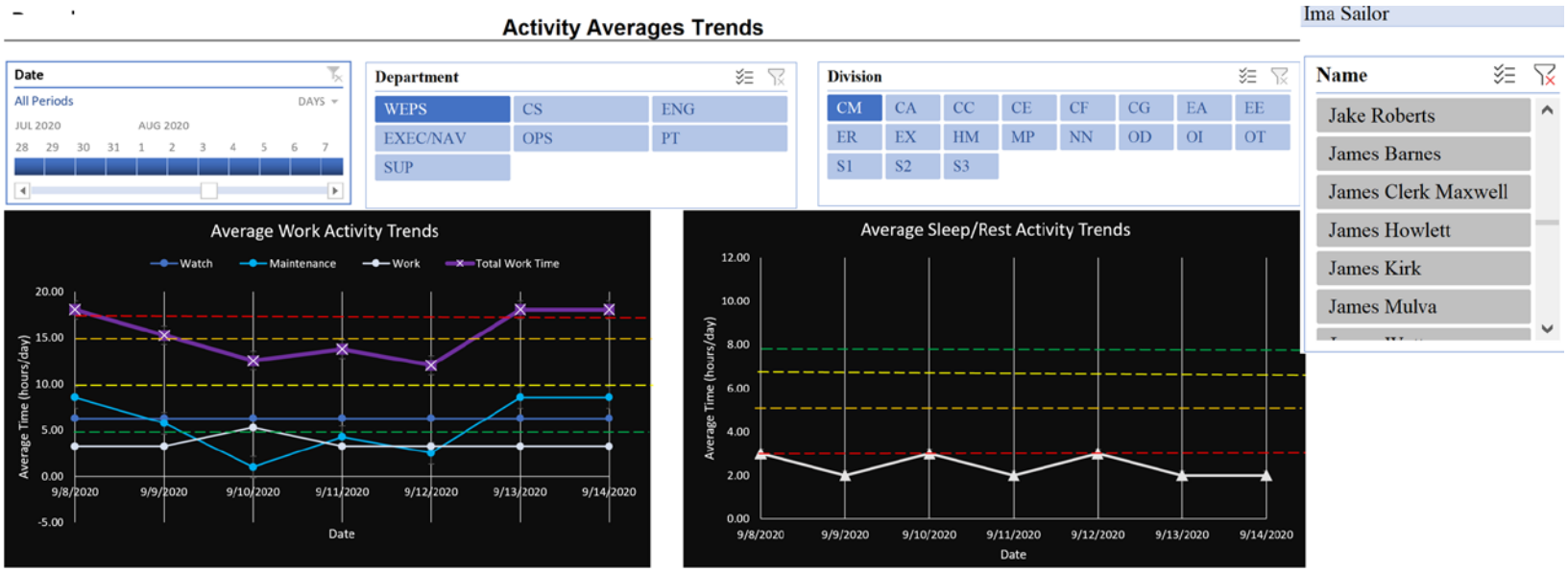
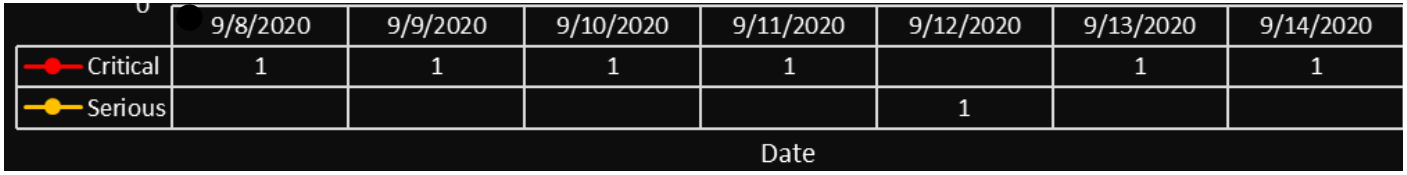


Figure 52. Average Activity Trends Dashboard for Individual Tracking



	9/8/2020	9/9/2020	9/10/2020	9/11/2020	9/12/2020	9/13/2020	9/14/2020
Critical	1	1	1	1		1	1
Serious					1		

Date

Figure 53. Risk Rating Trends for Individual Tracking

Despite the use of notional data for analysis, the SMART prototype demonstrated the capability of highlighting and quantifying human performance risk associated with work/rest activity data. While the SMART tool does not provide explicit recommendations for reducing risk, it begins to bridge the gap between intuitive and data-driven decision making. The illustrative examples were just a sampling of insights that could be gleaned from utilizing this prototype. The SMART tool showcased tangible ways to support the warfighter through data-driven decision making and risk management.

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V. DISCUSSION

The objective of this thesis was to create a prototype tracking tool capable of systematically assessing human performance risk associated with a Sailor's work and rest activities. This thesis produced a prototype tool in Excel and described how it can be used to highlight work/rest activity trends and provide users with activity-based human performance risk assessments. The prototype outputs can equip decision makers with a data-driven means for mitigating fatigue while developing judicious watchbills and work schedules. Moreover, COs can now have a methodical way of evaluating human performance risk to maximize crew resilience and improve warfighter performance. Commands can tailor this decision aid to address their own specific requirements and organizational structure while maintaining the underlying functionality of the tool. This chapter discusses some of the study limitations and insights gained during the tool development process.

A. LESSONS LEARNED AND DEVELOPMENT OBSERVATIONS

Modeling the notional data after historical watchbills was helpful in providing realism to the work/rest activity data; however, it also posed three major alignment challenges. First, there were several instances where watchstanders were assigned multiple watches during the same period. Multiple assignments made it difficult to accurately account for an individual's work times because it was unknown whether their other watches were activated and when they were activated. Second, there were other instances where watchstanders were assigned overlapping or concurrent watches during the same period which made accounting for an individual's cumulative watch hours challenging. Third, the sleep and maintenance times were used to round out a notional crew member's day but were not based on sleep/maintenance data from an actual ship. Instead of performing a direct comparison between actual and notional crew members and their schedules, the activity data population process was modified to ensure an adequate sampling for each study group.

Developing prototype functions and outputs with limited user feedback was challenging due to the need to deduce which functions and features users would find beneficial. This underscored the benefits of iterative development with consistent user feedback built-in to the process. Future prototype testing would be invaluable in improving the overall functionality of the tool to ensure that the outputs enable users to better assess human performance risk and implement more efficient crew resource management actions.

B. STUDY LIMITATIONS

This study and the prototype itself have several limitations to include the creation and application of the risk mitigation heuristics, the use of notional data to demonstrate the prototype, and the reliance on self-reported activity data to populate the spreadsheets.

First, the heuristics selected to track, detect, and quantify human performance risk are by no means a comprehensive listing. The default numerical thresholds chosen were based on a mixture of policy guidelines and scientific findings. They would benefit from operational validation studies. Developing human performance risk heuristics was particularly perplexing because of the many factors that influence human performance. Currently, the prototype does not incorporate a host of known human performance risk factors such as breaks between working periods (Folkard et al., 2007; Tucker et al., 2003; Tucker et al., 2006), cumulative sleep debt (Shattuck et al., 2014; Shattuck & Matsangas, 2016; Belenky et al., 2003), presence and effects of sleep disorders (Shattuck & Matsangas, 2019), use of stimulants e.g., caffeine and energy drinks (Lim & Dinges, 2008; Darwent et al., 2015), and circadian rhythms (Shattuck et al., 2018; Shattuck & Matsangas, 2016; Miller et al., 2007; Miller & Eddy, 2008; Mysliwiec et al., 2016). Moreover, identifying conclusive human performance activity thresholds specifically targeted towards the surface combatant community was challenging. Utilizing Excel to model complex heuristics and multifaceted human performance factors interactions also posed a considerable modelling challenge. Even though wake/rest activity times are available in the prototype, accounting for inconsistent sleep/wake rhythms and sleep fragmentation (Gonçalves et al., 2015) may be beyond the capability of the software. This limitation may constrain the human performance factors and relationships that can be incorporated within the prototype in the

future. With that said, the selected heuristics and their application do begin to address the fatigue and rest management issues cited in the *Comprehensive Review* as attributable causes for the mishaps (DON, 2017).

Second, the data used to test this prototype are notional and may not be representative of actual operational scenarios. While the notional data were based on a typical DDG crew complement, the number of individuals and the proportions between departments and divisions are subject to change. The notional watch and work times were based on historical watchbills and are expected to fluctuate depending on the platform, ship, or command. Moreover, the total work hours, maintenance hours, sleep/rest hours, watch rotation types, and number of watch sections were deliberately manipulated to illustrate best-case, mixed-case, and worst-case scenarios outlined in the Methodology chapter (Table 18). The notional crew and activity data will almost certainly not be representative of the entire fleet; the prototype outputs are not meant to represent any actual crews; consequently, they do not allow for direct comparisons.

Lastly, the outputs are based on self-reported activity data and are subject to bias. This bias could be addressed using wearable physiological monitoring devices or mobile applications to replace or verify the self-reported activity data (O'Connor & Patillo, 2003). Users may fail to record their activity data or over/underinflate their activity hours. Additionally, if the entire crew does not participate, those individuals who actively use the tool may not be representative of the crew, thereby leading to misleading results.

