2014-09

Optimization of Continuous Maintenance Availability Scheduling

Anderson, Cyrus K.

Monterey, California: Naval Postgraduate School

http://hdl.handle.net/10945/43868

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

OPTIMIZATION OF CONTINUOUS MAINTENANCE AVAILABILITY SCHEDULING

by

Cyrus K. Anderson

September 2014

Thesis Advisor:	Javier Salmeron
Second Reader:	Michael Dufek

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

<table>
<tr><td colspan="3">REPORT DOCUMENTATION PAGE</td><td>Form Approved OMB No. 0704–0188</td></tr>
<tr><td colspan="4">Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202–4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704–0188) Washington DC 20503.</td></tr>
<tr><td>1. AGENCY USE ONLY (Leave blank)</td><td>2. REPORT DATE
September 2014</td><td colspan="2">3. REPORT TYPE AND DATES COVERED
Master’s Thesis</td></tr>
<tr><td colspan="3">4. TITLE AND SUBTITLE
OPTIMIZATION OF CONTINUOUS MAINTENANCE AVAILABILITY SCHEDULING</td><td rowspan="2">5. FUNDING NUMBERS</td></tr>
<tr><td colspan="3">6. AUTHOR(S) Cyrus K. Anderson</td></tr>
<tr><td colspan="3">7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943–5000</td><td>8. PERFORMING ORGANIZATION REPORT NUMBER</td></tr>
<tr><td colspan="3">9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A</td><td>10. SPONSORING/MONITORING AGENCY REPORT NUMBER</td></tr>
<tr><td colspan="4">11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ____N/A____.</td></tr>
<tr><td colspan="3">12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited</td><td>12b. DISTRIBUTION CODE</td></tr>
</table>

13. ABSTRACT (maximum 200 words)

Every few months each United States submarine must return to a port to undergo major maintenance that cannot be conducted at sea. These maintenance periods are called Continuous Maintenance Availability (CMAV) periods. All CMAV scheduling aboard the two remaining submarine tenders in the United States fleet, the USS *Emory S. Land* (AS 39) and the USS *Frank Cable* (AS 40), is currently done manually. The schedulers rely on their experience and sound judgment with the goal of successfully completing the most maintenance as quickly and efficiently as possible for approximately 200 jobs, 50 maintenance shops and a host of other considerations.

In this thesis, we develop a job-shop scheduling model, the CMAV Scheduler (CMAV-S). This is a large-scale, mixed-integer, linear program that accounts for a variety of scheduling inputs commonly used by planners: job priority, duration, allowed window of execution, prerequisites, mandatory character, workforce used and available (by shop), and special submarine conditions (active or inactive) needed to perform a job. CMAV-S produces near-optimal schedules that achieve maximum value for all scheduled jobs in about one minute. When compared to our own manual scheduling, we observe CMAV-S improves up to 25% the required CMAV length to schedule all maintenance.

<table>
<tr><td colspan="3">14. SUBJECT TERMS
Optimization; Submarine Maintenance; Job-shop Scheduling; Continuous Maintenance Availability</td><td>15. NUMBER OF PAGES
69</td></tr>
<tr><td colspan="3"></td><td>16. PRICE CODE</td></tr>
<tr><td>17. SECURITY CLASSIFICATION OF REPORT
Unclassified</td><td>18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified</td><td>19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified</td><td>20. LIMITATION OF ABSTRACT
UU</td></tr>
</table>

NSN 7540–01–280–5500 Standard Form 298 (Rev. 2–89)
Prescribed by ANSI Std. 239–18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

OPTIMIZATION OF CONTINUOUS MAINTENANCE AVAILABILITY SCHEDULING

Cyrus K. Anderson
Lieutenant, United States Navy
B.S., United States Naval Academy, 2006

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
September 2014

Author: Cyrus K. Anderson

Approved by: Javier Salmeron
Thesis Advisor

Michael Dufek, CDR, U.S. Pacific Fleet, Submarine Force
Second Reader

Robert F. Dell
Chairman, Department of Operations Research

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Every few months each United States submarine must return to a port to undergo major maintenance that cannot be conducted at sea. These maintenance periods are called Continuous Maintenance Availability (CMAV) periods. All CMAV scheduling aboard the two remaining submarine tenders in the United States fleet, the USS *Emory S. Land* (AS 39) and the USS *Frank Cable* (AS 40), is currently done manually. The schedulers rely on their experience and sound judgment with the goal of successfully completing the most maintenance as quickly and efficiently as possible for approximately 200 jobs, 50 maintenance shops and a host of other considerations.

In this thesis, we develop a job-shop scheduling model, the CMAV Scheduler (CMAV-S). This is a large-scale, mixed-integer, linear program that accounts for a variety of scheduling inputs commonly used by planners: job priority, duration, allowed window of execution, prerequisites, mandatory character, workforce used and available (by shop), and special submarine conditions (active or inactive) needed to perform a job. CMAV-S produces near-optimal schedules that achieve maximum value for all scheduled jobs in about one minute. When compared to our own manual scheduling, we observe CMAV-S improves up to 25% the required CMAV length to schedule all maintenance.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

AOR	area of responsibility
ATEM	Air Tasking and Efficiency Model
CENTCOM	United States Central Command
CMAV	Continuous Maintenance Availability
CMAV-S	Continuous Maintenance Availability Scheduler
MAF	maintenance action form
PACOM	United States Pacific Command
pers. comm.	personal communication
PSOM	Planned Maintenance Scheduling Optimization Model
RSOM	Rescheduling Optimization Model

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

Every few months each United States submarine must return to a port to undergo major maintenance that cannot be conducted at sea. These maintenance periods are called Continuous Maintenance Availability (CMAV) periods. All CMAV scheduling aboard the two remaining submarine tenders in the United States fleet, the USS *Emory S. Land* (AS 39) and the USS *Frank Cable* (AS 40), is currently done manually, using Microsoft Project. The schedulers rely on their experience and sound judgment with the goal of successfully completing the most maintenance as quickly and efficiently as possible. As with all complex scheduling operations, this is a manpower intensive, tedious process. Even though all maintenance to be completed is known at the time of scheduling, there are often over 200 jobs to assign to approximately 50 maintenance shops and a host of other considerations, making CMAV scheduling a challenging task.

In this thesis, we develop a job-shop scheduling model, the CMAV Scheduler (CMAV-S). This is a large-scale, mixed-integer, linear program that accounts for a variety of scheduling inputs commonly used by planners: job priority, duration, allowed window of execution, prerequisites, mandatory character, workforce used and available (by shop), and special submarine conditions (active or inactive) needed to perform a job. In addition, we add a value parameter that planners can use to further establish prioritization of the jobs.

CMAV-S produces near-optimal schedules that achieve maximum adjusted value (which includes the job's priority, its value, and the time when the job is scheduled) for the total of all scheduled jobs. The schedules can be utilized for CMAV planning and potentially benefit the submarine community. Specifically:

- CMAV-S can generate near-optimal schedules from a desired list of maintenance in about one minute. This can alleviate the need to schedule maintenance manually and significantly improve the schedule production process.

- The short runtimes also allow schedulers to re-run the model a number of times with different inputs (e.g., schedule lengths, condition initial status, mandatory jobs) in order to plan for an upcoming CMAV. This allows

them to answer "what-if" questions about possible restrictions and alternate schedule possibilities in minutes rather than hours.

We anticipate the potential advantage of CMAV-S over manual scheduling to be significant. For example, when compared to our own manual scheduling, we observe improvements of up to 25% in reducing the required CMAV length to schedule all maintenance. However, CMAV-S still needs to be tested on large-scale, real-world instances in order to be validated for use by tender planners.

I. INTRODUCTION

A. BACKGROUND

Since World War I, submarine warfare has continually increased in importance and sophistication. Due to their inherently covert nature and requirement for high system-readiness, submarines are limited in the level of maintenance that can be completed underway. This restriction is significantly greater than for surface vessels due to the submarines' inability to easily receive spare parts and the confined environment of being mostly submerged at all times.

Historically, submarines have been supported by surface ships that became de facto submarine tenders; these ships were originally used as floating supply and weapon depots that would also help with maintenance. As submarines progressed in technological complexity so did the requirements for support. This gave rise to the designated submarine tenders developed just prior to World War II that repair ships at sea and provide logistical support. Submarine tenders were used heavily throughout World War II and up through the Cold War. The military downsize in the 1990s reduced the United States' tender fleet from ten to two, the USS *Emory S. Land* (AS 39) and the USS *Frank Cable* (AS 40) (Global Security 2011).

Tenders today are essentially floating factories, capable of large-scale maintenance due to their full complement of submarine repair shops aboard. Their ability to moor up to four nuclear attack submarines at once allows each tender to service an entire area of responsibility's (AOR's) worth of submarines (Global Security 2011). With the USS *Emory S. Land* and the USS *Frank Cable* home-ported in Diego Garcia and Guam, respectively, the two tenders can support large-scale submarine operations throughout Pacific Command (PACOM), Central Command (CENTCOM), and the western portion of African Command (Department of the Navy 2013b). As can be expected of an AOR of this size, scheduling to accomplish maintenance quickly becomes a herculean task.

The primary difficulty in scheduling arises from the duality in the tender's responsibility. They are charged with intermediate-level maintenance and are therefore under the same requirements and standards of work as the shore-based maintenance facilities in Hawaii, Bangor, and others. However, as an asset of the Military Sealift Command the tenders still have all of the requirements and responsibilities of a sea-going vessel. This unity of requirements given by a moving maintenance facility presents all the scheduling challenges of intermediate-level maintenance with the logistics, timing, and sea-qualification issues of a ship (Pickett 2013). In order to alleviate some of these challenges, the tenders asked for assistance in the development of a scheduling optimization tool to effectively allocate the submarine tenders' time and resources to the financial and readiness benefit of the United States Navy.

B. PREVIOUS WORK

In 2013, Major Josiah Pickett created the Planned Maintenance Scheduling Optimization Model (PSOM) and the Rescheduling Optimization Model (RSOM) (Pickett 2013). These mixed-integer, linear optimization models attempted to coordinate the allocation of work between the two submarine tenders.

