2018-09

OPTIMIZATION OF CUSTOMER PRIORITIES AND PERSONNEL PREFERENCES IN SCHEDULING RANGE OPERATIONS AT NUWC KEYPORT

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http://hdl.handle.net/10945/60451

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

OPTIMIZATION OF CUSTOMER PRIORITIES AND PERSONNEL PREFERENCES IN SCHEDULING RANGE OPERATIONS AT NUWC KEYPORT

by

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September 2018

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REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2018	**3. REPORT TYPE AND DATES COVERED** Master's thesis

4. TITLE AND SUBTITLE
OPTIMIZATION OF CUSTOMER PRIORITIES AND PERSONNEL PREFERENCES IN SCHEDULING RANGE OPERATIONS AT NUWC KEYPORT

5. FUNDING NUMBERS

6. AUTHOR(S) Douglas S. Ray

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

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.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release. Distribution is unlimited.

12b. DISTRIBUTION CODE
A

13. ABSTRACT (maximum 200 words)

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14. SUBJECT TERMS
integer linear programming, optimization, crew rostering, crew scheduling, NUWC Keyport, range operations, pre-emptive solutions

15. NUMBER OF PAGES
71

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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OPTIMIZATION OF CUSTOMER PRIORITIES AND PERSONNEL PREFERENCES IN SCHEDULING RANGE OPERATIONS AT NUWC KEYPORT

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Submitted in partial fulfillment of the
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MASTER OF SCIENCE IN SYSTEMS ENGINEERING MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

This thesis examines the use of integer linear programming with binary decision variables to maximize customer priorities for in-water range events at NUWC Keyport, ensure adequate craft manning, and optimize employee schedule preferences. The research presents an algorithm that balances customer demands with employee preferences by solving an integer linear program, referred to as the optimization model, in a preemptive manner (i.e., the customer priority objective is first met and once the optimal operational schedule is solved, then the optimal employee work schedule is found that will execute the operational schedule). If a feasible solution is found for both objectives, this preemptive method is guaranteed to find a Pareto optimal solution, meaning another solution cannot be found without making one or both objectives worse off. The employee preferences are constrained such that crew members are rostered together for that operational period. The program maximizes customer priorities and optimizes employee schedules for a variety of likely scenarios. It is a useful tool for better linking the operational schedule to employee availability.

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LIST OF ACRONYMS AND ABBREVIATIONS

AB	able seaman
CFMETR	Canadian Forces Maritime Experimental and Test Range
DDE	designated duty engineer
DoD	Department of Defense
FY	fiscal year
GAMS	Generalized Algebraic Modeling System
GPS	Global Positioning System
HP	horsepower
ILP	integer linear program
IP	integer program
MOU	memorandum of understanding
NP	nondeterministic polynomial time
NUWC	Naval Undersea Warfare Center
ROV	remotely operated vehicle
SUT	system under test
T&E	test and evaluation
TSPI	time space position information
TWR	Torpedo Weapons Retriever
USN	United States Navy
USV	unmanned surface vehicle
UUV	unmanned underwater vehicle
WA	Washington
YTD	year to date
YTT	Yard Torpedo Test

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EXECUTIVE SUMMARY

Naval Undersea Warfare Center (NUWC) Keyport supports Department of Defense and Canadian Ministry of Defence customers in test and evaluation (T&E) of naval undersea systems. These events occur on one of six in-water ranges. The two principal ranges are in Nanoose, Canada, and Keyport, Washington. T&E collects data on system performance to inform decision makers of system progress toward meeting key performance parameters.

To support customer T&E, NUWC Keyport's range operations division employs several craft. Civilians man, operate, maintain, fuel, mobilize and demobilize the craft for T&E events. The crews require time off from range events to train, take leave and carry out other administrative duties. Lack of proper craft maintenance and crew rest could compromise costly test events, leading to loss of desired data. Over-manning saps profits, while under-manning reduces customer satisfaction and service levels, and may hazard the craft. From the employee's perspective, a fair, stable schedule boosts morale and improves work-life balance.

Mathematical programming finds optimal solutions to real-life problems, such as what mix of products should be manufactured to yield the greatest profit for the company. This paper presents an algorithm that balances the demands of the customers with the preferences of the employees by solving an integer linear program, referred to as the optimization model, in a preemptive manner, that is, the customer priority objective is first met and once the optimal operational schedule is solved, then the optimal employee work schedule is found that will execute the operational schedule. If a feasible solution is found for both objectives, this preemptive method is guaranteed to find a Pareto optimal solution, that is, another solution cannot be found without making one or both objectives worse off.

