Quantifying the Impact of Secondary Duties on Sailor Workload Through Simulation

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Abstract: Designing crewing concepts for ships requires complete information regarding the tasks that sailors must perform, since an incomplete understanding could result in unreasonable crew workloads and fatigue. It is therefore important to look at all sources of sailor workload. Primary duties, which belong to a billeted position, have been studied extensively in the past and are well-represented in existing crew models. Secondary duties, which are tasks assigned to individual sailors in addition to their primary duties, are not as well understood. This creates a significant risk in crew design. In this study, a simulation model has been developed to quantify the impact of secondary duties on sailor workload. The stochastic nature of the model makes it suitable for use in Monte Carlo experiments and allows it to explore the impact of combining one or more secondary duties with a sailor's primary duties. This allows it to be used to create statistics suitable for applications, such as predicting fatigue rates, where extreme values are important. This paper describes the development, verification, and implementation of the model.

1 INTRODUCTION

1.1 Background

The state of the personnel aboard a vessel determines how effectively and safely the vessel can be operated. With this in mind, workload and fatigue are important areas of study for maritime organizations. While lots of effort goes into understanding the workload of each billeted position on a ship, the work that sailors do that does not belong to their assigned position can be overlooked. This creates a risk in crew design in that sailors may end up with far more workload and far less rest than designers anticipated. While this can be identified and corrected after the crew design is implemented, improving the original designs with more complete data would reduce the strain on first-of-class crews and reduce the work necessary to modify and validate crew designs after they are put into practice.

This paper describes a simulation model that was created to demonstrate the impact of secondary duties on Royal Canadian Navy sailor workload.

1.2 Definition of Sailor Duties

For the purpose of this study, the following definitions were developed:

- **Primary Duties:** tasks listed in terms of reference or a job description associated with an assigned billeted position.
- **Secondary Duties:** additional tasks assigned to an individual by their chain of command or nomination through voluntary means that contribute to the good order and functionality of a unit or crew.
- **Tertiary Duties:** tasks assigned to personnel on a watch and station bill that may vary with each iteration of the watch and station bill.

Note that because the definitions of primary, secondary, and tertiary duties depend only on how duties are assigned, the classifications may differ from organization to organization. For example, a task that is a primary duty in a navy that includes it in the job description of a billeted position would be a secondary duty in a navy where it is assigned to individual sailors regardless of their position.

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1.3 Literature Review

The United States Navy (USN) makes use of a Navy Availability Factor (NAF) to describe the time each sailor has available to complete tasks assigned to them (Chief of Naval Operations, 2021). These hours are broken down into productive and non-productive time, with the non-productive time further divided into training and service diversion. Service diversion consists of actions required by personnel through regulation or routine and includes things such as inspections and participating in committees (Chief of Naval Operations, 2021).

The USN's Navy Total Force Manpower Policies and Procedures provides breakdowns of the NAF of personnel in various states, but these hours are not broken down to a sufficient granularity to be able to attribute hours to specific secondary duties or even secondary duties in general (Chief of Naval Operations, 2021). This issue is also seen in studies that use the same definitions as the policy documents, such as the study of sailor workload that was performed by Garbacz (2019) and highlighted in Cordle (2019). Many of what are considered secondary duties in the modelling described in this paper would be captured as own-unit support in Garbacz (2019); however, values are only provided for the productive workload of sailors, a category that includes own-unit support along with primary duties such as standing watch. The result is a lack of available data describing the time required to complete secondary duties.

This lack of data means tools that model crew usage rates are unable to explicitly include secondary duties. Secondary duties cannot be included as discrete tasks in task networks when using tools such as the Improved Performance Research Integration Tool (IMPRINT) as in Hollins and Leszczynski (2014). This means that any workload related to the completion of secondary duties would be unaccounted for in such studies and the number of crew required to operate a vessel underestimated. Similarly, the accuracy of a tool developed by Defence Research and Development Canada, the Simulation for Crew Optimization and Risk Evaluation (SCORE), is reduced by the lack of secondary duty data. The tool combines a sailor's regular duties with the roles they are assigned during scenarios such as replenishment at sea to output a usage rate for the sailor and a list of instances of conflict where the sailor has concurrent taskings (Chow et al., 2016). Since the model cannot include the impact of secondary duties, the usage rates and number of conflicts predicted by the model are underestimates for any sailor assigned a secondary duty.