One of the most obvious deficiencies addressed by Major Pickett is the work disparity between the USS *Emory S. Land* and the USS *Frank Cable* (Pickett 2013). The *Emory S. Land* is stationed in Diego Garcia and primarily supports CENTCOM with its relatively light submarine activity. Conversely, the *Frank Cable* is based in Guam and supports PACOM, which arguably has the highest submarine traffic of any area in the world. This means the *Frank Cable* is often at maximum capacity while the *Emory S. Land* has time to spare simply due to geographic workload demands (Pickett 2013). PSOM is designed to take into account all current maintenance requests in both the CENTCOM and PACOM in order to prioritize and schedule the requests. A number of constraints are considered for correctly assigning maintenance assets:

- Tender presence: Most levels of maintenance require tender presence, but some can be addressed with a detachment of maintenance personnel that can be flown from the tender to a suitable port near the submarine in question. (Pickett 2013)

- Distance to travel: The tenders often traverse most of the distance to the submarine to reduce the amount of off-station time for the submarine. However, maintenance performed at remote, isolated areas constrains tender availability for other requests. (Pickett 2013)

- Cost: Tenders regularly receive more requests that can be immediately fulfilled. Along with maintenance urgency, cost is often a determining factor in whether or not the maintenance is completed on station or deferred until the next maintenance period. (Pickett 2013)

- Capacity: There is a limited amount of manpower available aboard a given tender. For example, if a job requires a large number of man-hours for a skill possessed by only a few workers (e.g., electrician, welder), the job may have to be postponed until the workers are available. (Pickett 2013)

Major Pickett's PSOM effectively optimizes a schedule for a month's worth of maintenance in an AOR for both tenders. However, the PSOM is based on an unrealistic assumption that all maintenance is known for the month and is not subject to change. To rectify this, Major Pickett builds RSOM, which is a rescheduling tool that allows a previously built and partially executed PSOM schedule to be optimally adjusted given new maintenance requests (Pickett 2013). The combination of the two models allows a flexible optimized balance for maintenance requests that are more evenly shared between the *Emory S. Land* and the *Frank Cable*.

C. RESEARCH PURPOSE AND OBJECTIVES

Although the PSOM and RSOM are an initial approach to alleviating some of the challenges in tender scheduling, they are not practical for use by the tenders' schedulers. Late in Major Pickett's thesis development, the tenders expressed interest in a job-shop scheduler that would assign specific maintenance actions to appropriate workshops aboard a single tender, as opposed to dividing all maintenance between tenders (Pickett 2013). Addressing that late-term request is the purpose of this thesis.

Currently, all scheduling of maintenance aboard the USS *Emory S. Land* and the USS *Frank Cable* is done manually (i.e., without the help of any formal, computational planning tool) using Microsoft Project (Commander Michael Dufek, pers. comm.). The schedulers rely on their experience and sound judgment to create effective, error-free schedules. These are created with the goal of successfully completing the most maintenance as quickly and efficiently as possible. As with all complex scheduling operations, this is a manpower-intensive, tedious process. Operations completed by the tenders range from a small detachment of personnel flying to the submarine in question to large-scale maintenance (excluding dry-dock). Since the variability and scope of the maintenance is rather broad, a job-shop scheduling model for all possible tender maintenance is beyond the scope of this research.

However, each submarine needs a Continuous Maintenance Availability (CMAV) period approximately every 3–4 months, and generally requires about a month to complete it. These are periods in which maintenance that cannot be completed (or is not important-enough to complete) at sea is accomplished. Essentially, a CMAV period is a maintenance period where a submarine fixes any system that has malfunctioned in the last months along with any preventative maintenance (Lieutenant Jimi Boydstun, pers. comm.). The maintenance action forms (MAFs), which are written when a known maintenance deficiency is discovered, document what maintenance will need to be addressed during the CMAV. Even though all tasks are known at the time of scheduling, there are often over 200 jobs to assign to approximately 50 maintenance shops and a host of other considerations, making CMAV scheduling a challenging task (Department of the Navy 2013a). This section of tender scheduling is limited-enough in scope to lend itself to modeling via formal mathematical optimization.

Accordingly, this thesis pursues to develop the CMAV Scheduler (CMAV-S), an optimization model and tool to guide scheduling decisions for submarine maintenance jobs performed by the submarine tenders. CMAV-S allows schedulers more time to handle time-sensitive issues and gives the produced schedule a degree of guaranteed optimality. CMAV-S can handle typical tender scheduling problems consisting of 200 jobs (including 20 submarine "conditions," see Section II.B.3.), and 20 heavily utilized shops, over the course of 25–50 days.

II. CONTINUOUS MAINTENANCE AVAILABILITY SCHEDULER MODEL

A. LITERATURE REVIEW

Maintenance scheduling has been studied for decades but still remains a difficult problem. The challenge is finding the best use of the limited time and manpower resources in order to complete repairs.

One common mathematical approach to maintenance scheduling is the job-shop scheduling model. Simon French begins his description of the general job-shop scheduling problem as follows: "Suppose that we have *n* jobs $\{J_1,J_2,\ldots J_n\}$ to be processed through *m* machines $\{M_1,M_2,\ldots M_m\}$" (French 1982, 5–6). Although astoundingly simple, this description is the core of job-shop modeling and can be adapted to a large spectrum of real-world scenarios. Augmenting this base case with job and machine characteristics as well as flow constraints allows the creation of models that accurately reflect the process being studied.

A major subdivision of job-shop scheduling is that of deterministic versus stochastic. For a deterministic model, all data (such as job duration) are assumed to be known in advance. Stochastic models are used in situations where some of the input values may not be exactly known; instead, only their probability distributions are known (Pinedo 2010, 7). Although it is likely that some data will not be known prior to scheduling, the nature of CMAV scheduling lends itself to deterministic job-shop modeling since the distribution of the maintenance uncertainty is difficult to establish by tender planners.

Within the deterministic subdivision of shop scheduling there exist a number of models to address problem-specific issues: the single-machine model, the parallel-machines model, flow shops, job shops, and open shops. Single machine models are used to represent the order of jobs through a single processor (Pinedo 2010, 35). Parallel machines models are used to study the effect of balancing a workload across a number of single machines. With parallel machines, the machines may be identical, different or a combination (Pinedo 2010, 111). Flow shops are a case of parallel machines in which all jobs follow the same path (Pinedo 2010, 151). Job shops are flow shops in which the route a job will take is predetermined but not necessarily the same as the other jobs in the model (Pinedo 2010, 183). Finally, open shops are job shops in which the routes a job may take are not predetermined, that is, they are optimized by the model (Pinedo 2010, 221).

The CMAV-S model can be viewed as a specialized job-shop model that consists of many groups (shops) of identical processors (workers). Each job occupies a number of processors from one or more shops until it is completed. Any job that requires more processors from a single shop than are currently available must be scheduled at a later time. Many job-shop scheduling problems require a job to be routed through a sequence of processors before being completed. The CMAV-S model is simpler in this regard because each job has only one stop in its routing; however, its complexity comes from the requirement that a job occupies all of its processors (i.e., workers from one or several shops) simultaneously. This compresses the job's routing process into a single step where it temporarily occupies a large amount of the available workforce for a short time.

For any job-shop model there are a number of constraints to be considered, one of which is precedence relationships: some jobs may not proceed until another job is started or has been completed (Pinedo 2010, 16). This relationship can also be dependent on a minimum or maximum lag time from a job's start or finish time, depending on the situation (Escudero and Salmeron 2005). The CMAV-S precedence relationship is "finish to start," meaning that all predecessors must be finished prior to the subsequent job's start. That is, the minimum lag time is always set as the preceding job's duration.

Another typical constraint is the addressing of due dates. Jobs may have a time period by which they are required to be completed. The requirement is often modeled as an elastic constraint, where a violation of the due date is allowed with a penalty (Baker and Trietsch 2009, 21–29). This variation can also be applied to an earliest possible start date. All jobs in the CMAV-S have hard earliest and latest start dates.

From maintenance and assembly to delivery and operation, job-shop scheduling is used in business, industry and a host of Department of Defense applications. The approach to creating these schedules varies from one application to the next. The use of a computational tool often increases the speed with which the schedules are produced and their quality. One such approach is genetic algorithms. For example, Thomas Stidsen and his team generate a tool to aid scheduling for Odense Steel Shipyard, the largest in Denmark. An algorithm is applied to determine the order in which a work station would assemble and weld a ship together to maximize throughput and workspace usage. The algorithm is a heuristic but it generates reasonable, tentative schedules that can be refined by the schedulers (Stidsen et al. 1996).

Optimality may not be a priority in the face of a time constraint. For example, the Air Tasking and Efficiency Model (ATEM) can be solved exactly as a mixed-integer program, but it requires long runtimes. Instead, the authors develop a heuristic that yields a much quicker solution (Brown et al. 2013). ATEM optimizes the routing and cargo loads for military cargo aircraft throughout Iraq. Based on the demand for cargo and personnel needing to be moved, ATEM optimally routes all available aircraft to satisfy the demand. It takes into account aircraft capability, cargo due dates, and even crew rest. The resulting efficiency increase allows a reduction in aircraft fleet size, satisfies nearly all demand, and allows greater aircraft down time for much needed aircraft maintenance. Although not guaranteed, the ATEM heuristic consistently satisfies nearly all demand and is close to optimal when checked against the long-run, exact solution (Brown et al. 2013). Although ATEM is not a job-shop model, it has many common elements to job-shop scheduling (e.g., cargo moved to a destination is similar to a job and the aircraft used to do so is similar to a shop).

Lieutenant Commander Roger Jacobs builds the Flight Training Scheduler to alleviate the challenges in scheduling training flights for Training Wing Two (Jacobs 2013). His optimization model assigns compatible pairs of instructors and students to available aircraft in order to progress students through the training syllabus as quickly as possible. The model has many characteristics of a standard flow-shop model in that students must move through the syllabus in a predetermined order. The pairs of students and instructors depend on the requirements needed for a particular flight. The students must have completed the required prerequisite flights and the instructor must be sufficiently qualified to instruct that event. The Flight Training Scheduler generates high-quality schedules in a fraction of the time that it takes to build them manually. A guaranteed 85%-optimal solution can be achieved in about 30 minutes, with the fully optimal solution requiring up to several hours (Jacobs 2013).