C. INSIGHTS

The coronavirus pandemic necessitated many changes to typical military operations. This current prototype can offer insight into how the pandemic has impacted already strained operational schedules and individual workloads. Additionally, the information on work/rest activities collected in this prototype could reduce the gap in current human performance risk analyses and enrich fatigue models tailored to the military maritime environment. The activity data can also be used to illustrate the disparity between the activity hours allocated versus the activity hours performed in manpower models to significantly influence manning decisions. With the prototype complete, we have the

opportunity to develop the SMART further, validate it by comparing it to commercially available software such as OWL FM or FAST, or potentially update software like RADM to include similar functionality.

VI. RECOMMENDATIONS

This chapter contains recommendations for future research and future prototype development ideas. With the prototype complete, the U.S. Navy can choose to develop the SMART further, field commercially available software (e.g., OWL FM or FAST), update software like RADM to include similar functionality, or include surface combatant-specific human performance risk factors into fatigue or sleep models like SAFTE.

A. FUTURE RESEARCH RECOMMENDATIONS

1. Test Prototype

The major next step for this prototype is to test it onboard ships and solicit user feedback mainly in the areas of usability, feasibility, and acceptability. Usability is defined as "a quality attribute that assesses how easy user interfaces are to use" and also "refers to methods for improving ease-of-use during the design process" (Nielsen, 2012, para. 1). Assessing the usability elements of learnability, efficiency, memorability, software and operator errors, and user satisfaction would improve the tool's functionality and utility for the users (Nielsen, 2012). Evaluating the prototype's feasibility should involve an analysis of the tool's practicality and how it could be integrated for regular use onboard ships (Bowen et al., 2009). Acceptability "refers to determining how well an intervention will be received by the target population and the extent to which the new intervention or its components might meet the needs of the target population and organizational setting" (Ayala & Elder, 2011, p. 1). For the study's purposes, the use of the prototype would be considered the intervention. Use of focus groups and stakeholder interviews during the acceptability assessment phase would reduce the risk of rejection by the target population (Ayala & Elder, 2011) so the tool can be used to collect data for additional human performance risk studies and workload metrics tracking.

Along the same vein, conducting a tradeoff analysis between minimizing the data entry burden and producing worthwhile outputs would contribute to the future success of this tool. Investigating the feasibility of incorporating wearable activity monitoring devices would allow for objective activity data collection and reduce the burden of data entry.

Changes to the output should be targeted toward helping Sailors work more efficiently and safely through the incorporation of risk-conscious planning practices. Determining which activity categories, metrics, and visualizations enable users to better assess human performance risk and implement more efficient crew resource management actions would be key to this effort. Moreover, gathering stakeholder feedback would assist in improving the heuristics and functionality of the tool.

2. Improve Heuristics

As mentioned in the study limitations section (p. 47), the selected activity thresholds were by no means a comprehensive listing of human performance risk factors. Given that there are many factors that influence human performance, finding ways to include additional human performance risk factors in a meaningful way would greatly improve the prototype's outputs. Bridging the human performance risk data gap for surface combatants could clarify the relationships between certain activity thresholds like cumulative sleep and work times to offer new insight into heuristic improvements. Researching the interplay between human performance risk factors and the extent to which they influence surface combatants would also enrich the tool's ability to assess human performance risk onboard ships. The current risk evaluation structure is based on summative values which may not be an accurate predictor of the risks Sailors face at sea.

3. Assess Operational Utility

Lastly, research should be devoted to assessing the operational utility of the prototype. The evaluation process could investigate whether the outputs of the prototype result in improved crew resource management decisions or fatigue management actions. The data from this research could reveal whether schedulers are more aware of risk when planning or scheduling personnel for evolutions. In addition, researchers could assess if the use of the prototype, in conjunction with other risk mitigation actions, results in a reduction of mishap occurrences, an increase in worker productivity and efficiency, or an improvement in combat effectiveness.

B. FUTURE DEVELOPMENT RECOMMENDATIONS

The SMART prototype offers four distinct advantages. The prototype's scalable data structure allows for its use on various ship platforms or shore-based organizations. Second, the prototype is readily available at no additional cost onboard ships and at shore installations. Third, the prototype does not require network connectivity, which is restricted during certain operations. Lastly, the prototype does not require the use of accessory devices such as cellphones or activity watches/monitors. Despite these advantages, there are still areas for improvement. Some of these ideas are listed below.

1. Auto-populate Activity Data

Developing a way to auto-populate activity data from existing databases like RADM or SKED would reduce the administrative burden of manual data entry and streamline the data collection process. Another way to decrease the data entry burden could be addressed by issuing physiological monitoring devices or mobile applications to support the self-reported activity data (O'Connor & Patillo, 2003). The current data collection scheme has the potential to be labor-intensive and may discourage users from adopting this tool into their risk mitigation and planning practices.

2. Watchbill Functionality

Incorporating certain watchbill-related functions into this tool could potentially make it a centralized place for personnel scheduling functions. Functions such as adding watch station, watch section, qualification, and projected rotation date (PRD) tracking would have many potential benefits. First, PRD, watch section, and watch station tracking could be used to create watch team replacement plans (WTRPs) which are required products for quarterly program and divisional reviews. Second, tracking watch station information would allow for the creation of validation checks to guard against multiple watch station assignments or overlapping watch time assignments. In addition to receiving confirmation notifications prior to assigning personnel numerous watches or inconsistent watch times, a scheduler could also benefit from alerts related to exceeding established watch hour limits. Alongside the other activity information from maintenance, meetings, or training events provided by the tool, these additional notifications would be useful tools

in taking other work responsibilities into consideration when assigning personnel work. Finally, tracking watch section information would be useful in monitoring watch station end strength so leaders could better plan for training reliefs or requesting temporary or permanent manning supplements to bolster undermanned sections.

3. Activity Category Determination

The prototype currently supports four activity categories, but its utility will improve by adding more activity options. The prototype does not record activity information as detailed as other NPS studies involving activity log tracking. These additional categories could include meetings and trainings (i.e., service diversions), eating/messing, and personal time. Future development must aim to strike a balance between the granularity level of the activity data collected and the time it takes users to accurately classify and input the data. Additionally, activity classification determination should be a standardized process. The activity information collected should be formatted and applied towards improving manpower models and human performance and fatigue modeling research efforts.

4. Metrics and Visualizations

User evaluation of the prototype will be critical in determining what additional features, metrics, and visualizations should be included for follow-on development. This evaluation may result in updates to the GUI, data collection structure and methodology, or the outputs of the prototype. One suggestion is to automate the Individual Risk Management Tool (IRMT) evaluation process so a user can incorporate the work/rest activity ratings directly into a completed form.

In conclusion, to increase warfighter performance, operational effectiveness, operational safety, and crew endurance, the U.S. Navy must invest in fatigue management tools and methods tailored to the surface combatant community. We need to foster innovation and support cultural shifts aimed at decreasing the risk associated with degraded human performance. The Scheduling Management Aid for Risk Tracking prototype is one small effort to standardize data-driven human performance risk assessment.

APPENDIX A. SUMMARY OF SEVEN HUMAN FATIGUE AND PERFORMANCE BIOMATHEMATICAL MODELS

	Two-Process Model	*Sleep/Wake Predictor Model*	*SAFE Model*	*Interactive Neurobehavioral Model*	*SAFTE Model*	*FAID Model*	*CAS Model*
Q.10 - Broad categorizations of what model seeks to predict							
Key aspects of:							
Subjective state (e.g., fatigue, sleepiness)	✓	✓	✓	✓		✓	✓
Performance (e.g., cognitive, physical)	✓	✓		✓	✓	✓	
Physiology (e.g., physiological alertness or physiological sleepiness)	✓	✓		✓			✓
Accident risk		✓					✓
Optimal work/rest schedules		✓			✓		✓
Impact of specific countermeasures (e.g., nap, caffeine)	✓	✓		✓	✓		✓
Other: (open-ended question)							
Biocompatibility of work schedules							✓
Circadian phase		✓		✓	✓		
Effects of non-linear metric	✓						
Homeostatic and circadian interaction	✓						
Specific task parameters		✓			✓		
Q.11 - Model's prediction goals/current focus							
Prediction of results from laboratory experiments on altered work/rest patterns:							
Simulated shift work	✓	✓		✓	✓	✓	
Simulated sustained or continuous operations	✓	✓		✓	✓	✓	
Chronic partial sleep deprivation	✓	✓		✓	✓		
Simulated jet lag	✓	✓		✓	✓		
Effects of countermeasures (behavioral, pharmacological, technological)	✓	✓		✓	✓		
Other: (open-ended question)							
Circadian effects of light exposure				✓			
Circadian phase					✓		
Effects of sleep deprivation	✓						
Sleep fragmentation/times					✓		
Prediction of results from field operations:							
Length of shift work		✓		✓	✓		✓
Shift work/night work operations		✓		✓	✓	✓	✓
Sustained or continuous operations		✓		✓	✓		✓
Jet lag	✓	✓		✓	✓		
Other: (open ended question)							
Accident risk in transportation							✓
Army, Navy watch systems		✓					
Civil air operations		✓	✓			✓	
Effects of irregular work schedules							✓
Non-24 h schedules				✓			
Sleep environment					✓		
Space mission scheduling	✓						
Time of sleep					✓		

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Copyright: Aerospace Medical Association
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Figure 54. Table of Current Prediction Goals of Biomathematical Models of Fatigue and Performance. Source: Mallis et al. (2004).