1.4 Goal of the Modelling

The goal of the simulation model described in this paper is to generate daily work schedules that are suitable for computing statistics describing the impact that secondary duties have on sailor workloads. Using Monte Carlo simulation, statistics can be computed from daily schedules that allow for a more comprehensive understanding of sailor workload than broad measures such as the number of hours a sailor must commit to various tasks per week, as is done in the USN's NAF (Chief of Naval Operations, 2021).

For example, suppose a secondary duty is understood to require approximately 100 hours to complete over the course of a year. A crew design model could take this secondary duty into account by reducing the availability of a sailor by two hours each week, similarly to what is done in the NAF using the non-productive time category (Chief of Naval Operations, 2021). However, if the required hours are not evenly distributed across the weeks of a year and instead happen in a limited number of time periods that are unpredictable in nature, a sailor assigned the secondary duty may find themselves with extreme short-term workloads. A simulated schedule generated by the model contains this information, and so it can be used to predict how often the sailor will face extreme workloads. In this way, the model can identify conditions that will lead to sailor fatigue in a crew design that otherwise may go undetected until crew validation takes place.

The simulation model also improves upon simple estimates of secondary duty time requirements by layering multiple stochastic processes. This will allow for analysis that includes days where a sailor's primary duty workload is above average and they must work on more than one secondary duty. This sort of randomized schedule can then be combined with other excursions from typical workload including taking part in a special evolution such as a resupply at sea or collective training to model the true schedule of a sailor and identify unsustainable combinations of primary and secondary duties.

2 MODEL ASSUMPTIONS

2.1 Workload

In most work settings, the expected workload of a position is the sum of the time taken by each task assigned to the position and any additional tasks taken on by the individual worker filling the position. For office workers, this is often as simple as 7.5 hours per day of assigned work plus any additional time spent taking part in committees, labour organizations, or other voluntary activities. Sailor workload is similar, in that sailors are responsible for their primary and secondary duties, but there are several complicating factors that present themselves when the workplace is a vessel. This is especially true when the vessel is at sea.

First, many sailors stand watches. Depending on the nature of the watch, it may or may not be possible for a sailor to work on other tasks while standing watch. In the USN, hours spent standing watch are included in the productive time within the NAF with the acknowledgement that additional productive work will have to take place outside of the hours spent standing watch (Chief of Naval Operations, 2021). This builds in the assumption that none of the non-productive items (training or service diversion), and by analogy many secondary duties, can be completed on watch. For the simulation model, it was decided to consider all watch hours as primary duty hours and require that secondary duties be completed when sailors are off watch. Since some sailors can complete secondary duties during a watch, this assumption will result in the model results being the upper bound of sailor workload.

A further complication in analysing the workload of sailors is that the length of the workday, which tasks are to be completed, and how long many tasks take to complete depend on what the ship or unit is doing. In the broadest sense, sailor workload depends heavily on whether they are currently ashore or at sea. At a more detailed level, each individual primary and secondary duty will likely change depending on whether it is being performed on shore or at sea, with further considerations often being necessary to include the types of shore duty and sails.

The USN addresses the disparity in sailor workload based on unit state by generating multiple NAFs: afloat, ashore (peacetime), and mobilization (Chief of Naval Operations, 2021). Ashore is further divided into whether the unit is stationed in the continental US or internationally. A similar approach was taken in this study after reviewing the secondary duties to be considered.

In the simulation model, the state of a unit or ship is divided into four categories: alongside home port, alongside foreign port, at sea on routine sail, and at sea on operation. These states were selected based on the impact they are expected to have on secondary duties. For example, a unit alongside a home port will have extensive shore facilities to make use of, reducing the need for many secondary duties that aim to recreate these services at sea. A unit alongside a foreign port will have some shore-based facilities to make use of, but not as many as one alongside a domestic port. Time at sea is divided into routine and operational sails to take into account the difference in crew composition and operational tempo in the two states. The four states, and short labels used to refer to them, are provided in Table 1.

Table 1: The four ship/unit states considered in the model.

Name	Code
At sea on routine sail	SR
At sea on operation	SO
Alongside home port	AH
Alongside foreign port	AF

Combining all these considerations, a sailor's workload is described in the model as the time they require to complete their primary and secondary duties in each of the four unit states described above. Watch standing, and therefore all associated tertiary duties, are counted as primary duty workload in the model.