The ultimate goal in building these models is accurately reflecting reality so that the output is useful, a challenge unique to each potential application. As discussed in Section I.B., the CMAV-S model developed in this thesis is a continuation of the work by Pickett (2013) who develops a submarine tender scheduler from the view of coordination between the two tenders for an optimal distribution of AOR workload. A novel section of CMAV-S is representing the ship conditions (see Section II.B.3.). These constraints do not fall into any scenario in the literature reviewed and to our knowledge are unique to our model: Conditions behave as jobs in that they require shop workforce for set-up and take-down periods; they behave like precedence constraints in that they are required for other maintenance to be accomplished; yet, unlike jobs or precedence constraints, they are required to be active only while the job needing them is ongoing and require no workforce while they are active. They also require a unique set of constraints to establish the cyclical system that rotates them from inactive to active and vice versa.

B. PROBLEM SPECIFICATIONS

The completion of a CMAV is a highly variable process as one CMAV period can be completely different from the next. For example, its duration can range from three weeks to several months depending on the amount of maintenance required. The complexity of work can encompass everything from minor system corrections to depot-level repair; it can also include preventative maintenance. On the other hand, all CMAVs are similar in that each one is comprised of a list of jobs to accomplish, the shops that will complete them, and the required ship conditions that allow jobs to proceed. We describe these specifications next.

1. Jobs

The list of jobs that will be accomplished during a particular CMAV is generated from the MAFs for the submarine and any preventative maintenance for which the submarine is due. Anytime a system, item, or piece of machinery is broken or degraded a MAF is written to log the issue. Issues that are mission-critical and can be repaired at the time are completed and removed from the list of outstanding maintenance. Anything that remains uncorrected is set to be completed during the CMAV period. Each job has a number of parameters that are required to appropriately schedule and complete the repair.

a. Prerequisites

Certain jobs can only be started after another job has been completed. Therefore, the jobs must be scheduled in the correct sequence to ensure the working order of all supporting systems. This need not be limited to a single prerequisite. For example, replacement of a valve may be a prerequisite for a hydraulic pump and pneumatic vent. On the other hand, two or more maintenance actions may be required prior to replacing the valve.

b. Duration

The approximate time required for the completion of a job is assumed to be known prior to scheduling. In this thesis, that parameter is estimated to the nearest day. There could be consideration given to the notion that a job could be completed more quickly or more slowly if the allotted workforce were increased or decreased, respectively. However, due to the fact that the man-hours relationship is non-linear (and difficult to estimate), the CMAV-S will use the approximate duration given the "typical" workforce needed for each job.

c. Job Workforce

The standard number of workers required to complete the maintenance is known for each shop contributing to the maintenance action. The workforce, along with the duration, is an educated estimation assigned by skilled schedulers experienced with submarine maintenance. The workers assigned to a job are considered engaged, and therefore unusable for any other job, for the entire duration of the MAF in question. Although this "non-preemption" assumption is not completely accurate (since maintenance personnel assigned to a large, high-priority job will often work on quick jobs in between), it is an effective simplification for deconfliction of the large maintenance actions.

d. Priority

MAFs can have priority "1," "2," "3," or "4." Priority "1" jobs are often mission- or safety-critical, with the lower priorities gradually reducing in criticality. Priority "4" jobs are often cosmetic or convenience-related and will be corrected if the time and resources are available; they will also be the first to be differed in a maintenance-constrained environment. The priority category of a job is set by maintenance personnel and regulations, and is not subject to change.

e. Value

In order to replicate the flexibility a manual schedule allows, we introduce a job-value parameter to single out jobs that may ignore a priority rule in case of special circumstances. For example, if a certain low-priority job is more urgent than its priority would suggest, due to a special mission or an admiral's behest, it can be given a high value. There is also a slight value decrease for maintenance actions scheduled later in the maintenance period to ensure that jobs are scheduled as early as possible (provided that they do not negatively impact the scheduling of other jobs). This deduction is small enough that it will never forego maintenance late in a period, but encourages moving jobs toward the beginning of the period. That is, no gaps are left in the schedule that can be avoided. Thus, the overall adjusted value given to a job scheduled at a certain period is given by three terms: job priority, job value, and period (see calculation in Section II.C.2).

f. Earliest and Latest Day

Aside from the prerequisite requirements, jobs may need to be delayed; for example, if a needed part will not be available until two weeks into the CMAV period.

Likewise, if there is an important inspection that happens early in a CMAV and a job must be completed prior to that inspection, the latest start day would have to be set forward in order to meet the deadline. We note that, by specifying earliest and latest days, a job can also be "hard-scheduled" (i.e., set to begin on a particular day with no flexibility).

g. Mandatory Jobs

The list of mandatory jobs is the minimum sub-set of jobs that must be completed in order for the CMAV to even be scheduled. This allows the scheduler to bypass the value and priority system for must-do jobs. If any job on the mandatory list cannot be completed, the scheduling problem is deemed infeasible and a schedule will not be generated.

2. Shops

Shops are the individual work centers available to the tender for maintenance. The list of shops remains mostly unchanged between CMAVs. Additional shops can be utilized in special cases, such as when hiring specialized contractors.

a. Shop Workforce

The total number of workers qualified to perform maintenance and assigned to a particular work center is the shop workforce. When a job is underway the required workforce is subtracted from the shop workforce for the duration of the job. This prevents the scheduler from overloading any shop. We assume the shop workforce remains constant for the duration of the CMAV.

b. Primary and Secondary Workshop

Since all jobs are coded to a particular shop, there is never confusion as to which shop conducts the maintenance; this is referred to as the lead or primary shop. However, some jobs may have secondary shop assignments if technicians from more than one shop are required. As with the primary shop, we assume all workforces required from secondary shops will be occupied until the job is completed.

3. Conditions

Submarines have many conditions that must be set in order to enable maintenance actions. For example, most welding done on the exterior sail of a submarine requires the setup of a scaffolding system called the racetrack. Each condition has four possible statuses: active, inactive, set-up or take-down. Between these four statuses, all possible forms of condition requirements for maintenance can be represented.

a. Condition Workforce

Like each job, conditions require maintenance personnel to set up and take down. The condition is also assigned to a particular shop and has a workforce that is required to change the condition's status. There is no penalty associated with a change in condition status other than the temporary consumption of workforce.

b. Job-condition Requirements

Any job may require a condition to be active or inactive in order for maintenance to proceed. The condition must be in the required state for the entirety of the job's duration. A job may have any number of condition requirements.

c. Mutually Exclusive Conditions

Certain conditions cannot be active at the same time. This allows any number of conditions affecting the same area to exist. For example, there may be three possible reactor conditions that are mutually exclusive (i.e., only one can be active at a time).

d. Initial Status

Each condition must start either active or inactive. For large condition changes that will be active for a long time (such as erecting scaffolding around the submarine's sail), it may be the practice to set it up prior to the CMAV's initiation. The initial status does not affect subsequent condition changes.

C. CREATING THE CONTINUOUS MAINTENANCE AVAILABILITY SCHEDULER MODEL

The CMAV-S model employs a linear, mixed-integer program designed to maximize the total adjusted value of all completed maintenance within a given planning period. A job's adjusted value is determined by priority, value and time.

1. Model Inputs

Adhering to the specifications in Section II.B., the CMAV-S model requires four categories of input: jobs, shops, conditions, and their interactions. These inputs are provided by the user via tables of data (described below in this section).

In addition, the user must input the length of the CMAV period (in days), which will affect the amount of maintenance that can be accomplished. CMAV-S will always maximize total (adjusted) value of the scheduled jobs. However, if the CMAV period length is too short, CMAV-S may not be able to schedule all maintenance. On the other hand, if the period is long enough to ensure all maintenance will be scheduled, CMAV-S will still attempt to schedule all jobs in the shortest amount of time because, barring job priorities and values, the adjusted values reward early scheduling.

a. Jobs

MAFs always contain both a job description and unique code (see Table 1). CMAV-S disregards the job description and uses the job code as its name (the description can be used as a reference list later). Aside from the job list, there is also a parameter table that assigns jobs their appropriate priority, value, duration and start day limitations (Table 2).

Table 1. Sample list of jobs

Job Description	Job Code
DSL VERT DRIVE	EA01_9537
EJECTION PUMP	WI01_2947
RUDDER RAM	CS15_Q929
TD-46 ACCUATOR	EA01_9494
LEAD HYDRAULIC PUMP	EA01_9569
SAIL PLATE FASTENERS	OC01_2845
TT#3 SLIDE VALVE	WI01_2783
MT #6 HATCH	WI01_2952
WEAPONS SHIPPING HATCH	WK01_1755

Table 2. Sample list of job parameters

	Priority	Value	Duration	Earliest	Latest
CS15_Q929	1	1	3	4	13
EA01_9494	2	5	4	12	14
EA01_9537	1	4	10	3	15
EA01_9569	1	1	3	12	14
OC01_2845	1	1	4	5	15
WI01_2783	1	2	14	16	19
WI01_2947	2	1	12	4	16
WI01_2952	1	1	12	5	10
WK01_1755	1	3	3	3	16

As can been seen in Table 2, a large portion of the jobs have priority “1.” The higher-priority jobs are more likely to involve greater deconfliction due to increased requirements (for manpower, equipment, or time) and therefore have a greater need for scheduling. For the purposes of the submarine tender scheduling, the lower-priority jobs (“3” and “4”) are not normally scheduled but are instead given to their corresponding shop to be completed when time permits (Dufek, pers. comm.). This is not a limitation to CMAV-S, which may or may not include the lower priority jobs as input data.

Often, the lower-priority jobs that are scheduled are important for reasons not obviated by their priority; correctly representing these jobs is the primary function of the value parameter. For example, job “EA01_9494,” in Table 2, has priority “2” and a value of five units. This incentivizes the CMAV-S model to prioritize it over, for example, a priority "1" job with a value of only one unit.

Some jobs require other maintenance to have been completed prior to the job in question's start day. For example, Table 3 shows that job "WI01_2783" cannot begin until its predecessor, "WI01_2947," has been completed. This can also affect strings of jobs. For example "OC01_2845" cannot be started until "EA01_9494" has been finished; however, "EA01_9494" has its own predecessor, "EA01_9537," which must be completed prior to "EA01_9494." This constraint allows for effective modeling of major quality assurance inspections that have many predecessors and sequences of maintenance.

Table 3. Sample of jobs with predecessors

Job	Job Predecessor
WI01_2783	WI01_2947
EA01_9494	EA01_9537
OC01_2845	EA01_9494

The final job-only table is for the "mandatory" job list. For the example in Table 4, if either job "EA01_9494" or "EA01_9537" cannot be completed with the time and resources provided, and even if every other job in Table 1 is completed, CMAV-S will return an infeasible status and no schedule will be generated.