	Two-Process Model	*Sleep/Wake Predictor Model*	*SAFE Model*	*Interactive Neurobehavioral Model*	*SAFTE Model*	*FAID Model*	*CAS Model*
Q.12 - Capabilities currently implemented							
Estimates of:							
Changes as a function of time awake	✓	✓	✓	✓	✓		✓
Changes as a function of work time or time on task			✓			✓	✓
Type of work (e.g., cognitive vs. physical)		✓					✓
Recovery potential of sleep (e.g., sleep timing, sleep duration)	✓	✓	✓	✓	✓	✓	✓
Endogenous circadian parameters (e.g., period, phase)	✓		✓	✓	✓		✓
Sleep inertia	✓	✓	✓	✓	✓		
Cumulative sleep debt	✓	✓		✓	✓		✓
Individual variability in any of above parameters		✓	✓				✓
Effects of environmental variables (e.g., light, temperature, noise)	✓			✓	✓		
*Other: (open ended question)							

* No responses from modelers on this category

Figure 55. Table of Capabilities Currently Implemented in the Models. Source: Mallis et al. (2004).

	Two-Process Model	*Sleep/Wake Predictor Model*	*SAFE Model*	*Interactive Neurobehavioral Model*	*SAFTE Model*	*FAID Model*	*CAS Model*
Q.13 - Types of required input for each model (open ended question)							
Aviation specific variables:							
Bunk availability			✓				
Number of pilots working			✓				
Number of sectors			✓				
Pilot augmentation			✓				
Environmental variables:							
Light levels	✓			✓			
Location(s)			✓				
Sleep variables:							
Sleep length					✓		
Sleep quality					✓		
Sleep/wake time	✓			✓	✓		
Time allotted for sleep				✓			
Work variables:							
Work hours		✓	✓			✓	✓

Figure 56. Table of Required Inputs to Models. Source: Mallis et al. (2004).

	Two-Process Model	*Sleep/Wake Predictor Model*	*SAFE Model*	*Interactive Neurobehavioral Model*	*SAFTE Model*	*FAID Model*	*CAS Model*
Q.16 - Types of primary output generated by each model (open ended question)							
Circadian/sleep variables:							
Circadian phase/period	✓			✓			
Estimate of sleep accumulated		✓				✓	
Sleep latency		✓					
Sleep start/end		✓					✓
Objective performance variables:							
Cognitive throughput				✓			
Lane drifting (driving simulator)		✓					
Performance effectiveness		✓			✓		
Reaction time		✓					
Vigilance performance		✓					
Violations based on risk threshold levels						✓	
Subjective variables:							
Alertness ratings	✓	✓	✓	✓			✓
Fatigue level/scores	✓	✓				✓	✓

Figure 57. Table of Primary Outputs for Models. Source: Mallis et al. (2004).

	Two-Process Model	*Sleep/Wake Predictor Model*	*SAFE Model*	*Interactive Neurobehavioral Model*	*SAFTE Model*	*FAID Model*	*CAS Model*
Q.2 - Model name and version	Two-Process Model and related approaches	Sleep/Wake Predictor 1.4.3.2	System for Aircrew Fatigue Evaluation 2.09	Interactive Neurobehavioral Model	Sleep, Activity, Fatigue, & Task Effectiveness Model	Fatigue Audit InterDyne 1W13E	Circadian Alertness Simulator
Q.1 - Survey respondent	Peter Achermann	Torbjorn Åkerstedt	Mick Spencer	Megan Jewett	Steven Hursh	Greg Roach	Anneke Heitmann
Q.4 - Patent information							
Model patented							✓
Country of patent							USA
Patent holder							Moore-Ede, Mitchell
Patent date							7/18/1995
Patent number							5,433,223
Patent pending					✓		
Intending to patent				✓	✓		✓
Q.5 - Proprietary information							
Model proprietary			✓			✓	✓
Q.6 - Commercial information							
Model commercially available					✓	✓	✓
Available from					NTI, SAIC	Interdynamics	Circadian Technologies
Q.7 - Target market (open ended question)							
Aviation specific:							
Airlines			✓				
Boeing/Airbus ultra-long range plane developers				✓			
Civil aviation regulators			✓				
24/7 operations:							
Companies with irregular work hours		✓					✓
24-h transportation operations							✓
Industrial settings/regulators		✓			✓		
Research:							
Scientific community	✓						
NASA/DOD scientists				✓			
Organizations/operations/ researchers with shiftworkers		✓				✓	✓
Scientific/sleep/wake regulation researchers	✓	✓		✓			
Other:							
Accident investigators						✓	
Military settings					✓		

Figure 58. Table of Model Information. Source: Mallis et al. (2004).

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APPENDIX B. CONCEPT MAP OF COMMANDING OFFICER (CO) SCHEDULING CONSIDERATIONS AND CONSTRAINTS

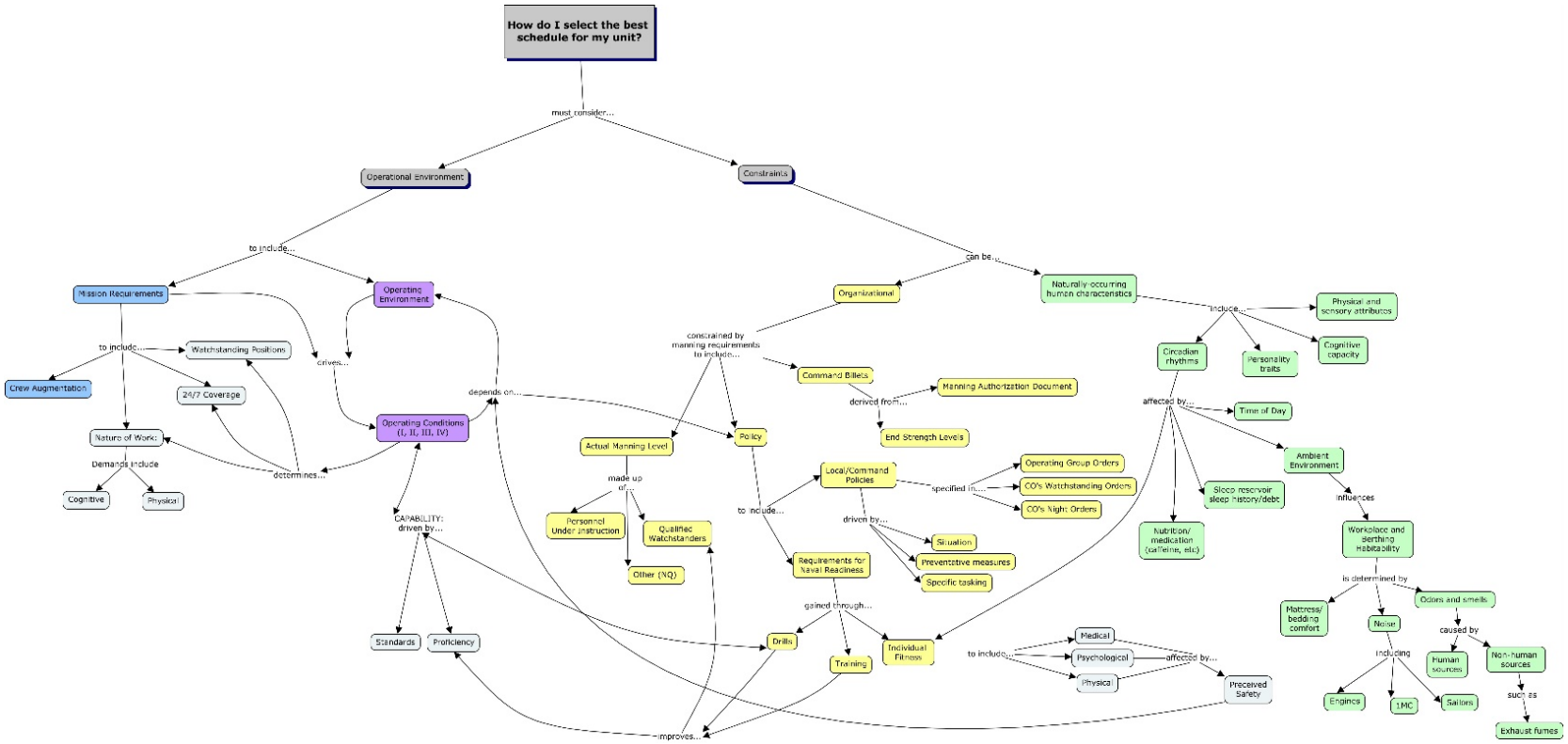

Figure 59. Complete Concept Map of Commanding Officer Scheduling Considerations and Constraints. Source: Brown (n.d.).