2.2 Time Estimation

Due to a lack of historical logs or other means of accurately tracking how sailors spend their time, the workload modelling described here will rely on time estimation done by sailors based on their experience. Given the number of billeted positions, secondary duties, and unit states to be considered for a typical ship, many individual time estimates are required and a quick means of expressing them is necessary. A single-point estimate, such as the mean time spent on a secondary duty each month, is simple but does not describe the variance of the value or the uncertainty in the estimate. The uncertainty in such estimates may be large, especially if sailors are generating them from memory. Two-point estimates, such as a minimum and maximum, may describe the variance and uncertainty of a time value but do not include an estimate of the most-likely value. In this study, a three-point estimation is used: all time estimates are expressed as the minimum value, the most-likely value, and the maximum value. These three values are often used in studies that aim to predict how much time a combination of tasks will take (Clark, 1962). They are more intuitive than abstract values such as the mean, variance, or standard deviation.

Multiple distributions can be built from three-point estimation. Further knowledge of the distribution of time values will be necessary to inform a decision around the most suitable distribution for this application. As of writing, the triangular distribution is being used. Other three-variable distributions, such as the Project Evaluation and Review Techniques (PERT) distribution (Clark, 1962), or even two-variable distributions such as the uniform distribution, will be considered if empirical data supports it.

2.3 Treatment of Secondary Duties

With the understanding that secondary duties are often made up of many distinct tasks, a simple way of expressing them in the model is required, especially since each secondary duty must be described four times: once for each unit state. It was decided to express instances of a secondary duty requiring attention as a recurring event of variable length. The rate of occurrence of instances of a secondary duty is defined by a frequency, and the amount of time required by each instance is described by a triangular distribution defined by three-point time estimation. It is the range of time requirements that is intended to take the different tasks involved in a secondary duty into account.

Some tasks associated with secondary duties follow a set schedule or must be completed at a set frequency. For example, a secondary duty may include generating a monthly report. In its current configuration, the model does not allow for rigid scheduling of secondary duty events: the beginning of secondary duty instances are computed stochastically. This is to better capture tasks that must be completed in response to unscheduled events or the fact that the work required by a scheduled task may not itself be scheduled. To return to the example of the generation of a monthly report, a sailor may choose to complete the report days before it is due if that is when they have the required time available.

Each secondary duty instance is allowed to span a number of days to allow for tasks that need not be completed all at once. The number of days spanned by a secondary duty instance is referred to as a window, and a heuristic approach was devised to allocate the required work hours within the window. The heuristic approach for allocating hours will be described in Section 3.4. Note that the length of the window, like the other values that describe a secondary duty, must be provided for all four unit states.

Allowing separate occurrences of the same secondary duty to overlap may or may not make sense depending on the secondary duty being considered. For tasks such as inspecting equipment, overlaps are senseless; however, when a task is in response to a need that can arise at random, such as in response to a workplace accident, overlaps may occur. Since most secondary duties contain multiple tasks, instances of the secondary duty overlapping can also be treated as different tasks overlapping and not a single task overlapping. For this reason, the model allows for overlaps in secondary duty instances. Upon review of collected data, the code can be modified to disallow overlaps for specific secondary duties if needed.

The model is flexible in the number of sailors and secondary duties it can consider in a single run: the scope of the simulation can range from a single sailor to an entire unit. To allow this flexibility, the model simulates each sailor's schedule independently with no knowledge of the schedule of other sailors.

For simulations with more than one unit position, secondary duties can be assigned to multiple sailors simultaneously. To account for the reduction in workload required of a single sailor when a secondary duty is shared, a number in the interval [0,1] is used to represent the fraction of a secondary duty that each sailor is responsible for. These fractional assignments scale the three-point time estimates of the associated duty for each sailor, but they do not affect the frequency of occurrences. Note that the schedule of each sailor is simulated independently, so while sailors may share the total workload of a secondary duty, instances of the secondary duty requiring attention will not correspond in their schedules.