Table 4. Sample of the mandatory job list

Madatory Jobs
EA01_9494
EA01_9537

b. Shops

All shops have an associated code. For example, “31F” is the hydraulics shop and “67H” is the antenna-repair shop (Table 5). The list of shops can be changed between CMAVs to account for personnel losses or newly qualified individuals. This allows non-tender personnel such as contractor specialists to be easily added to the system for a single CMAV and then nullified for subsequent schedule by assigning a workforce of zero.

Table 5. Sample shop list and associated workforce

Shop	Workforce
11A	10
31F	16
38A	13
31A	10
91E	5
67H	10

c. Conditions

The list of ship conditions used by CMAV-S is not the comprehensive list of all conditions set during a CMAV. The condition list is used to represent only the large-scale conditions that affect a number of jobs or that require a day’s worth of time or workforce to set up or take down. For example, the weapons shipping hatch repair, job “WK01_1755” shown in Table 1, has a required condition that the hatch be secured open. However, since this condition would not likely require a full day, a dedicated workforce, or affect other jobs in that area, it is not deemed significant enough for a CMAV-S condition. Conversely, the racetrack scaffolding assembly around the sail of the submarine (“Racetrack” in Table 6) will (a) require a significant workforce for most of a day to complete (set up or take down), and (b) be required active for some jobs and inactive for other jobs (significantly affecting nearly any maintenance on the sail exterior). For these two reasons, the “Racetrack” condition is considered significant enough to be a CMAV-S condition.

Table 6. Sample list of conditions

Conditions
Racetrack
VLS
DTO
Reactor_A
Reactor_B
Reactor_C

The initial status of a condition is determined by the scheduler (input table not shown). This function allows for the immediate scheduling of jobs that require conditions without waiting one day for set up, if the appropriate conditional requirements are initially set.

If conditions have mutual exclusivity requirements, these are listed in a separate table. For example, there are multiple reactor conditions that cannot all be active at once (see Table 7). Reactor conditions "A" and "B" can both be active at once or separately, but reactor condition "C" can only be active if "A" and "B" are inactive.

Table 7. Sample of mutually exclusive conditions

Mutually Exclusive Conditions	
Reactor_A	Reactor_C
Reactor_B	Reactor_C

d. Job-shop Interactions

The job-shop interactions determine the shops to which jobs are assigned, as well as the required workforce needed from that shop.

The primary shop assignment, dictated by the MAF or maintenance manual, is the first instance in the required-workforce list that bares the job's code. For example, job "CS15_Q929" seen in Table 8 has "38A" (outside machine shop) as its primary shop and will require three workers during its duration (three days, see Table 1). This job has no secondary shop. On the other hand, the ejection pump repair, job "EA01_9537," requires three workers from its primary workshop ("11A," shipfitters–welding) and one worker from its secondary workshop ("31A," inside machine shop). The model can allow many shops for a single job but more than three is not realistically needed.

Table 8. Sample of job-shop assignment and required workforce

Job	Shop	Required Workforce
CS15_Q929	38A	3
EA01_9494	31F	2
EA01_9537	11A	3
EA01_9537	31A	1
EA01_9569	38A	2
OC01_2845	31A	2
WI01_2783	31F	4
WI01_2947	11A	3
WI01_2952	31F	2
WK01_1755	31A	2

e. Job-condition Interactions

As stated previously, jobs may require a combination of conditions to be active or inactive in order for the job to be scheduled. For instance, job "WI01_2947," which is an ejection pump repair, requires an active "DTO" (danger tag out) condition (Table 9) and an inactive "Racetrack" condition (Table 10). Another example is job "WK01_1755A" (weapons shipping hatch) which requires both the "VLS" (vertical launch system platform) and "DTO" conditions to be inactive (Table 10). This also infers that the two jobs cannot be scheduled at the same time since one requires an active "DTO" condition and the other requires the same condition to be inactive.

Table 9. Sample of jobs requiring active conditions

Job	Active Condition
WI01_2947	DTO
CS15_Q929	DTO
EA01_9494	DTO
EA01_9569	DTO
OC01_2845	Racetrack
WI01_2783	DTO

Table 10. Sample of jobs requiring inactive conditions

Job	Inactive Condition
WI01_2947	Racetrack
WK01_1755	VLS
WK01_1755	DTO

f. Shop-condition Interactions

Required workforces for conditions function similarly as those for jobs. For example, taking down and setting up the "Racetrack" requires four workers from shop "67H" (antenna repair) as shown in Table 11. CMAV-S may accommodate any condition to require asymmetric workforces for set-up and take-down, as well as multiple shops. However, that is not the case for any of the real-world conditions tested in this research.

Table 11. Sample of condition workforce requirements

Condition	Shop	Workforce
Racetrack	67H	4
VLS	91E	3
DTO	31A	2

2. Continuous Maintenance Availability Scheduler Formulation

This section describes the CMAV-S mathematical formulation as a mixed-integer program.

a. Sets and Indices

$j \in J$	Jobs, e.g., $J = \{EA01\_9494(\text{real}),\ J1,\ J2(\text{created})\}$
$s \in S$	Shops, e.g., $S = \{31A, 67H(\text{real}),\ S1,\ S2(\text{created})\}$
$c \in C$	Conditions, e.g., $C = \{DTO, VLS(\text{real}),\ C1,\ C2(\text{created})\}$
$t \in T$	Days, e.g., $T = \{1,\ 2, ..., 35\}$ (ordered set)
$J_j \subset J$	Predecessors to job *j*
$J^M \subset J$	Subset of mandatory jobs
$C_j^A \subset C$	Active conditions required by job *j*
$C_j^I \subset C$	Inactive conditions required by job *j*
$C_c \subset C$	Mutually exclusive conditions to condition *c*
$C^{A0} \subset C$	Conditions which are active on day zero

b. Derived Sets

$T_j \subset T$ Days on which job *j* can start: $T_j = \{i_j, i_j + 1, ..., f_j\}$, (see i_j, f_j below)

c. Parameters [units]

p_j	Priority of job *j* [1 for highest, 4 for lowest]
d_j	Duration of job *j* [days]
i_j	Earliest start day of job *j* [day]
f_j	Latest start day of job *j* [day]
v_j	Value of job *j* [value units]
$r_{j,s}$	Required workforce of job *j* from shop *s* [workers]
w_s	Available workforce from shop *s* [workers]
$rc_{c,s}^{ON}$	Required workforce from shop *s* to activate (set up) condition *c* [workers]
$rc_{c,s}^{OFF}$	Required workforce from shop *s* to deactivate (take down) condition *c* [workers]

d. *Derived Parameters*

$\underline{v}$ Minimum input value of all jobs: $\underline{v} = \min_j \{v_j\}$ [value units]

$v_{j,t}$ Adjusted value of job *j* if started on day *t* [value units]:

$$v_{j,t} = \left(\frac{v_j}{p_j}\right) - 0.01 \times \frac{\underline{v}}{|T|} \times t \quad \forall j,t \tag{1}$$

e. *Decision Variables*

$X_{j,t}$ 1 if job *j* is started on day *t*

$X^A_{j,t}$ 1 if job *j* is in progress on day *t*

$Y^{ON}_{c,t}$ 1 if condition *c* is being activated on day *t*

$Y^A_{c,t}$ 1 if condition *c* is active on day *t*

$Y^{OFF}_{c,t}$ 1 if condition *c* is being deactivated on day *t*

$Y^I_{c,t}$ 1 if condition *c* is inactive on day *t*

f. *Objective*

$$\max_{X, X^A, Y^{ON}, Y^A, Y^{OFF}, Y^I} \sum_{j,t|t \in T_j} \mathrm{v}_{j,t} \times X_{j,t} \tag{2}$$

g. *Constraints*

$$\sum_{t \in T_j} X_{j,t} = 1 \quad \forall j \in J^M \tag{3}$$

$$\sum_{t \in T_j} X_{j,t} \leq 1 \quad \forall j \notin J^M \tag{4}$$

$$X^A_{j,t} = \sum_{t' \in T_j | t - d_j + 1 \leq t' \leq t} X_{j,t'} \quad \forall j,t \tag{5}$$

$$\sum_{j | i_j \leq t \leq f_j + d_j - 1} r_{j,s} \times X^A_{j,t} + \sum_c rc^{ON}_{c,s} \times Y^{ON}_{c,t} + \sum_c rc^{OFF}_{c,s} \times Y^{OFF}_{c,t} \leq w_s \quad \forall\ s,t \tag{6}$$

$$Y^I_{c,t-1} = Y^I_{c,t} + Y^{ON}_{c,t} \quad \forall c,t \tag{7}$$

$$Y_{c,t}^{I} \geq Y_{c,t-1}^{OFF} \quad \forall c,t \mid t>1 \tag{8}$$

$$Y_{c,t-1}^{A} = Y_{c,t}^{A} + Y_{c,t}^{OFF} \quad \forall c,t \tag{9}$$

$$Y_{c,t}^{A} \geq Y_{c,t-1}^{ON} \quad \forall c,t \mid t>1 \tag{10}$$

$$Y_{c,t}^{ON} + Y_{c,t}^{A} + Y_{c,t}^{OFF} + Y_{c,t}^{I} = 1 \quad \forall c,t \tag{11}$$

$$X_{j,t}^{A} \leq Y_{c,t}^{A} \quad \forall \left(j,t,c\right) \mid c \in C_{j}^{A}, i_{j} \leq t \leq f_{j} + d_{j} - 1 \tag{12}$$

$$X_{j,t}^{A} \leq Y_{c,t}^{I} \quad \forall \left(j,t,c\right) \mid c \in C_{j}^{I}, i_{j} \leq t \leq f_{j} + d_{j} - 1 \tag{13}$$

$$X_{j,t} \leq \sum_{t' \in T_{j'} \mid t' \leq t - d_{j'}} X_{j',t'} \quad \forall t, \left(j, j'\right) \mid j' \in J_{j}, t \in T_{j} \tag{14}$$

$$Y_{c',t}^{A} + Y_{c,t}^{A} \leq 1 \quad \forall t, \left(c, c'\right) \mid c' \in C_{c} \tag{15}$$

$$Y_{c,0}^{A} = 1 \quad \forall c \in C^{A0} \tag{16}$$

$$Y_{c,0}^{I} = 1 \quad \forall c \notin C^{A0} \tag{17}$$

$$X_{j,t}, X_{j,t}^{A}, Y_{c,t}^{ON}, Y_{c,t}^{A}, Y_{c,t}^{OFF}, Y_{c,t}^{I} \in \{0,1\} \quad \forall j,c,t \tag{18}$$

Equation (1) computes the total adjusted value for each job. It takes the job's input value times the priority inverse: priority "1" equals one, priority "2" equals one-half, and so on. It then adds a time component to the value of each job by subtracting a very small portion of the value for completing a job later in the CMAV period. The portion we use is one percent of the lowest job's value per day of delay divided by the total number of days, but this can be modified.