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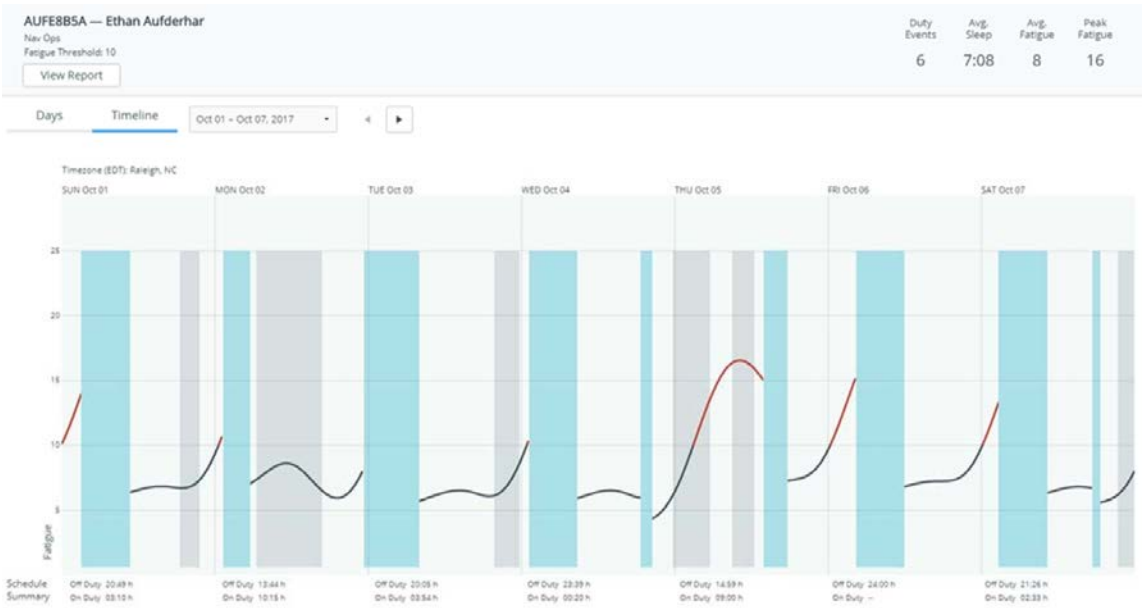
APPENDIX C. ADDITIONAL FIGURES FROM THE OPTIMIZED WATCHBILL AND LOGISTICS FATIGUE METER (OWL FM)

The following three figures are additional screenshots from OWL FM which illustrate other useful functions for personnel scheduling and fatigue management.



Fatigue estimate regression indicated with the black and red curved lines.

Figure 60. Weekly View of a Crewmember's Duty Schedule. Source: Mollicone and Bruneau (2018).

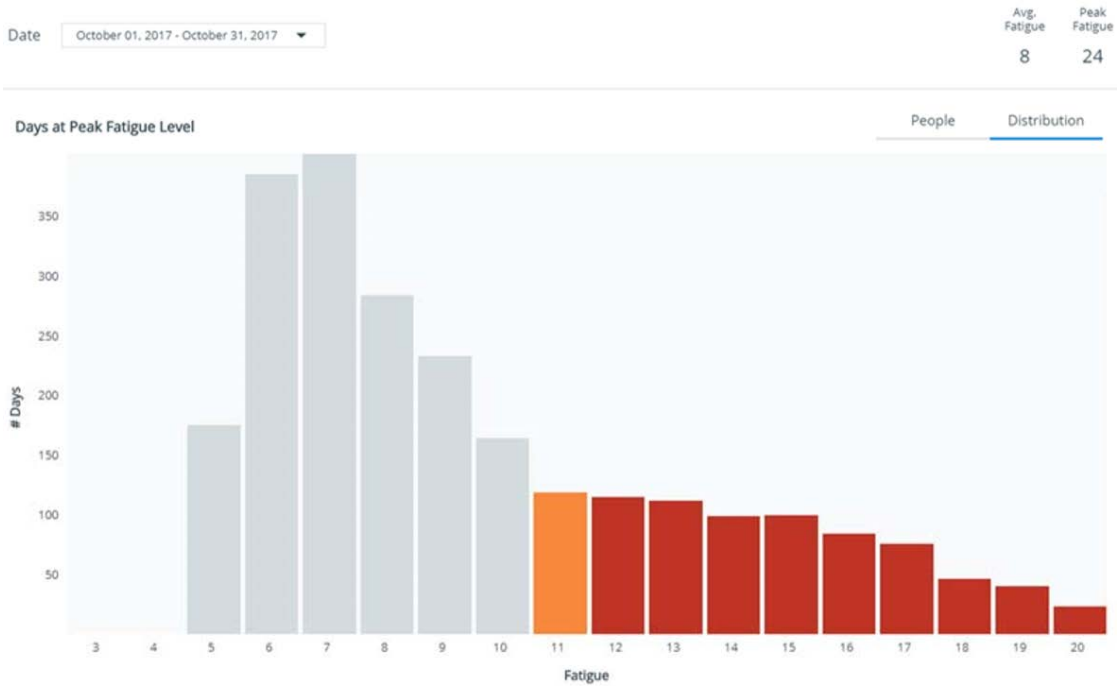


Figure 61. Histogram View of Fatigue Levels Exhibited by Crewmembers Over a Chosen Timeframe. Source: Mollicone and Bruneau (2018).

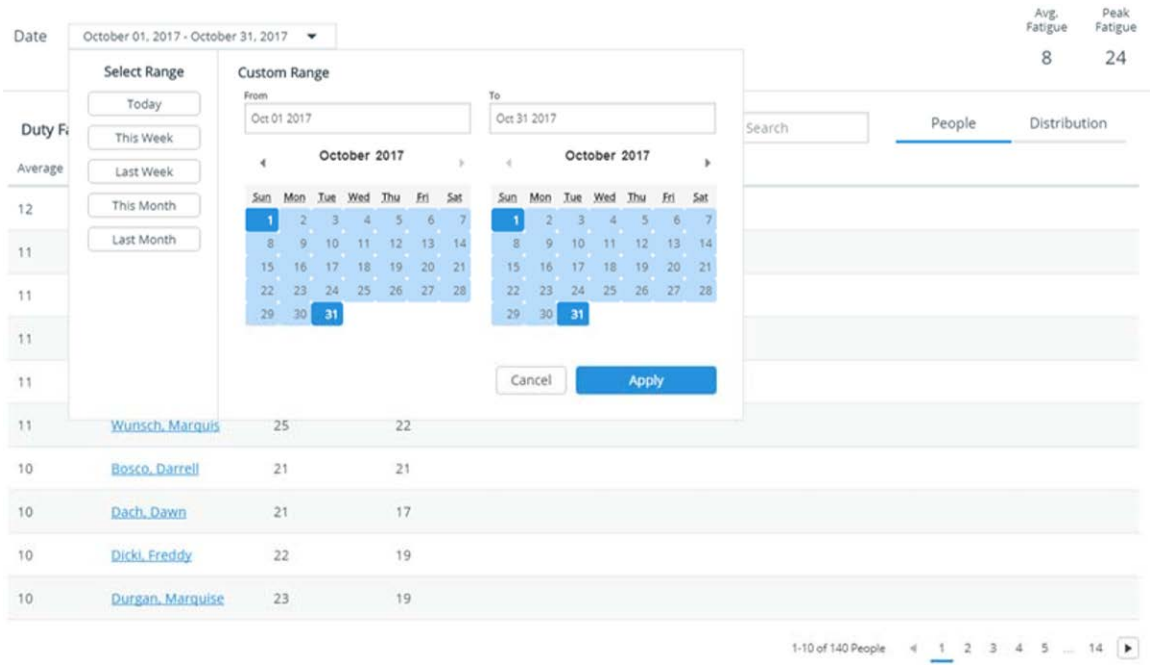


Figure 62. Custom Date Range Selection for Analysis Screenshot. Source: Mollicone and Bruneau (2018).

APPENDIX D. INDIVIDUAL RISK MANAGEMENT TOOL

Individual Risk Management Tool

Watchstation	Watch/Rest	Experience	Weather	Equipment	IRM
OOD: LT Red	2	4	3	2	11
CONN: ENS Blue	3	2	3	2	10
Helm: BM3 Green	2	1	3	2	8
Lee Helm: EN3 Orange	3	4	3	2	12
Nav Evaluator: LTJG White	3	1	3	2	9
Overall	13	12	15	10	Avg 10

Watch to Rest Ratio:
4: No watch leading into event (or during scheduled watch), 7 hours of sleep in last 24 hours
3: 7 hours of sleep in last 24 hours, stood a full watch before event
2: Between 5 and 7 hours of sleep in last 24 hours
1: Less than 5 hours of sleep in last 24 hours

Experience:
4: 11 or more details in last 3 mos
3: 5-10 details in last 3 mos
2: 5 or less details in last 3 mos or UI
1: First time as qual'd watschstander

Equipment:
4: All equip operational
3: Moderately degraded equip
2: Severely degraded equip
1: Primary / backup Equipment OOC

Weather:
4: Good weather
3: Moderate weather
2: Significant weather
1: Heavy weather

IRM Code:
<8: Critical
8-10: Serious
11-13: Moderate
13-14: Minor
15-16: Negligible

Figure 63. Individual Risk Management Tool. Source: DON (2017a, p. 4)

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APPENDIX E. ADDITIONAL SMART FIGURES