3 OVERVIEW OF THE SIMULATION MODEL

3.1 Brief Description of the Model

The simulation model is a stochastic, discrete model that utilizes a time step of one day as it simulates sailor workload. It makes use of an idealized calendar consisting of months of 30 days each, with each day being assigned a day of the week. This allows flexibility in including things like weekly routines or leave into the model, if desired. The product of the model is a schedule for each input unit position that contains the amount of time a sailor occupying that position would spend on their primary and secondary duties each day. In its current configuration, the model generates three schedules for each position: the time spent on primary duties, the time spent on secondary duties, and total workload.

Each simulation consists of a user-specified number of replications of a single year. Since events do not carry over from one simulated year to the next, it is incorrect to interpret the replications as consecutive years of a multi-year period. Instead, each replication should be considered as an independent simulation of the same year. As such, they are suitable for use in Monte Carlo experiments.

3.2 Model Inputs

A sailor's workload depends on the state of their unit or vessel, so the first input the model makes use of is a table containing the state of the unit being studied in each month of the simulation. The four states used in the model are described in Section 2.1 and summarized in Table 1.

The system being studied by the model ranges from a single sailor to an entire unit or vessel's crew. Information regarding each position is loaded into the model as a table that contains the number, name, and daily primary duty time requirement estimate for each position. Given that each daily time requirement estimate consists of a minimum, most-likely, and maximum value, and that each value must be given for each unit state, a total of 12 time values are provided for the primary duty workload of each position.

Next, a list of secondary duties is required by the model. To fully describe a secondary duty, the model requires the minimum, most-likely, and maximum time required by the secondary duty during each instance it occurs, the length of the window (in days) that these hours must be completed within, and the frequency at which instances occur. Since this information is required for each unit state, a total of 20 numerical values are necessary to fully describe a secondary duty in the model.

The final piece of information required by the model is the assignment of secondary duties to the sailors occupying the unit positions. This takes the form of a matrix with each unit position represented as a row and each secondary duty as a column. The value of each matrix element determines the portion of the corresponding secondary duty that is assigned to the sailor occupying the position in question. Fractional values allow duties to be split between multiple sailors, although their individual schedules are still modelled independently as is discussed in Section 2.3.

3.3 Generation of Simulated Schedules

The model begins by generating a 14-month, 420-day calendar and then attaching the day of the week and unit state to each day using the unit state input file. The length of the calendar corresponds to an idealized 12-month year with an additional month added to the beginning and end. These additional months are included so that the 12-month schedule they encompass does not include any edge effects such as a lack of secondary duty events beginning before the first day of the simulation or secondary duty events carrying over past the last day of the simulation. The additional months are not included in the simulation outputs and do not contribute to analysis of simulated schedules. 30-day months are used in place of true month lengths for ease in computing monthly statistics.

The model then simulates the primary duty schedule of each sailor by determining the number of hours worked by each sailor each day using a triangular distribution and the inputs that correspond to the unit state of that calendar day.

To simulate the secondary duty schedule of a sailor, the model iterates over each secondary duty assigned to the sailor. In larger crews, most sailors will have a single or no secondary duty assigned to them; however, smaller crews will see more instances of sailors being responsible for multiple secondary duties.

To begin, the probability of an instance of the secondary duty requiring attention beginning is computed for each day. This is done by dividing the annual frequency for the unit state of the day by 360. Random number generation using a uniform distribution is then performed to determine when instances occur. For example, if the probability of an event starting on a given day is 0.1, a random number is generated between zero and one and an event is created beginning on that day only if the number is less than or equal to 0.1. An illustrative example of this process is shown in Table 2.

Table 2: Example of the stochastic treatment of secondary duty occurrences. Only a single unit state is considered.

Frequency of secondary duty	20 events per year
Probably of instance beginning each day	20 ÷ 360 = 0.056
Distribution of random number generation	Uniform distribution
Interval of random number generation	[0,1]
Requirement for instance to begin on day	Random number ≤ 0.056

Each instance of a secondary duty requiring attention is spread across a number of days equal to the window length of that secondary duty during the unit state at the beginning of the instance. From this, an end date is computed for each date on which an instance begins. In cases where an end date would extend beyond the end of the calendar, the beginning date is moved up. Recalling that the final month is discarded to avoid edge effects, the shifting of the start and end dates will not impact the simulated schedules output by the code unless a very long window is being considered.