Equation (2) is the objective function. Its purpose is to maximize the total adjusted value of the completed maintenance. Since adjusted values have a small component that rewards early start of the jobs, we do not expect unnecessary gaps in the schedule produced by CMAV-S.

Equations (3) and (4) establish the jobs scheduling limits. Equation (3) ensures that all mandatory jobs are scheduled exactly once. There is no allowance for unscheduled mandatory jobs. Equation (4) ensures that non-mandatory jobs are scheduled at most once. This is also the constraint that allows non-mandatory jobs not to be scheduled if it is infeasible or not important enough in the case of a limited timeframe.

Equation (5) establishes an active job period. It ensures that each job's start date decision variable forces an active decision variable for that day and each subsequent day for the duration of the job.

Equation (6) ensures that a given shop's workforce limit is not exceeded at any time. The workforces required by all active jobs and by conditions being activated or deactivated are limited to the daily available workforce.

Equations (7)–(10) are the condition relationships. Equation (7) ensures that if a condition was inactive yesterday it can only continue being inactive or being set up today. Equation (8) states that if a condition was being taken down yesterday it must be inactive today. Both set-up and take-down times are limited to one day. Equation (9) is the reciprocal of equation (7) and states that if a condition was active yesterday it can only continue being active or being taken down today. Equation (10) is the reciprocal of Equation (8) and ensures that if a condition was set up yesterday it must be active today. These four equations manage the cyclical pattern for condition status. There is no penalty for the number of times this cycle is repeated, but this could be individually added as needed.

Equation (11) forces one (and only one) of the possible condition states (set up, active, take down, and inactive) to be true.

Equations (12) and (13) establish the condition requirements for each job. Equation (12) ensures that for each day a job is active, all conditions required to be active for the job must also be active. Equation (13) serves the same function as (12) but ensures all conditions required to be inactive are inactive.

Equation (14) establishes job precedence relationships. It mandates that in order for a job to start on a particular day, its predecessors must have started at least the preceding job’s duration earlier.

Equation (15) represents the conditions’ mutual exclusivity constraints. It is used to ensure at most one of any two mutually exclusive conditions is active on a given day. There are no constraints for exclusivity in the set-up, take-down, or inactive status of conditions.

Equations (16) and (17) establish the initial condition status. Equation (16) sets all conditions starting in the active status to active. Equation (17) sets the rest to inactive. No conditions start in the set-up or take-down phase.

Equation (18) establishes domains for the decisions variables.

3. Implementation

CMAV-S is a linear, mixed-integer program. We have implemented it in the General Algebraic Modeling System (GAMS) utilizing GAMS/CPLEX (GAMS 2014) as the solver engine. In the largest cases exercised, CMAV-S solves the problem to within 0.1% of optimality in less than one minute using a typical CMAV workload as a guide for the test set. This assumes the optimal assignment of over 17,000 binary variables considering over 21,000 constraints. Model testing and validation are discussed further in the following chapter.

III. TESTING AND VALIDATION

The purpose of this chapter is to describe the testing carried out for a preliminary validation of the CMAV-S model. CMAV-S is developed as a proof-of-concept to show the benefits of an automated scheduling system as a complement to current practices aboard the submarine tenders. Even though this model does not encompass all possible aspects considered by the schedulers, it shows the potential for guiding scheduling decisions aboard the tenders using formal optimization.

A. MODEL TESTING

This section displays the validation of the basic components of the CMAV-S model. Step-by-step from the basic model constraints to the mounting complexity of full CMAV workloads, we have tested CMAV-S to ensure our intended design behavior is followed. Table 12 shows the validation test runs as well as their outcomes.

Table 12. Model tests and outcomes

Test	Goal	Input	Output	Result
1	Verify a job is only scheduled once for its whole duration	A single job from a single shop	Job scheduled only once for its entire duration	Pass
2	Verify a single job-shop-condition combination scheduled	The same input as test 1 with an added active condition requirement	Job scheduled during condition-active period	Pass
3	Verify job scheduled after condition activation	The same input as test 2 except condition starts inactive	Condition starts inactive and job scheduled only after condition is activated	Pass
4	Verify job scheduled as early as possible	The same input as test 2 except job has a delayed start day	Job scheduled on earliest start day	Pass

Test	Goal	Input	Output	Result
5	Verify jobs do not violate shop workforce capacity	The same input as test 2 except an added second job	Jobs staggered to stay within shop workforce limits	Pass
6	Verify jobs of increased priority are scheduled first	The same input as test 5 except job 1 has priority “2”	Job 2 is now scheduled prior to job 1	Pass
7	Verify jobs of increased value are scheduled over lower value in a time constrained environment	The same input as test 5 except job 1 has a value higher than job 2 and there is not enough time to complete both	Job 1 is scheduled, job 2 is not.	Pass
8	Verify jobs of increased priority are scheduled over lower priority jobs in a time-constrained environment	The same input as test 5 except job 1 has a priority higher than job 2 and there is not enough time to complete both	Job 1 is scheduled, job 2 is not.	Pass
9	Verify jobs of low priority and high value can be scheduled over jobs of high priority and low value	The same input as test 5 except job 1 has a low priority and high value, job 2 has a high priority and low value	Job 1 is scheduled, job 2 is not.	Pass
10	Verify conditions do not violate shop workforce capacity	The same input as test 3 except workforce for condition activation is greater than shop capacity	Nothing scheduled	Pass
11	Verify inactive condition requirements are met	Same input as test 2 except job requires an inactive condition	Job scheduled only after condition has been deactivated	Pass
12	Verify predecessor relationship	Three jobs required to be scheduled in sequence 2–3–1 with conditions and workforces to allow simultaneous scheduling	Jobs scheduled 2–3–1	Pass

Test	Goal	Input	Output	Result
13	Verify predecessor relationship with toggling active and inactive condition requirements	Same input as test 12 except job 3 requires inactive condition 1 while all other jobs require active condition 1	Jobs scheduled 2–3–1 and are staggered by condition changes	Pass
14	Verify condition's mutual exclusivity	Two jobs require mutually exclusive conditions with enough workforce to complete all jobs	Jobs scheduled in concert with condition's exclusivity deconfliction	Pass
15	Verify condition's mutual exclusivity functions with multiple conditions affecting a single area	Same as test 14 except a third condition is not compatible with condition 1 but is with condition 2	Conditions 2 and 3 proceed at the same time and condition 1 has been deactivated	Pass
16	Verify shop workforce limitations for jobs requiring multiple shops	Same as test 5 except both jobs require two shops and only one of them is workforce restraining	Jobs staggered to fall within shop workforce limitations	Pass
17	Verify infeasible model when all mandatory jobs are impossible to schedule	Same test as input 16 except all jobs are mandatory and time frame is too short to accomplish all jobs	Infeasible model	Pass
18	Verify feasible model when all mandatory jobs are scheduled	Same test as input 17 except time restriction lifted	All jobs scheduled	Pass
19	Verify small scale real-world case schedules all jobs – time unconstrained	Real-world data from sub tenders	All maintenance scheduled	Pass
20	Verify small scale real-world case schedules as much as possible – time constrained	Same as test 19 except dates and workforces changed to force a compressed timeframe	Maximum maintenance scheduled. Impossibilities and low value (or priority) first to be left unscheduled	Pass
21	Verify full CMAV-equivalent schedules all jobs – time unconstrained	Real-world data augmented with fabricated data to mimic a full CMAV	All maintenance scheduled	Pass

Test	Goal	Input	Output	Result
		workload		
22	Verify full CMAV equivalent schedules as much as possible – time constrained	Same input as test 21 except CMAV period of only 30 days instead of 40	Most maintenance scheduled (138 of 139 jobs scheduled)	Pass

There are a few tests worthy of additional discussion. For example, tests 6-8 verify whether or not jobs of higher priority or value are scheduled earlier in the period than other jobs. As expected, high-priority jobs are scheduled first in situations where all other constraints are equal and the jobs cannot be scheduled simultaneously.

Tests 20 and 22 are both time-compression tests. Their goal is to judge the scheduler's reaction to a shorter CMAV period or severely limited workforces. Our initial expectation was to see low adjusted-value jobs left off the schedule in favor of the high adjusted-value jobs. This does happen, but it is more common that the first jobs to be left off a schedule are due to their infeasibility in the constrained time period. High-priority jobs are more likely to become infeasible first due to the fact that they often have more stringent requirements (conditions, prerequisites, or workforce) for scheduling. Since most of the low adjusted-value jobs are shorter in duration, more flexible in completion window, and require fewer workers, they are easily accommodated. Only after severely reducing both workforce and CMAV length does the schedule reduce to the most-valued jobs with a few low-priority jobs to fill in any leftover resources. This also omits many high-priority jobs that are infeasible in a short time window. It is the list of mandatory jobs that determines the minimum CMAV length: the minimum time in which the mandatory jobs can feasibly be completed.

B. CONTINUOUS MAINTENANCE AVAILABILITY SCHEDULER OUTPUT

CMAV-S outputs a schedule for the full CMAV period. Each day is listed in a column and the rows are divided into two sections: The first section dictates the condition activity: set-up (turn the condition on), active, or take-down (turn the condition off) as seen in Figure 1. The inactive status is depicted by empty cells. For example, condition "VLS" is initially active, and remains active for the first two days until it is deactivated on day three. On the other hand, condition "C2" begins inactive, is activated on the first day, and remains active until day five when it is turned off.

The condition activity on day one also gives the CMAV-S user a better approximation of what conditions will be utilized first (see Figure 1). Given that conditions "C2," "C3," "C4," "C7," and "C8," are all activated immediately, changing their initial status to active might allow some jobs to proceed quicker. Conversely, the "Racetrack" and "DTO" conditions both start active and are immediately deactivated; switching their initial status to inactive would save the set-up and take-down crew from unnecessary work on day one.