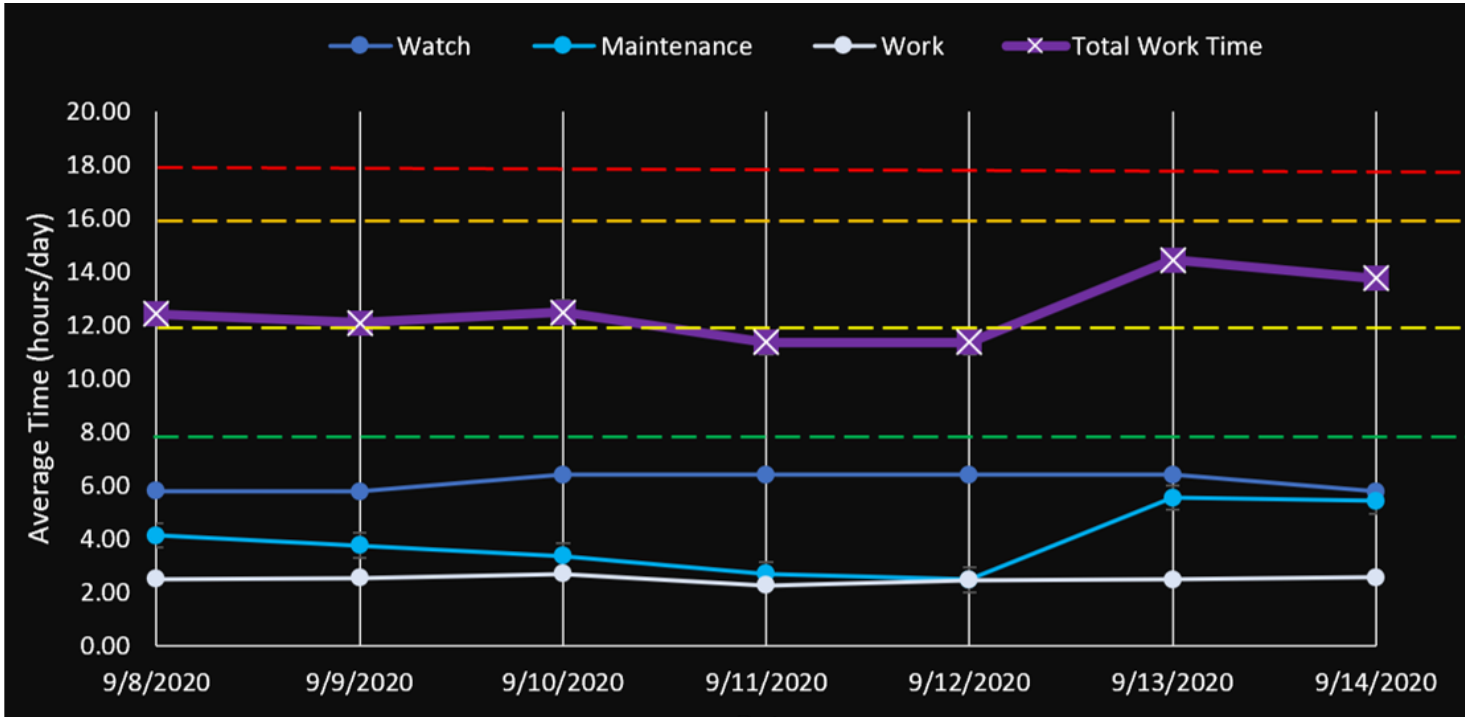

Figure 64. Operations Department Filtered Average Work Activity Trends from September 8–13, 2020

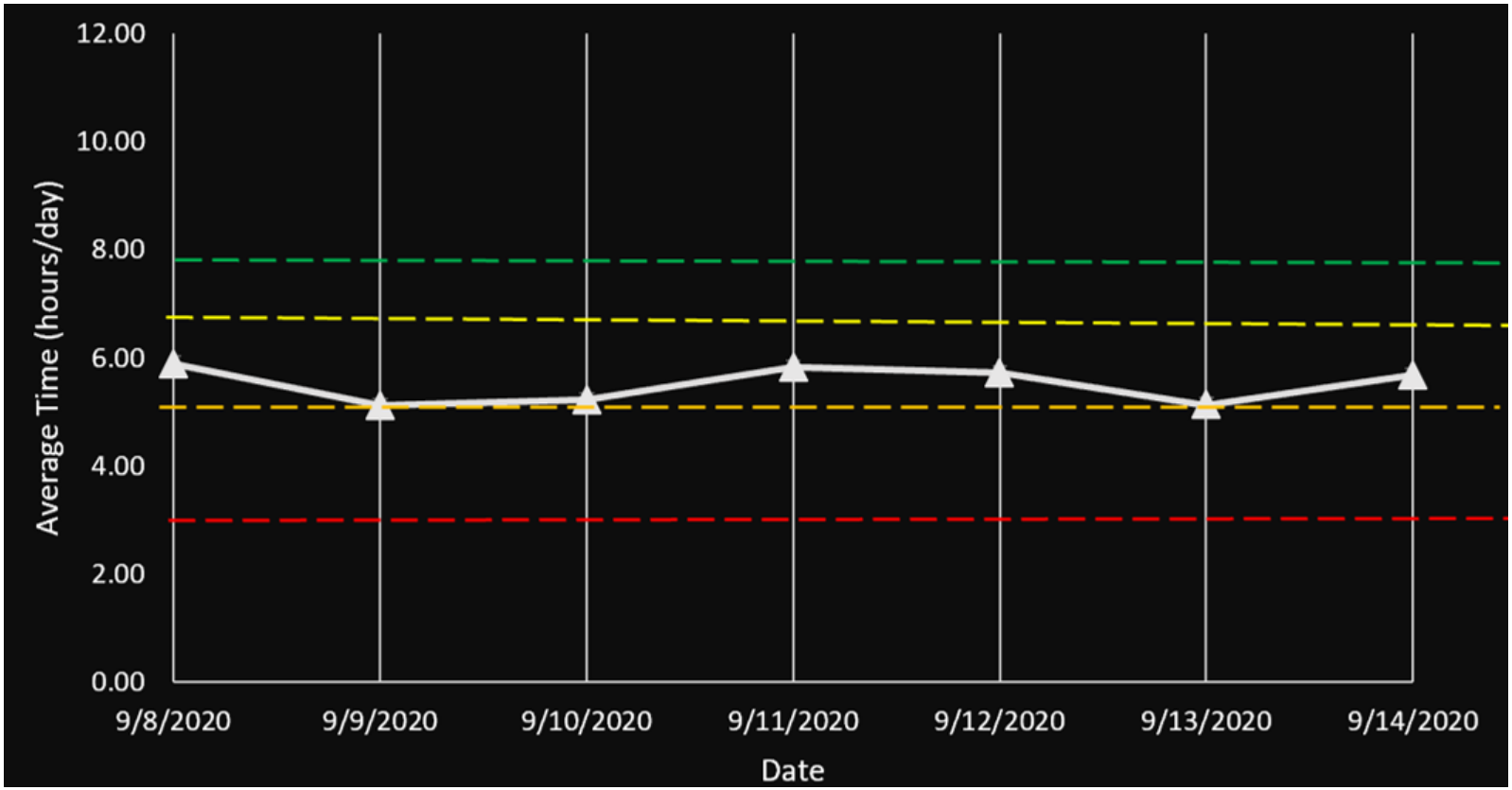

Figure 65. Operations Department Filtered Average Sleep/Rest Activity Trends from September 8–13, 2020

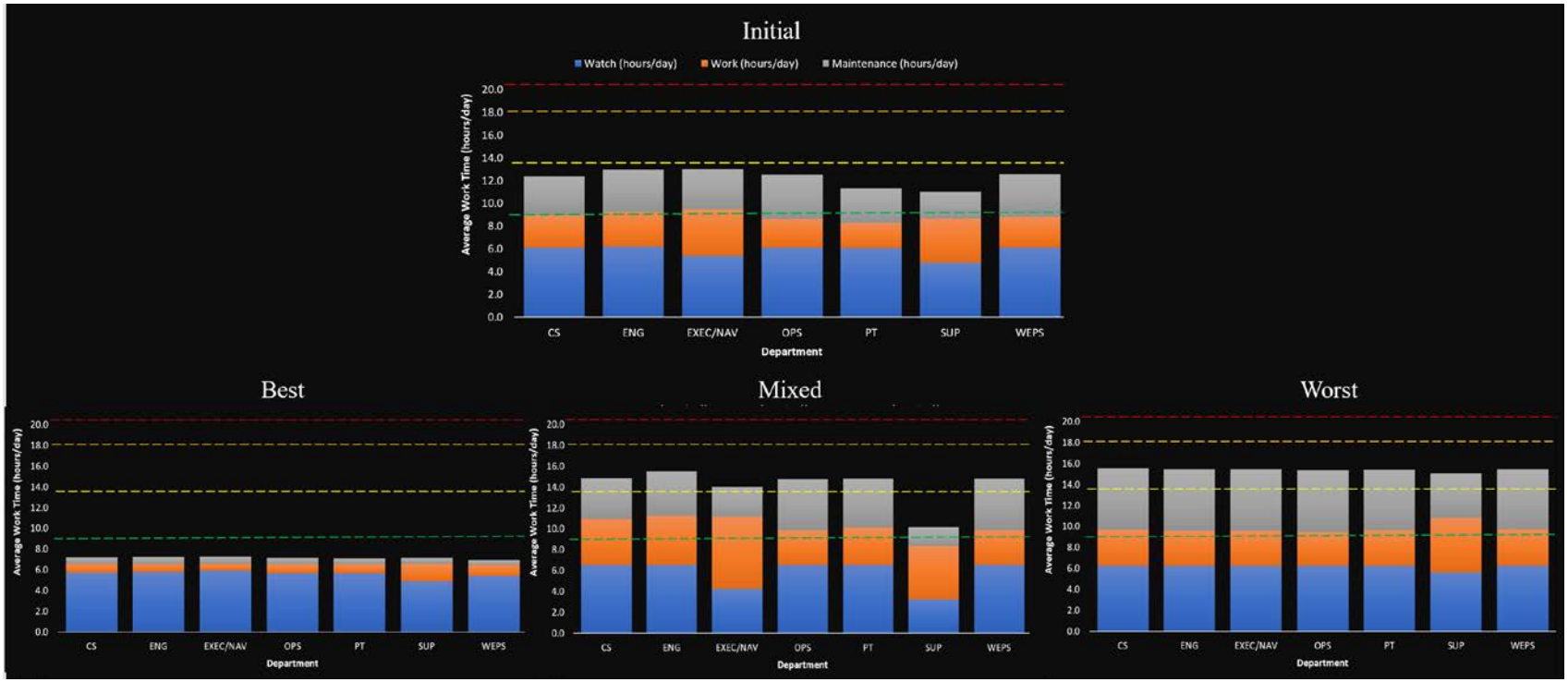

Figure 66. Initial versus Case Comparisons for Average Work Activity by Department