Secondary duty instances that begin in one unit state are allowed to extend to the following one, with the secondary duty values for the entire instance being those of the first day of the instance. For example, if a secondary duty instance begins on the last day a ship is at sea on operation before returning to its home port, the three-point time estimate and window length corresponding to being at sea on operation are used for the entire instance even though some days occur while the ship is no longer at sea.

The model then simulates the completion of secondary duties by assigning hours to days within the corresponding windows. The number of hours to be allocated is generated using random number generation from the triangular distribution defined by the three-point estimate available for that secondary duty and unit state. Rather than distribute the hours among the days within the secondary duty window evenly, a heuristic approach is used to balance the total workload of the days. The heuristic approach is described in Section 3.4.

In cases where a sailor is assigned more than one secondary duty, the model iterates over them, adding the hours they require to both the secondary duty and total workload schedule. Once all secondary duties for a unit position are completed, the model moves on to simulating the schedule of the next unit position until all schedules have been generated. At this point, the primary duty, secondary duty, and total workload schedules for all unit positions are output separately as comma-separated-value files for analysis or import into other programs.

3.4 Heuristic Approach for Assigning Hours

In the heuristic approach, what is known of the total workload of the sailor is used to decide how the time required by a secondary duty instance is distributed between the days within that instance's window. Before any secondary duties are considered, the total workload of the sailor is simply their primary duty workload. As the schedule of each of their secondary duties are simulated, the hours required by those duties are added to the total workload.

The goal of the approach is to follow how sailors manage their time by attempting to distribute the hours required by a secondary duty in a way that avoids creating days with extreme workload. In practice, this means assigning more hours to days with light workloads than days with heavy workloads. This is done by dividing the amount of work required by the secondary duty instance by the number of days in the window of that secondary duty instance to create several units of time that must be allocated. In an iterative approach, each unit of time is added to the day in the window with the lowest number of hours in the total workload schedule, with the total workload schedule being updated to account for each added unit.

As an example, consider a scenario where a sailor is serving aboard a ship at sea and is working roughly 12 hours per day. The total workload of the sailor before any secondary duty hours are scheduled is shown in Figure 1 where Day 1 corresponds to Monday.

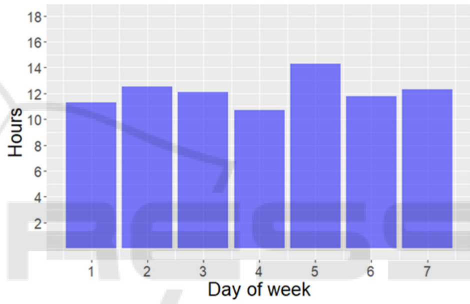

Figure 1: Plot of one week of total workload before secondary duty hours are added.

The sailor is assigned a secondary duty. On Thursday morning, the sailor becomes aware that they have two days to complete four hours of work for their secondary duty. This means that four hours of secondary duty work have to be assigned to Thursday and Friday, which correspond to the two-day window of this instance. If the time is divided equally between the two days, they end up working 16.3 hours on the Friday and only 12.7 hours on the Thursday, as shown in Figure 2.

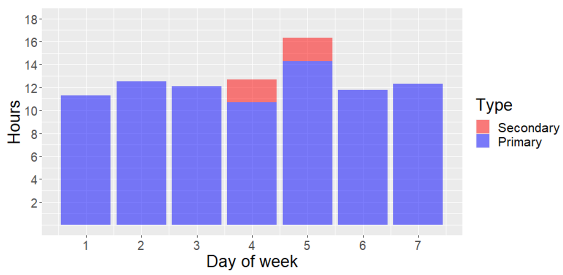

Figure 2: Plot of one week of total workload when the secondary duty hours are evenly distributed. Two hours are added to both Thursday and Friday in red.

If the sailor knew that they were going to be working more hours on Friday than Thursday, they may choose to complete all four hours of the secondary duty on Thursday. The heuristic approach has the same effect, since the four required hours are divided into two units of two hours each, both of which are assigned to Thursday. This leads to a total workload of 14.7 hours on Thursday and 14.3 hours on Friday, as is seen in Figure 3.