The second section is the job schedule which shows a start day and then an active status for the rest of the job duration (see Figure 2). For example, job "J108" starts on day six, and it only lasts one day. This output style has been modeled based on the schedule style currently being employed by the tenders using Microsoft Project.

	Day T1	Day T2	Day T3	Day T4	Day T5	Day T6	Day T7	Day T8
Ship Conditions								
Racetrack	Turn OFF			Turn ON	Active	Active	Active	Active
VLS	Active	Active	Turn OFF					
DTO	Turn OFF			Turn ON	Active	Active	Active	Active
C1								
C2	Turn ON	Active	Active	Active	Turn OFF			
C3	Turn ON	Active	Active	Turn OFF				
C4	Turn ON	Active	Active	Active	Active	Turn OFF		
C5								
C6			Turn ON	Active	Active	Active	Active	Active
C7	Turn ON	Active	Active	Active	Active	Active	Active	Active
C8	Turn ON	Active	Active	Active	Active	Active	Active	Active
C9				Turn ON	Active	Active	Active	Active
C10								

Figure 1. Sample CMAV-S condition output

	Day T1	Day T2	Day T3	Day T4	Day T5	Day T6	Day T7	Day T8
Jobs								
J100								
J101								
J102					Start	Active	Active	
J103		Start	Active	Active	Active	Active		
J104				Start	Active	Active	Active	Active
J105				Start	Active			
J106		Start	Active	Active	Active	Active	Active	
J107								
J108						Start		
J109	Start	Active	Active	Active	Active	Active	Active	Active
J110								
J111	Start	Active	Active	Active	Active	Active	Active	Active
J112								
J113					Start	Active	Active	Active
J114								
J115								
J116								
J117								
J118					Start	Active	Active	Active
J119	Start	Active	Active	Active				
J120								Start

Figure 2. Sample CMAV-S job output

C. CONTINUOUS MAINTENANCE AVAILABILITY SCHEDULER COMPARISON TO MANUAL SCHEDULING

One unfortunate shortcoming of this research is the lack of a complete set of real-world data. Although we received and analyzed a small sample of real inputs, it was not enough to stress the CMAV-S model. However, it has enabled us to build representative test cases, realistic enough to conduct comparison analysis between CMAV-S results and manual scheduling.

To ascertain an understanding of CMAV-S's capability we create a comparison data set about one-fourth the size of a standard CMAV. The inputs consist of 50 jobs, six conditions and eight shops. The jobs consist of 30 priority "1" jobs, 10 priority "2" jobs and 10 priority "3" jobs. To mimic reality, the priority "1" jobs tend to require more workforce and time to complete. They also have a greater likelihood of requiring a condition status or prerequisites. The input data for this test is provided in Appendix A.

We try to mimic actual tender schedules by producing a by-hand heuristic schedule using some “common-sense” rules. This task takes hours and is rather tedious. The rules generally prioritize mandatory and high-adjusted-value jobs. Then, we fill the remaining openings in the schedule with low-value but mandatory jobs, and finally with the less-important maintenance. In the interest of producing the best schedule possible, we continue to move jobs, for example, by switching, shifting (i.e., advancing or delaying), or combining blocks of jobs in order to complete all maintenance with as much value as possible. Our rules correlate, to a large extent, with early scheduling of top jobs.

However, as the schedule begins to take shape, it becomes apparent the inherent difficulty to adjust the already-assigned jobs. At about the half-way point, any attempt to move the high-value jobs essentially means starting the schedule over from scratch. This is due to a combination of the workforce requirements and the condition requirements. The final schedule completes all maintenance in 75 days. The achieved objective value is 99.67 value points. We are confident a higher-value schedule could have been achieved but it would have required repeating the process a number of times. The full manual schedule is provided in Appendix B.

For this case, the CMAV-S produces an optimal 56-day schedule that includes all maintenance in about one minute of computational time. The achieved objective value is 99.73 value points. That time frame can be reduced to 50 days if one low-priority job is allowed to be uncompleted. By adjusting the period length and values, we have created a number of test cases that fit a range of priorities. Each of these can be solved near-optimally (within 0.1% gap) in under one minute. The optimal schedule for the abovementioned baseline case is provided in Appendix C.

As a clarification, the achieved objective value between the manual and optimal schedules is deceivingly small. The values are close because both schedules accomplish all the maintenance, which accounts for the lion’s share of objective value. The small deduction for delaying a job creates the difference in objective values. In this case, the 0.06 value point improvement of the optimal solution actually represents a 25% reduction in required CMAV schedule length, which is a desired outcome.

Even though this exercise is conducted by the author of this research, who is not an expert tender scheduler, we believe by-hand scheduling is difficult because of the obvious rigor required by the human brain to keep track of the ripple effects that reorganizing one part of the schedule will have on the rest of it. For example, the different types of constraints (conditions, workforce, prerequisites, etc.) become unwieldy after about five jobs in the same time window. The CMAV-S's input flexibility allows the scheduler to control many aspects of the schedule while letting the solver engine find the optimal solution. In our above example, the CMAV-S significantly reduces the required CMAV period length, provides optimal use of the available workforces, and allows us to produce several optimal schedules based a range of inputs.

IV. CONCLUSIONS AND FUTURE WORK

This chapter presents conclusions and discusses the possible improvements to CMAV-S that could be attempted in future.

A. CONCLUSIONS

In this thesis, we have developed CMAV-S, a mixed-integer linear program, to address the challenges of CMAV scheduling aboard the two remaining submarine tenders in the United States fleet. CMAV-S produces near-optimal schedules that can be utilized for CMAV planning and potentially benefit the submarine community:

- CMAV-S can generate near-optimal schedules from a desired list of maintenance in about one minute. This can alleviate the need to schedule maintenance manually and significantly improve the schedule production process.

- The short runtimes also allow schedulers to re-run the model a number of times with different inputs (e.g., schedule lengths, condition initial status, mandatory jobs) in order to plan for an upcoming CMAV. This allows them to answer "what-if" questions about possible restrictions and alternate schedule possibilities in minutes rather than hours.

We anticipate the potential advantage of CMAV-S over manual scheduling to be significant. However, CMAV-S still needs to be tested on large-scale, real-world instances in order to be validated for use by tender planners.

B. FUTURE WORK

The first area of future work is giving CMAV-S the opportunity to be tested on real data for a full CMAV. Additionally, there are other improvements that could broaden CMAV-S's scope and facilitate its use by the submarine tenders.

1. Real-world Testing

CMAV-S should be tested with real-world data and compared against the actual schedules produced by the tender planners (with which they are familiar). This will allow schedulers to assess CMAV-S outputs and validate or show the faults in the functionality of the model, highlighting areas that can be more accurately represented.

2. Interface

As it currently stands, all inputs must be put into carefully named and formatted comma-separated-values files in order to be run by GAMS. The creation of a user-friendly interface would be beneficial. Input might come from a single database and output could be automatically converted into scheduling charts, allowing the tool to be used by schedulers unfamiliar with programming.

In addition to the interface, an input database would also need to be created. The initial conversion of jobs from MAFs to CMAV-S inputs (predecessors, maintenance conditions, workforces, etc.) requires a significant effort to gather and quantify. As a starting point, we could convert the approximately 1,500 planned maintenance requirements for SSN-class submarines to a database of CMAV-S ready inputs. As CMAV-S schedules additional CMAVs, the unique jobs (not in the database) would be added for future use. After a few iterations, only the occasional job or condition would have to be converted into CMAV-S specific detail and added to the database.

3. Cost Functionality

CMAV-S ignores cost (beyond the temporary consumption of workforce). The model can be improved by adding the cost of parts needed for a job, contractors, or additional equipment. For example, a ship condition requiring the use of a depot crane that is rented by the day. This would give priority to only utilizing the condition as long as needed. Another example would be a condition that has a cost for set-up and take-down. In this case it would be advantageous to only set it up once instead of cycling it on and off multiple times.

4. Perquisite Flexibility

CMAV-S only allows jobs to begin after their prerequisite jobs have been completed. This is a very rigid time-lag system. For example, a job may need to start two days after its prerequisite job starts. The lag date could be hard (it must be exactly two days) or soft (it must be at least two days). Flexibility could also be used for a maximum lag time (the job can only lag a maximum of two days). This functionality would allow the scheduler to represent additional prerequisite relationships.

5. Re-scheduler

One assumption in the CMAV model is that once a schedule has been started it does not change. A re-scheduler would allow planners to take the progress completed on a given day and reschedule the remaining portion of the CMAV optimally when changes (such as an additional job) occur.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX A. SCHEDULE INPUTS

This appendix provides the input data for our comparison exercise.

Job Inputs

Job	Priority	Value	Duration	Earliest	Latest	Mandatory	Prerequisites	Primary Shop	Workforce	Secondary Shop	Workforce	Active Condition	Inactive Condition
J1	1	1	10	3	35	YES	J21	S1	4	S2	5	C1	
J2	1	1	12	4	36	NO	J13	S3	6	S4	4	C2, C3	
J3	1	1	3	4	33	NO	J13	S5	2			C4	
J4	1	1	4	12	34	NO	J13	S6	5	S7	4	C1, C6	
J5	1	1	3	12	34	YES	J13	S8	3	S1	8	C2	
J6	1	1	4	5	35	NO	J13	S2	6				
J7	1	1	14	16	39	NO		S3	5	S4	7		C1
J8	1	1	12	5	30	NO		S5	5			C5, C6	
J9	1	1	3	3	36	NO		S6	9			C1, C4	
J10	1	1	10	2	40	YES	J9	S7	6				C2
J11	1	2	2	1	48	NO		S8	5				C3
J12	1	2	5	2	45	NO		S1	4				C4
J13	1	2	3	3	42	NO		S2	2	S3	3		C5
J14	1	2	6	1	44	NO	J16	S4	5			C5	C6
J15	1	2	4	5	39	NO		S5	1	S6	2		
J16	1	2	8	4	42	NO		S7	4	S8	4	C3	
J17	1	2	4	6	45	NO		S1	8			C4	
J18	1	2	4	4	46	NO		S2	6	S3	5		
J19	1	2	10	2	40	NO		S4	2				
J20	1	2	15	4	35	NO		S5	3	S6	2		
J21	1	5	2	5	48	NO		S7	5				
J22	1	5	3	1	47	YES		S8	4				
J23	1	5	11	1	39	YES		S1	9				
J24	1	5	12	1	38	YES		S2	6				
J25	1	5	6	1	44	NO		S3	7	S4	9	C2	
J26	1	5	10	2	40	NO	J25	S5	4	S6	6	C3	C1
J27	1	5	15	2	35	NO		S7	8	S8	4	C3, C5	
J28	1	5	4	7	46	NO		S2	2	S1	5	C6	