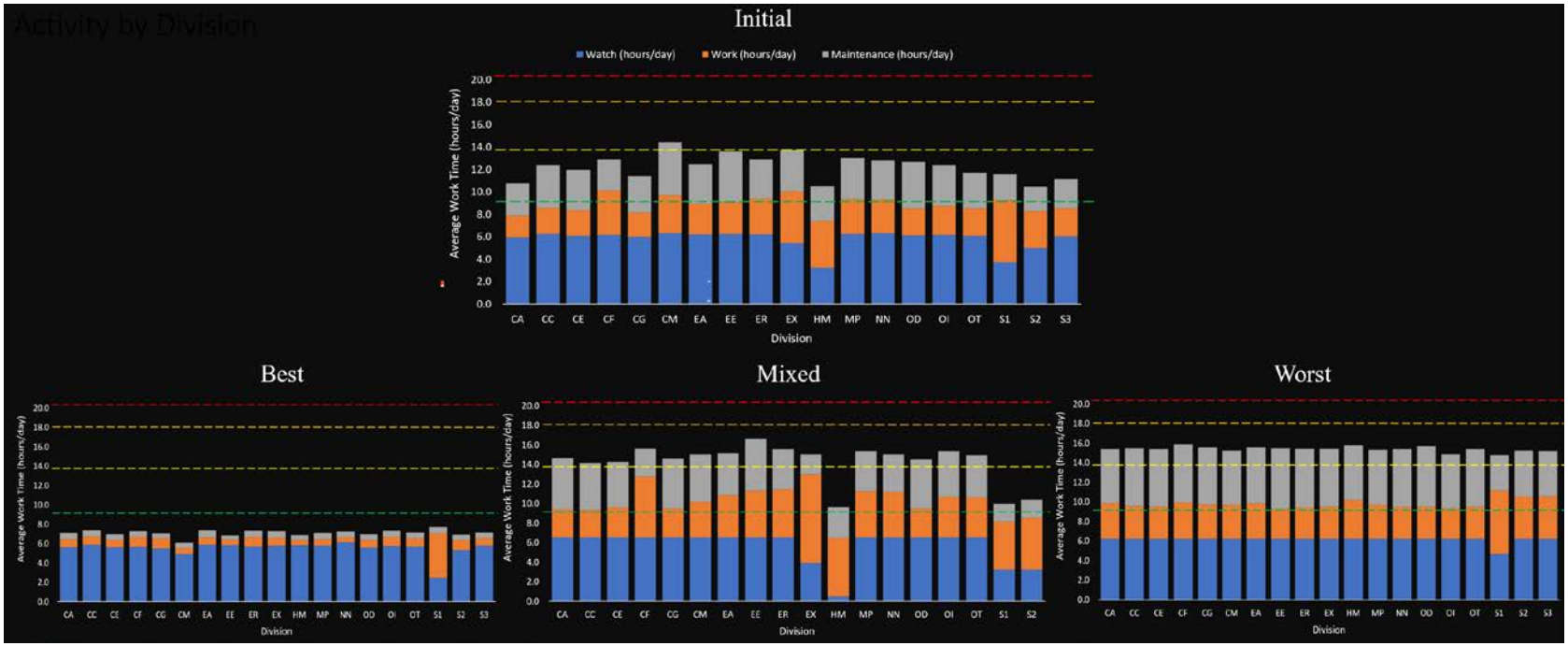

Figure 67. Initial versus Case Comparisons for Average Work Activity by Division

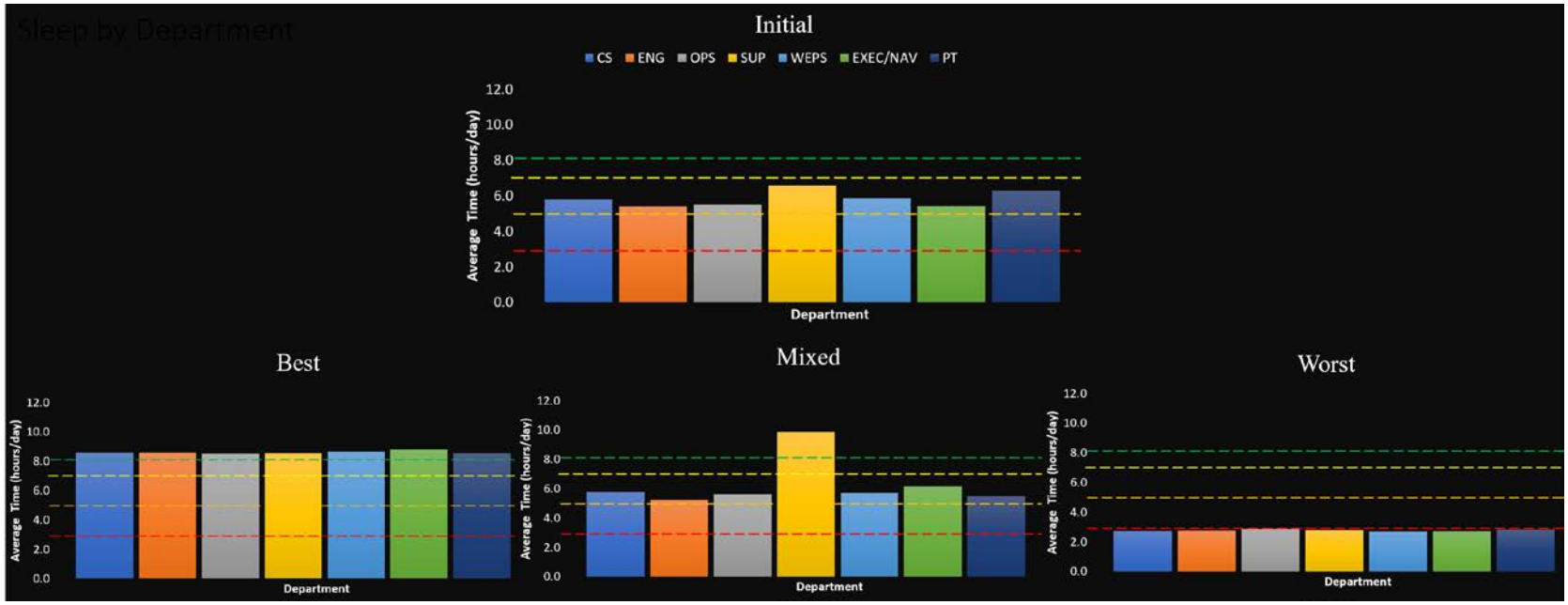

Figure 68. Initial versus Case Comparisons for Average Sleep/Rest Activity by Department