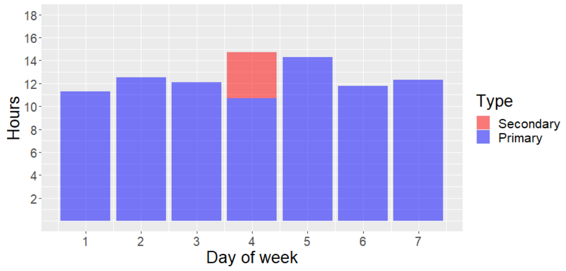

Figure 3: Plot of one week of total workload when the heuristic approach is used to allocate the secondary duty hours. All four hours are added to Thursday in red.

Through use of the heuristic approach to allocate hours, the maximum workload encountered on a single day is reduced from 16.3 to 14.7. More importantly, the heuristic approach follows how individuals manage time, making the model more representative of reality.

4 NOTIONAL EXAMPLE OF RESULTS

An example of the application of the simulation model is presented in this section. Notional data is used.

Consider a sailor serving aboard a ship that will spend the first half of a year at sea in an operational footing before returning to home port for the remainder of the year. The unit state inputs for this case are shown in Table 3, where an additional month has been added to the beginning and end to avoid edge effects, as discussed in Section 3.3. It is the year spanning from the 2nd to 13th months that is output for analysis.

Table 3: Unit state for each month in the notional example.

Months	Unit state
1-7	At sea on operation (SO)
8-14	Alongside home port (AH)

The sailor's primary duties require between 10 and 15 hours per day when at sea on operation, with a most-likely value of 12.5. When in home port, their primary duty time requirements are shorter and less varied and range from seven to nine hours per day with a value of eight being the most likely. This is summarized in Table 4, which shows only the relevant data from the primary duty input file.

Table 4: The primary duty input values for the sailor being described in the notional example.

SO: Minimum required hours per day	10
SO: Most-likely required hours per day	12.5
SO: Maximum required hours per day	15
AH: Minimum required hours per day	7
AH: Most-likely required hours per day	8
AH: Maximum required hours per day	9

On top of their primary duties, the sailor is also responsible for two secondary duties. They do not share the duties with any other sailors, so they are responsible for the full time requirements of both. The first duty requires just as much work when the ship is at sea on operation as when it is alongside its home port, but the other is much more demanding when the ship is at sea. The relevant data from the secondary duty input file are shown in Table 5.

Table 5: The input values for the two secondary duties assigned to the sailor in the notional example.

Duty	**1**	**2**
SO: Instances per year	26	8
SO: Minimum required hours of instance	2	10
SO: Most-likely required hours of instance	4	15
SO: Maximum required hours of instance	6	20
SO: Days in window	2	5
AH: Instances per year	26	2
AH: Minimum required hours of instance	2	3
AH: Most-likely required hours of instance	4	6
AH: Maximum required hours of instance	6	9
AH: Days in window	2	2

Based on the input values, and without running the simulation, the sailor is expected to spend 12.5 hours on their primary duties each day when at sea on operation. Over the course of the six months spent on operation, they would expect to spend 52 hours on their first secondary duty and 60 hours on their second. With no further knowledge of the secondary duties, one could assume that they can be divided up over all 180 days of the time period and result in a daily workload of approximately 37 minutes per day. This would bring the length of the overall sailor's workday from 12.5 hours to roughly 13.1 hours, leaving 10.9

hours for rest and recovery. It is unlikely that such a case would be flagged as unreasonable or as putting the sailor at high risk of becoming fatigued.

When the simulation model is run using the inputs, the impact of the secondary duties on individual days becomes clear. An example of a single simulated year (a single replication) is shown in Figure 4, where it is seen that the sailor works many more hours during some days than others regardless of the state of the ship.

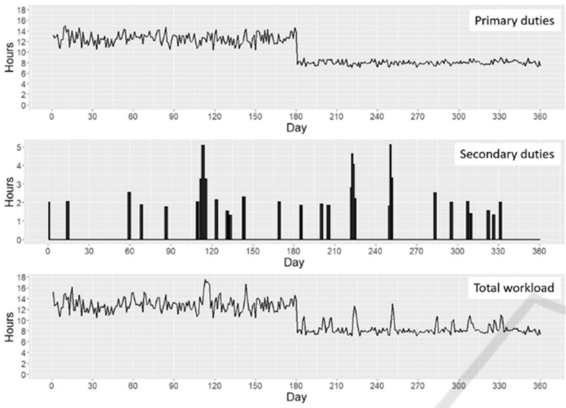

Figure 4: Primary duty, secondary duty, and total workload of a single simulated year for the sailor in the notional example.