Job	Priority	Value	Duration	Earliest	Latest	Mandatory	Prerequisites	Primary Shop	Workforce	Secondary Shop	Workforce	Active Condition	Inactive Condition
J29	1	5	8	8	42	NO		S3	3	S4	5	C1	
J30	1	5	7	5	43	NO	J8,J31,J32,J50	S6	8	S5	4	C2, C3	
J31	2	1	2	3	43	NO		S7	2				C2
J32	2	1	3	2	47	NO		S8	3				
J33	2	1	4	5	46	NO		S1	5			C4	
J34	2	1	2	4	48	NO		S2	2	S3	3	C5	
J35	2	1	1	3	49	NO		S4	1			C6	
J36	2	2	6	2	44	NO		S5	2			C1	
J37	2	2	8	1	42	NO		S6	3			C2	C3
J38	2	2	7	5	41	NO	J42	S7	1				C4
J39	2	5	5	3	45	NO	J43	S8	4	S1	2		C5
J40	2	5	6	20	44	YES	J1	S2	3				
J41	3	1	2	1	48	NO	J35,J37	S3	2	S4	3		
J42	3	1	3	2	47	NO	J20	S5	4			C3	
J43	3	1	5	5	39	NO		S6	2			C4	
J44	3	1	4	4	46	NO		S7	2			C5	
J45	3	1	2	3	48	NO	J20	S8	3				C6
J46	3	1	3	5	47	NO		S1	2				C1
J47	3	1	5	11	45	NO		S2	2				C2
J48	3	1	2	2	48	NO		S3	1				
J49	3	3	3	3	47	NO		S4	1			C6	
J50	3	5	8	8	42	YES		S5	2	S6	3	C2	

Shop Inputs

Shop	Available Workforce
S1	10
S2	16
S3	13
S4	10
S5	5
S6	10
S7	12
S8	8

Condition Inputs

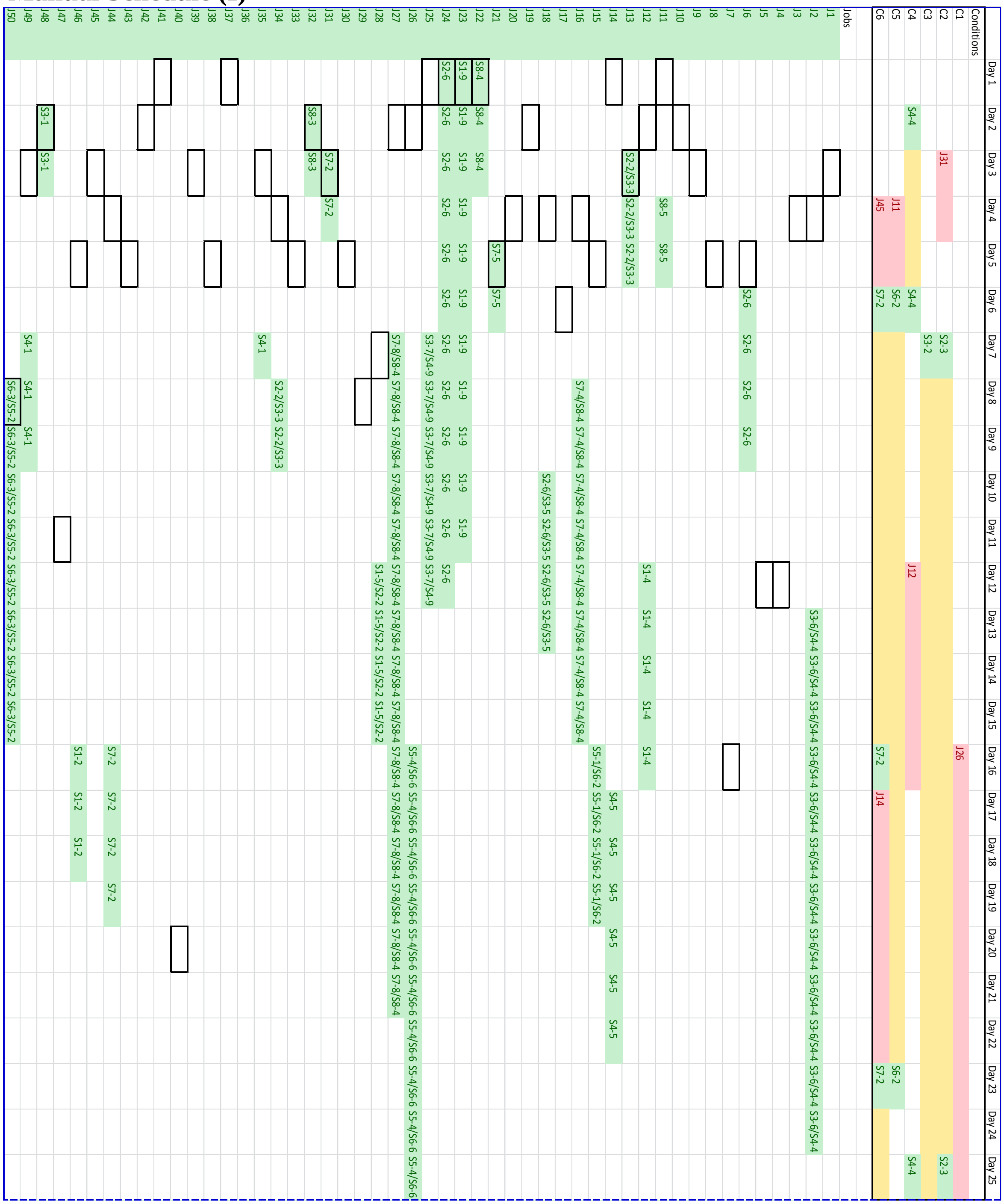
Conditions	Initial Status	Mutually Exclusive	Setup Shop	Workforce	Take-down Shop	Workforce
C1	Inactive	C2,C3	S1	2	S1	2
C2	Inactive	C1	S2	3	S2	3
C3	Inactive	C1	S3	2	S3	2
C4	Inactive	C5	S4	4	S4	4
C5	Inactive	C4	S6	2	S6	2
C6	Inactive		S7	2	S7	2

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX B. MANUAL SCHEDULE

This appendix provides the manual schedule for our comparison exercise.

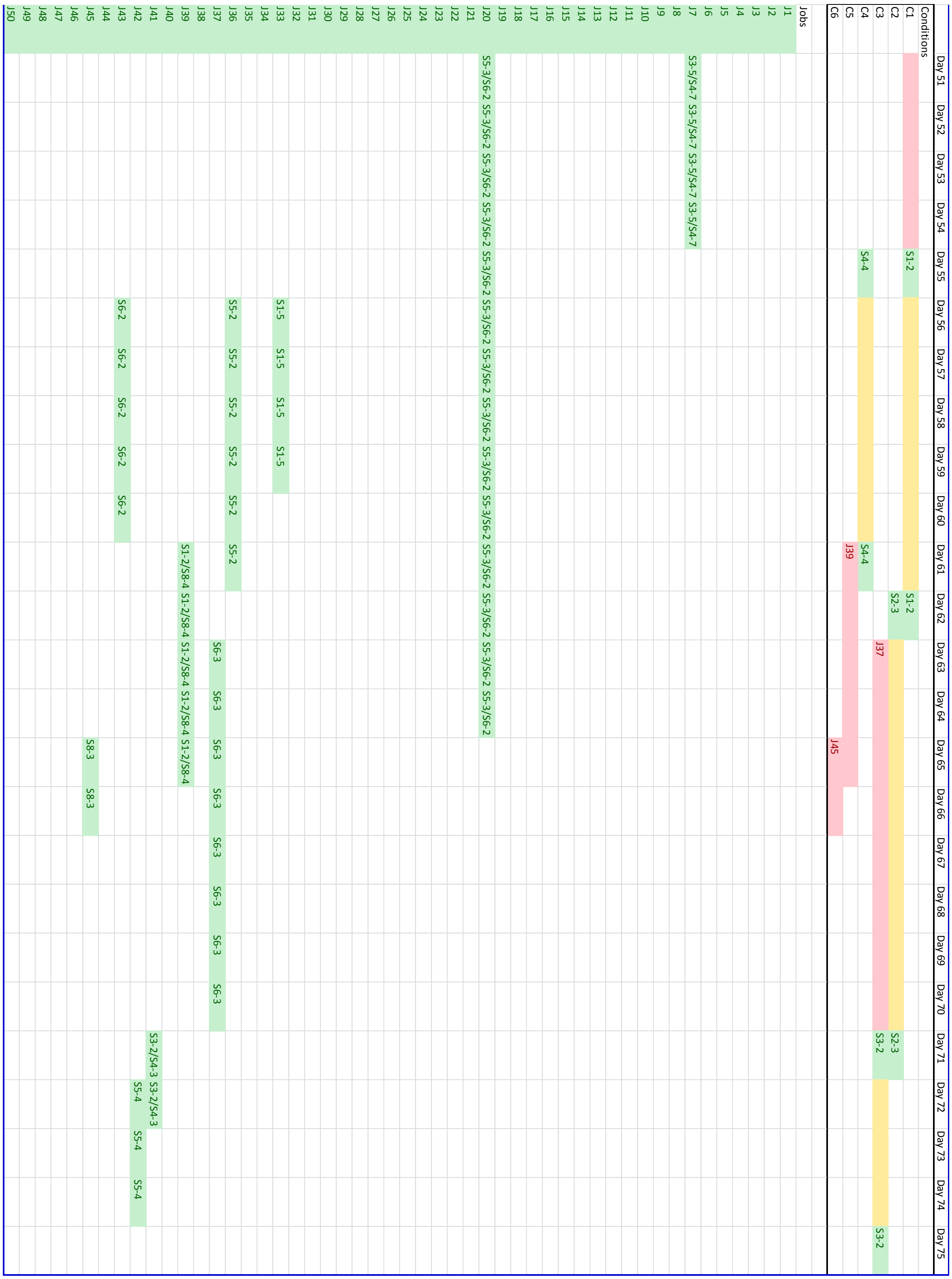
Manual Schedule (I)



Manual Schedule (II)