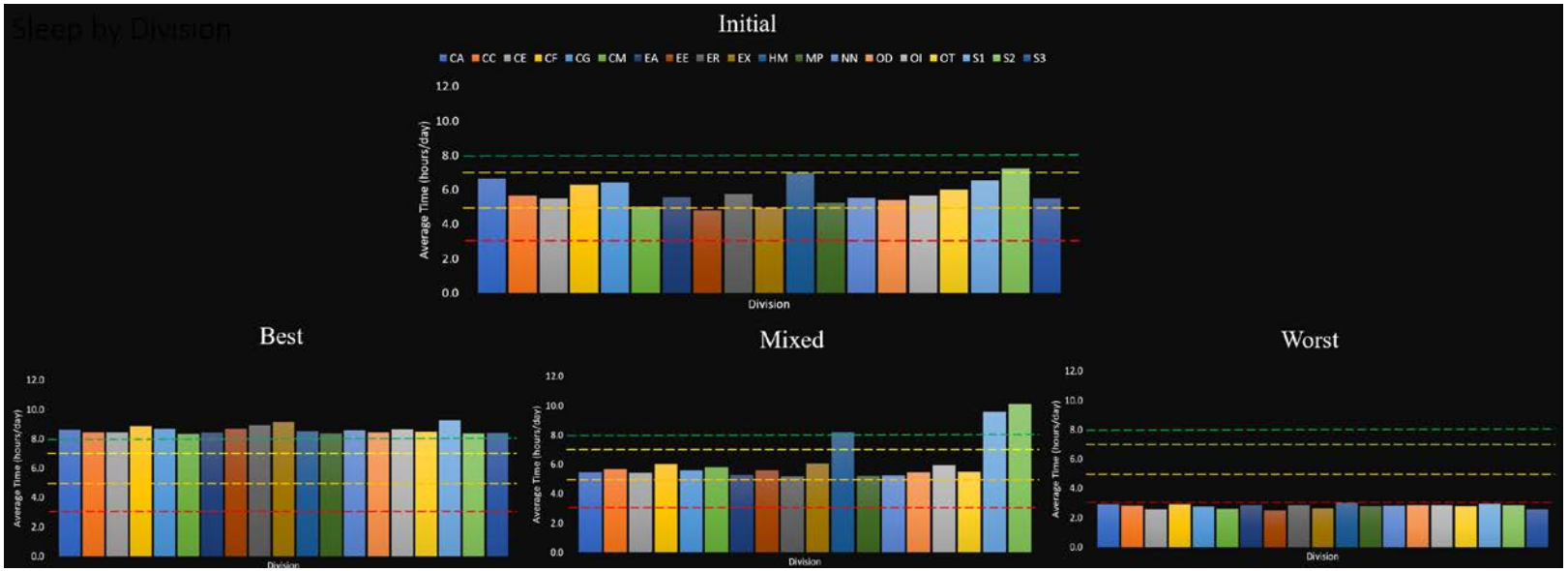

Figure 69. Initial versus Case Comparisons for Average Sleep/Rest Activity by Division

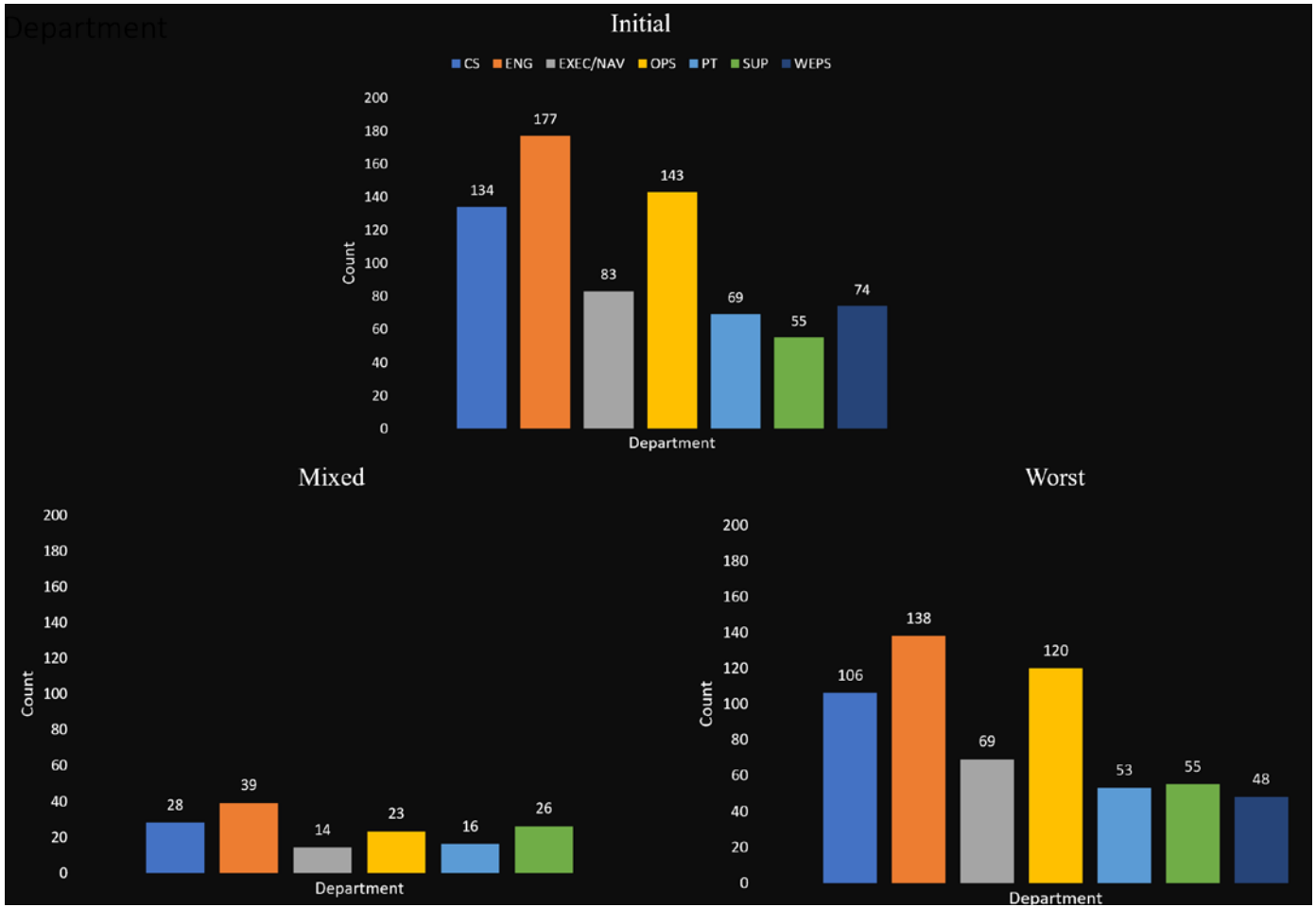

Figure 70. Initial versus Case Comparisons for the Number of Critical Risk Individuals by Department

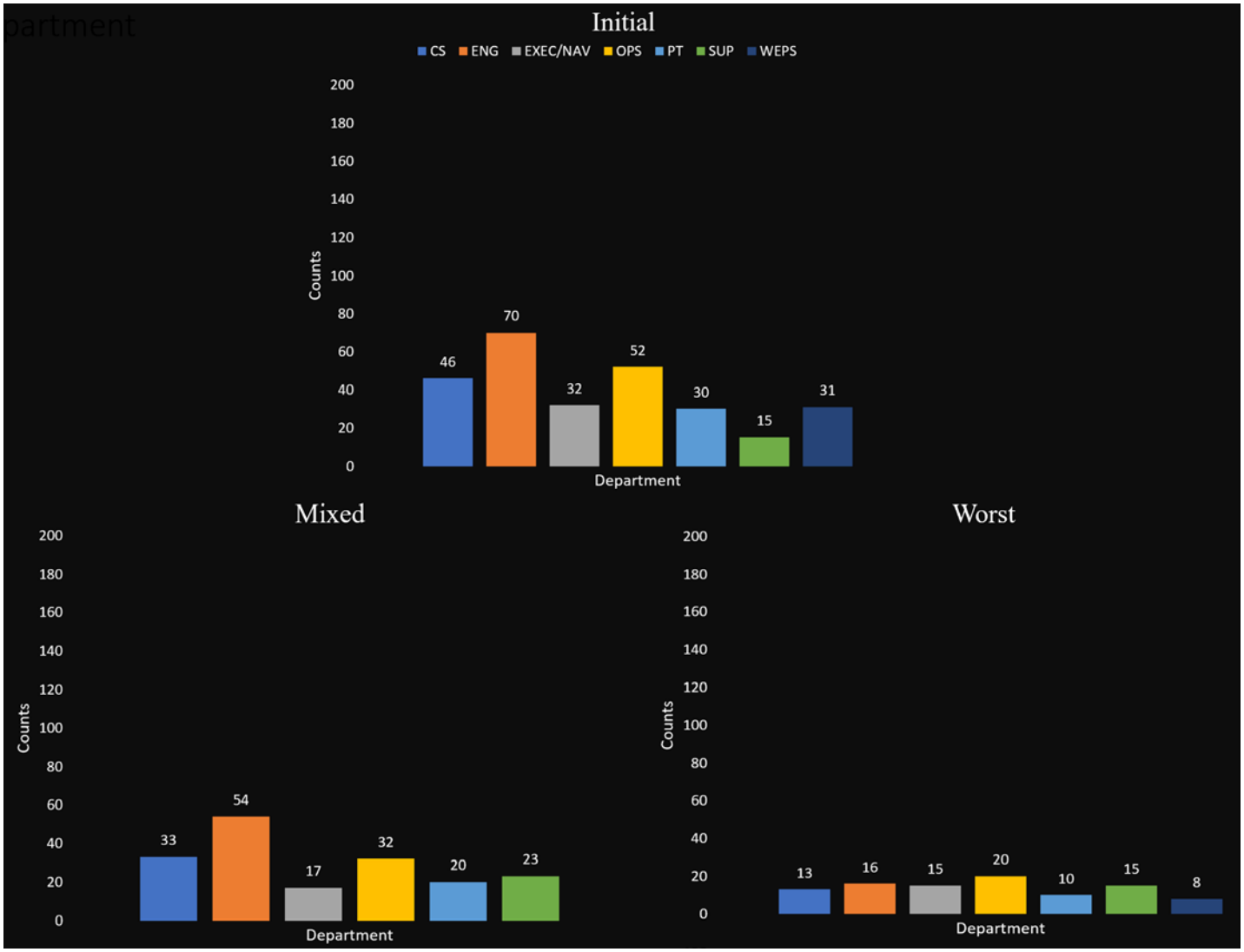

Figure 71. Initial versus Case Comparisons for the Number of Serious Risk Individuals by Department