Looking specifically at the first six months of this replication, corresponding to when the sailor is at sea on operation, the sailor works between 10.39 and 17.52 hours each day with a mean of 12.89 hours. The sailor is assigned secondary duty work hours on 26 of the 180 days.

The stochastic nature of the model makes it necessary to analyze multiple replications to ensure accurate statistics are generated, since consecutive replications will differ. For example, the next four replications of the notional experiment are plotted in Figure 5. The minimum number of hours worked in each replication are 10.23, 10.07, 10.25, and 10.31, respectively. The corresponding maximum values are

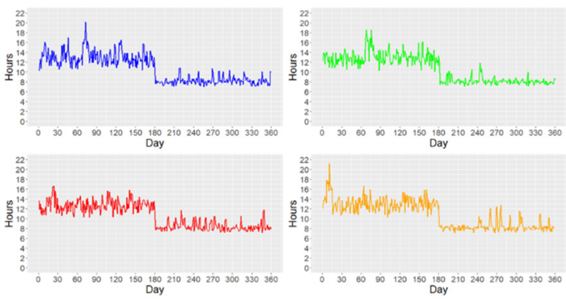

Figure 5: Four additional replications of a simulated year for the sailor in the notional example.

20.17, 18.65, 16.64, and 21.12. Far more variation is seen in the maximum total workload values than the minimum values due to the difference in sample size of days with low and high workload. This is due to small total workload values occurring when no secondary duties are performed, which is relatively common, and high total workload values occurring when multiple instances of secondary duties being performed overlap, which is less common.

In total, 100 replications of the notional example simulation were completed and aggregate statistics were generated from those. Focusing on the first six months of the simulated year, when the ship is at sea, a total of 18,000 simulated days are contained in the 100 replications. The mean of all the simulated days is 13.10 hours, which agrees with the calculation performed without using the model. The shortest workday seen is 10.04 hours and the longest is 23.71 hours. The maximum value represents a day where many secondary duty instances are occurring concurrently. While an outlier, the existence of such a day demonstrates the risk associated with assigning multiple secondary duties to a single sailor.

The total workloads of all 18,000 days are represented in the distribution shown in Figure 6. It is seen that the triangular distribution of the primary duty workload, which ranges from a minimum of 10 to a maximum of 15, is the dominant feature of the distribution, although the addition of secondary duty hours adds significant positive skew.

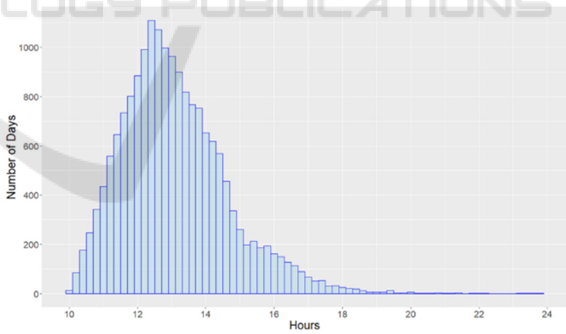

Figure 6: The distribution of total workload in the 18,000 simulated days falling within the first six months of the notional example.

In Table 6, the probability of workloads exceeding certain thresholds are given. This probabilistic treatment provides a much better sense of the workload the sailor would experience during the time at sea than the mean value of 13.1 hours computed before completing the simulation. For example, more than five percent of days require the sailor to work at least 16 hours, leaving less than eight hours for rest and recovery. Such a statistic is more suitable for predicting fatigue than the daily mean.

Table 6: Probability of daily workloads more than various numbers of hours computed for the first six months of the notional example.

Number of hours worked	Probability of day requiring more work
10	1
11	0.9415
12	0.7530
13	0.4679
14	0.2426
15	0.1082
16	0.0524
17	0.0197
18	0.0078
19	0.0034
20	0.0014
21	0.0008
22	0.0003
23	0.0002
24	0

5 VERIFICATION

The model was first implemented in the R programming language version 4.1.1 (R Core Team, 2021). Verification of the R version was first completed by comparing statistics generated using simulated schedules to those computed analytically. Next, several experiments were designed to isolate and challenge code features so that errors in the implementation could be identified and corrected.