	Day 26	Day 27	Day 28	Day 29	Day 30	Day 31	Day 32	Day 33	Day 34	Day 35	Day 36	Day 37	Day 38	Day 39	Day 40	Day 41	Day 42	Day 43	Day 44	Day 45	Day 46	Day 47	Day 48	Day 49	Day 50
Conditions																									
C1	S1-2														S1-2	J7									
C2	J147				J10										S2-3										S2-3
C3	S3-2														S3-2										S3-2
C4					S4-4	J38																			
C5					S6-2													S6-2							
C6																		S7-2							
Jobs																									
J1					S1-4/S2-5	S1-4/S2-5	S1-4/S2-5	S1-4/S2-5	S1-4/S2-5	S1-4/S2-5	S1-4/S2-5	S1-4/S2-5	S1-4/S2-5	S1-4/S2-5											
J2																									
J3		S5-2	S5-2	S5-2																					
J4					S6-5/S7-4	S6-5/S7-4	S6-5/S7-4	S6-5/S7-4																	
J5																S1-8/S8-3	S1-8/S8-3	S1-8/S8-3							
J6																									
J7																S3-5/S4-7	S3-5/S4-7	S3-5/S4-7	S3-5/S4-7	S3-5/S4-7	S3-5/S4-7	S3-5/S4-7	S3-5/S4-7	S3-5/S4-7	S3-5/S4-7
J8						S5-5	S5-5	S5-5	S5-5	S5-5	S5-5	S5-5	S5-5	S5-5	S5-5	S5-5	S5-5								
J9		S6-9	S6-9	S6-9																					
J10					S7-6	S7-6	S7-6	S7-6	S7-6	S7-6	S7-6	S7-6	S7-6	S7-6											
J11																									
J12																									
J13																									
J14																									
J15																									
J16																									
J17	S1-8	S1-8	S1-8	S1-8																					
J18																									
J19						S4-2	S4-2	S4-2	S4-2	S4-2	S4-2	S4-2	S4-2	S4-2	S4-2										
J20																									S5-3/S6-2
J21																									
J22																									
J23																									
J24																									
J25																									
J26																									
J27																									
J28																									
J29		S3-3/S4-5	S3-3/S4-5	S3-3/S4-5	S3-3/S4-5	S3-3/S4-5	S3-3/S4-5	S3-3/S4-5	S3-3/S4-5																
J30																		S5-4/S6-8	S5-4/S6-8	S5-4/S6-8	S5-4/S6-8	S5-4/S6-8	S5-4/S6-8	S5-4/S6-8	
J31																									
J32																									
J33																									
J34																									
J35																									
J36																									
J37																									
J38						S7-1	S7-1	S7-1	S7-1	S7-1	S7-1	S7-1													
J39																									
J40															S2-3	S2-3	S2-3	S2-3	S2-3	S2-3					
J41																									
J42																									
J43																									
J44																									
J45																									
J46																									
J47	S2-2	S2-2	S2-2	S2-2	S2-2																				
J48																									
J49																									
J50																									

Manual Schedule (III)



THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX C. CONTINUOUS MAINTENANCE AVAILABILITY SCHEDULER OPTIMAL SCHEDULE

This appendix provides the CMAV-S optimal schedule for our comparison exercise.

Optimal Schedule (I)

	Day T1	Day T2	Day T3	Day T4	Day T5	Day T6	Day T7	Day T8	Day T9	Day T10	Day T11	Day T12	Day T13	Day T14	Day T15	Day T16	Day T17	Day T18	Day T19	Day T20	Day T21	Day T22	Day T23
Ship Conditions																							
C1	Turn ON	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Turn OFF						
C2																Turn ON	Active	Active	Active	Active	Active	Active	Active
C3																							
C4	Turn ON	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Turn OFF				Turn ON	Active	Active	Active	Active	Active	Active	Turn OFF
C5											Turn ON	Active	Active	Active	Active	Turn OFF							
C6	Turn ON	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active
Jobs																							
J1							Start	Active	Active	Active	Active	Active	Active	Active	Active	Active							
J2																							
J3						Start	Active	Active															
J4												Start	Active	Active	Active								
J5																						Start	Active
J6								Start	Active	Active	Active												
J7																							
J8																							
J9			Start	Active	Active																		
J10						Start	Active	Active	Active	Active	Active	Active	Active	Active	Active								
J11	Start	Active																					
J12																							
J13			Start	Active	Active																		
J14																							
J15									Start	Active	Active	Active											
J16																							
J17																		Start	Active	Active	Active		
J18				Start	Active	Active	Active																
J19		Start	Active	Active	Active	Active	Active	Active	Active	Active	Active												
J20								Start	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	
J21					Start	Active																	
J22			Start	Active	Active																		
J23																							
J24												Start	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active
J25																	Start	Active	Active	Active	Active	Active	
J26																							
J27																							
J28									Start	Active	Active	Active											
J29									Start	Active	Active	Active	Active	Active	Active	Active							
J30																							
J31			Start	Active																			
J32		Start	Active	Active																			
J33					Start	Active	Active	Active															
J34													Start	Active									
J35			Start																				
J36		Start	Active	Active	Active	Active	Active																
J37																	Start	Active	Active	Active	Active	Active	Active
J38																							
J39																	Start	Active	Active	Active	Active		
J40																				Start	Active	Active	Active
J41																							
J42																							
J43						Start	Active	Active	Active	Active													
J44												Start	Active	Active	Active								
J45																							
J46																						Start	Active
J47											Start	Active	Active	Active	Active								
J48		Start	Active																				
J49			Start	Active	Active																		
J50																	Start	Active	Active	Active	Active	Active	Active

Optimal Schedule (II)

	Day T24	Day T25	Day T26	Day T27	Day T28	Day T29	Day T30	Day T31	Day T32	Day T33	Day T34	Day T35	Day T36	Day T37	Day T38	Day T39	Day T40	Day T41	Day T42	Day T43	Day T44	Day T45	Day T46
Ship Conditions																							
C1																							
C2	Active	Turn OFF		Turn ON	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active
C3		Turn ON	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active
C4																							
C5	Turn ON	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active
C6	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Turn OFF								Turn ON	Active
Jobs																							
J1																							
J2															Start	Active	Active	Active	Active	Active	Active	Active	Active
J3																							
J4																							
J5	Active																						
J6																							
J7	Start	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active									
J8		Start	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active										
J9																							
J10																							
J11																							
J12		Start	Active	Active	Active	Active																	
J13																							
J14															Start	Active	Active	Active	Active	Active			
J15																							
J16			Start	Active	Active	Active	Active	Active	Active	Active													
J17																							
J18																							
J19																							
J20																							
J21																							
J22																							
J23							Start	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active						
J24																							
J25																							
J26																							
J27			Start	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active	Active						
J28																							
J29																							
J30																	Start	Active	Active	Active	Active	Active	Active
J31																							
J32																							
J33																							
J34																							
J35																							
J36																							
J37	Active																						
J38																	Start	Active	Active	Active	Active	Active	Active
J39																							
J40	Active	Active																					
J41		Start	Active																				
J42														Start	Active	Active							
J43																							
J44																							
J45															Start	Active							
J46	Active																						
J47																							
J48																							
J49																							
J50	Active																						

Optimal Schedule (III)

	Day T47	Day T48	Day T49	Day T50	Day T51	Day T52	Day T53	Day T54	Day T55	Day T56	Day T57
Ship Conditions											
C1											
C2	Active	Active	Active	Turn OFF		Turn ON	Active	Turn OFF			
C3	Active	Active	Active	Turn OFF				Turn ON	Active	Turn OFF	
C4			Turn ON	Active	Turn OFF						
C5	Active	Active	Active	Turn OFF							
C6	Active	Turn OFF						Turn ON	Active	Active	Active
Jobs											
J1											
J2	Active	Active	Active								
J3											
J4											
J5											
J6											
J7											
J8											
J9											
J10											
J11											
J12											
J13											
J14											
J15											
J16											
J17											
J18											
J19											
J20											
J21											
J22											
J23											
J24											
J25											
J26	Start	Active	Active	Active	Active	Active	Active	Active	Active	Active	
J27											
J28											
J29											
J30											
J31											
J32											
J33											
J34											
J35											
J36											
J37											
J38											
J39											
J40											
J41											
J42											
J43											
J44											
J45											
J46											
J47											
J48											
J49											
J50											

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

Baker, Kenneth, and Dan Trietsch. 2009. *Principles of Sequencing and Scheduling*. Hobokoen, NJ: John Wiley & Sons.

Brown, Gerald G., Matthew W. Carlyle, Robert F. Dell, and John W. Brau. 2013. "Optimizing Intratheater Military Airlift in Iraq and Afghanistan," *Military Operations Research***,** 18(3): 35–52.

Department of the Navy. 2013a. *Joint Fleet Maintenance Manuel-Volume II: Integrated Fleet Maintenance* (COMUSFLTFORCOMINST 4790.3 REV C Change 1) Washington, DC: U.S. Department of the Navy.

Department of the Navy. 2013b. "U.S. Navy Fact File, Submarine Tenders – AS" November 13. http://www.navy.mil/navydata/fact_display.asp?cid=4200&tid=2400&ct=4

Escudero, Laureano, and Javier Salmeron. 2005. "On a Fix-and-Relax Framework for a Class of Project Scheduling Problems." *Annals of Operations Research* 140: 163–188.

French, Simon. 1982. *Sequencing and Scheduling: An Introduction to the Mathematics of the Job-Shop*. England: Ellis Horwood Limited.

GAMS/CPLEX. (2014). *CPLEX 12 Solver Manual*. Retrieved from http://www.gams.com/dd/docs/solvers/cplex.pdf

Global Security. 2011. "Submarine Tenders" July 7. http://www.globalsecurity.org/military/systems/ship/as.htm

Jacobs, Roger. 2013. "Optimization of Daily Flight Training Schedules." Master's thesis in Operations Research, Naval Postgraduate School.

Pickett, Josiah. 2013. "Pacific Fleet Submarine Tender Optimization." Master's thesis in Applied Mathematics, Naval Postgraduate School.

Pinedo, Michael. L. 2010. *Scheduling Theory, Algorithms, and Systems.* 4th ed. New York, NY: Springer.

Stidsen, T., L. V. Kragelund, and O. Mateescu. 1996. "Jobshop scheduling in a shipyard" August 11. http://www.researchgate.net/profile/Thomas_Stidsen/publications/2

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California