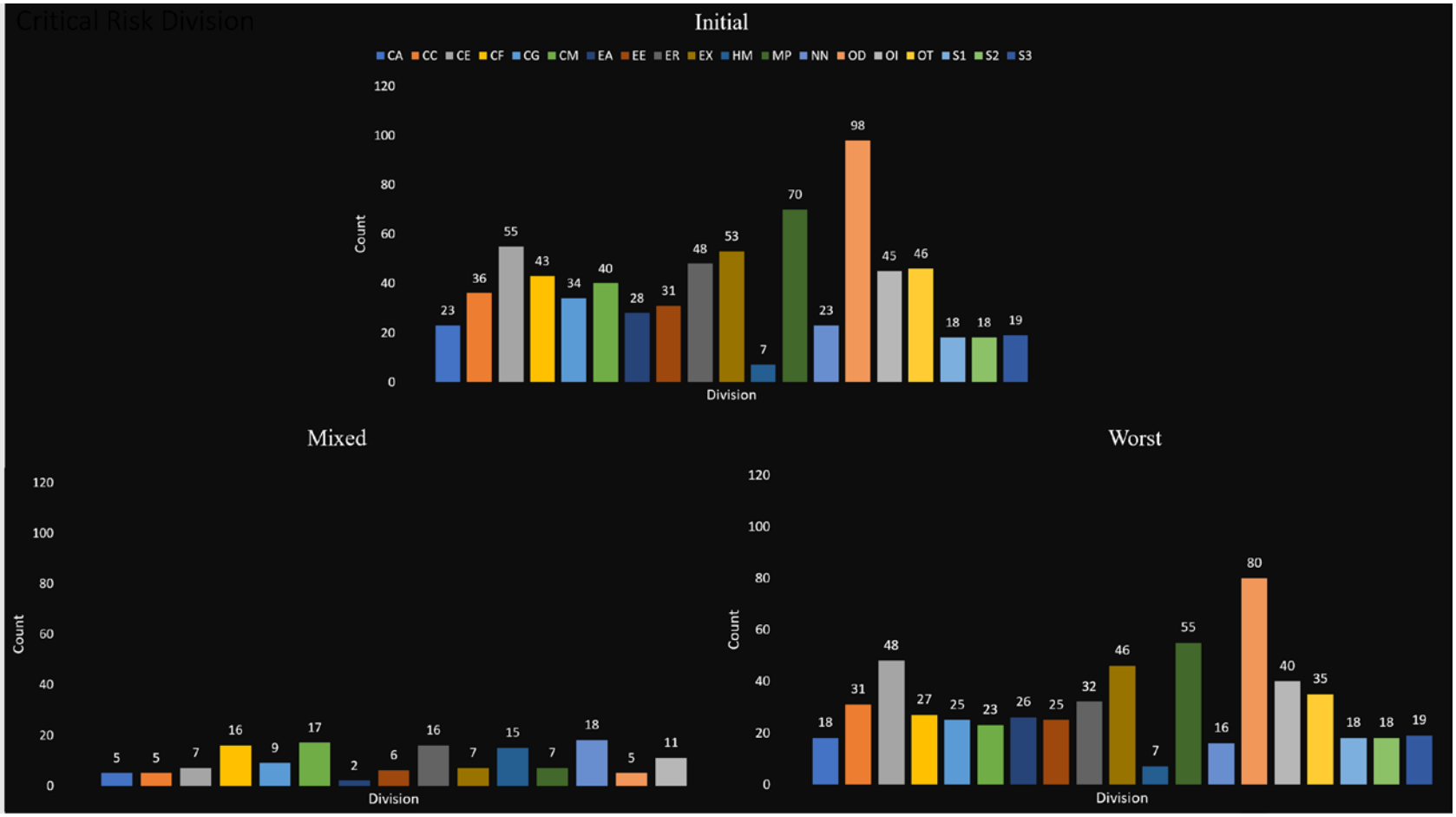

Figure 72. Initial versus Case Comparisons for the Number of Critical Risk Individuals by Division

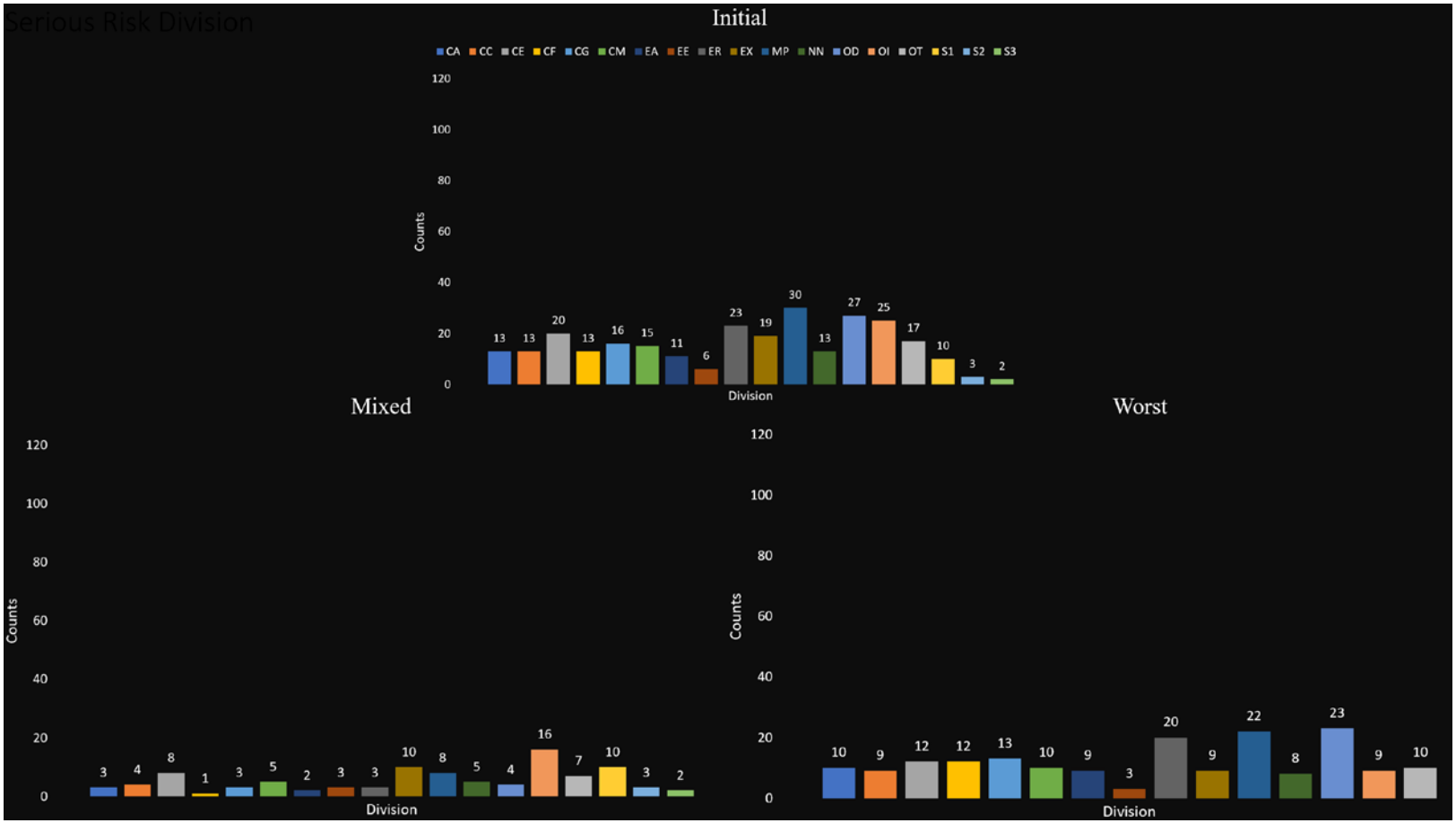

Figure 73. Initial versus Case Comparisons for the Number of Serious Risk Individuals by Division

SUPPLEMENTALS: WORKBOOK, MANUAL, TOOL AND VIDEO

The Scheduling Management Aid for Risk Tracking (SMART) tool was developed in Microsoft Excel. The decision aid systematically collects user activity data and provides users with trend analysis and human performance risk assessment data. The prototype's heuristics and outputs enable users to make data-driven crew resource management decisions and implement targeted human performance risk mitigations. A description of the supplemental materials included with this work are listed as follows:

1. SMART Template: This macro-enabled workbook contains the SMART prototype. The file contains some pre-filled data fields to provide users with illustrative examples.
2. SMART User Manual: This file contains detailed information regarding the technical aspects of the prototype (e.g., formatting structure, formulas, etc.), operator instructions, and troubleshooting steps.
3. SMART Data File: This macro-enabled spreadsheet contains the notional data created for the thesis along with the results utilized during data analysis.
4. SMART Tutorial Demonstration: This presentation contains visual and audio narrations to assist users with employing the SMART prototype. The presentation also contains troubleshooting recommendations, functionality demonstrations, and user tips for the prototype.

Parties interested in obtaining a copy of any or all the supplementals listed above are directed to contact the Naval Postgraduate School Dudley Knox Library.

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