The simulation model was then implemented a second time in Python version 3.8.8 (Python Software Foundation, 2021). The Python implementation made use of the Pandas package (Pandas Development Team, 2021) to allow it to closely follow the R implementation. Identical experiments could then be run in both implementations and the results could be compared to check for issues with either implementation or the functionality of the packages involved.

As an example, the experiment discussed in the notional example was run in both Python and R. Table 7 summarizes results from both implementations. Values from the first six months are shown to avoid conflating time at sea with time in port. The results of single replications differ in R and Python, but this is expected due to the stochastic nature of the model. Similar differences were seen when comparing individual replications performed in the same programming language. The results converge when many replications are considered, as is done in the table. It is also noted that values that include secondary duties tend to display more variation in the mean between replications, which manifests as a larger standard error. This is due to the limited number of secondary duty instances in a year, meaning the sample size of days with secondary duty hours is smaller than that for days with primary duty hours.

The distributions of daily total workload hours simulated for the sailor from the notional example in one replication and 100 replications are compared in Figure 7. Again, only the first six months are included. When considering all 100 replications, only the outliers are discernibly different when comparing the Python and R outputs.

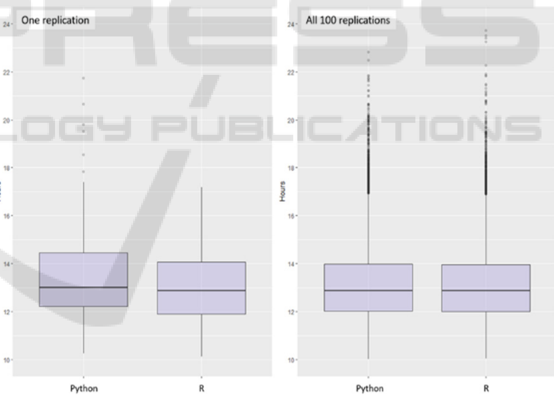

Figure 7: Distributions of total workload hours computed in both Python and R.

Table 7: Summary of results for an experiment performed in both R and Python. 100 replications were completed.

Output variable	Mean			Standard Error	
	Python	R	|Δ|	Python	R
Mean daily primary duty workload (hours)	12.49865	12.50428	0.00563	0.00676	0.00748
Mean daily secondary duty workload (hours)	0.61707	0.59184	0.02523	0.01640	0.02001
Mean daily total workload (hours)	13.11571	13.09612	0.01959	0.01752	0.02125
Minimum daily total workload (hours)	10.25510	10.26931	0.01421	0.01256	0.01384
Maximum daily total workload (hours)	18.93740	18.58606	0.35134	0.17311	0.16486
Days with > 16 hours of total workload (days)	9.68	9.43	0.25	0.44	0.53

6 PERFORMANCE

Performance benchmarking was completed using an experiment designed to imitate simulating a large crew: 100 replications of schedule simulation for a crew consisting of more than 200 positions that is assigned 58 secondary duties. Primary duty workload inputs were identical for most unit positions, with a few excursions inserted manually. Similarly, the inputs of only a few secondary duties were unique. The assignment of secondary duties to unit positions was mostly ordinal: the Nth secondary duty was assigned to the unit position occupying the Nth position in the list. A few exceptions were inserted manually so shared secondary duties and cases of sailors being assigned multiple secondary duties would exist in the test data.

Testing was done on a laptop with a four-core 1.9 GHz processor. The results are presented in Table 8, where it is seen that the Python version executes roughly 12 times faster than the R version despite being structured similarly through the use of the Pandas package and data frames.

Table 8: Benchmarking of the R and Python versions.

	Run time (minutes:seconds)
R	6:01
Python	0:34

7 CONCLUSION

A model that simulates sailor workload has been presented. By combining primary and secondary duties stochastically, it is seen that schedules produced by the model provide a fuller description of sailor working life than deterministic estimates of expected workday lengths. The simulated schedules are ideal for use in applications where extreme values in daily workload must be considered including crew design and research into crew fatigue.

Monte Carlo experimentation using the model can be used to identify individual secondary duties or combinations of secondary duties that have a large impact on sailor workload. In this way, the model can be used to guide the assignment of secondary duties or identify secondary duties that may need to be adjusted or shared between multiple sailors.

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