This thesis uses four scenarios to test the optimization model, accounting for the priorities of four hypothetical customers and the preferences of 15 able seamen for a hypothetical employee work schedule. The objective function for customer priorities

maximizes the values of the customers' priorities with respect to operation schedules, location, and boat type, where a value from 100 to 500 is assigned to each customer request. The optimization model constraints allow each customer one operation schedule, location and boat type per week. The objective function for employee work preferences minimizes total employee work preference (lower is better) with respect to a location and workday, where 1 was most preferred and 5 was least preferred. For employees, a penalty of 100 is assigned to a day if having the employee work that day meant disrupting leave, canceling training or missing a medical appointment.

The scenarios model real-world range scheduling situations such as the ability of two customers to share a range day; the benefit to have a boat crew at the Nanoose range stay together for the entire operation schedule; the ability to swap crew members out during back to back but separate operation schedules; and the assignment of employees with the total lowest work preference value (better) to the longer operation schedules first, and assignment of employees with total highest preference value (worse) to shorter operation schedules second. The model is useful for actual real-range events and scheduling.

The optimization model is purposely limited in scope in several ways. There are many ways it could be modified to allow more range sites, a greater variety of craft, and the ability to allow customers to schedule more than one craft per operation schedule.

The customer value and employee preference optimization algorithms could be applied to many everyday applications in the Navy such as creating a watch bill for a ship for both underway operations and for in-port duty sections or for watch bills at fleet command centers that must be manned around the clock. It could also be used to create and assign teams of varying engineering disciplines to undertake projects.

ACKNOWLEDGMENTS

I offer my gratitude to Dr. Paul L. Ewing for assisting in the formulation of the mathematical program and implementing it using the Generalized Algebraic Modeling System (GAMS) software. This thesis would not have been possible without his unstinting dedication of time, effort, and advice. Thanks to Professor John T. Dillard for his many helpful comments.

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I. INTRODUCTION

A. BACKGROUND

One of Naval Undersea Warfare Center (NUWC) Keyport's missions is to support research, development, testing, and evaluation of naval undersea systems. To carry out this mission, NUWC Keyport operates multiple in-water test and evaluation (T&E) ranges in the Pacific Northwest of the United States and in British Columbia, Canada. In the Pacific Northwest, in-water ranges are located at Keyport, Washington, Hood Canal, Dabob Bay, and off the coast of Washington, while in Canada, in-water ranges are located off of Nanoose, Canada (Figure 1). The majority of in-water testing takes place at the Dabob Bay range complex and at the Nanoose range sites.

The Nanoose and Dabob Bay ranges are instrumented with sensors to track the positions of objects on the range. Radar and/or the Global Position System (GPS) track the positions of ships or aircraft operating on the range, while underwater hydrophone arrays track the positions of submarines, torpedoes, and unmanned underwater vehicles (UUVs) operating on the range. Other underwater hydrophones monitor the acoustic signature of the submarine, torpedo, or UUV. The time-space-position-information (TSPI) provided by the position sensors and the measured acoustic signatures allow the comparison of the system under test's (SUT's) performance against its design requirements.

The NUWC Keyport ranges employ yard torpedo test (YTT) boats, YTT-10, shown in Figure 2, and YTT-11 as well as torpedo weapons retrievers, TWR-7, shown in Figure 3, and TWR-8. The YTTs are designed to launch torpedoes and other test vehicles, while the TWRs are designed to recover torpedoes and other test vehicles. Civilian crews man these boats. Along with YTTs and TWRs, NUWC Keyport operates barges, yard patrol craft, and other small craft in support of UUV operations and events not requiring torpedo or test vehicle operations.

The areas in orange denote the coverage of the in-water ranges at the Nanoose, Canada, site, Keyport site, and Quinault site where undersea testing takes place. The inset of the Keyport site shows a small range off of Keyport and a larger complex in Dabob Bay and Hood Canal.

Figure 1. Geography of NUWC Keyport In-Water Test and Evaluation Ranges. Source: NUWC Keyport (2018).

NUWC Keyport range craft are based out of KB Docks, located on Hood Canal and part of Naval Submarine Base Bangor. To support range operations all range craft must transit to ranges at Keyport, WA or Nanoose, Canada. It takes a range craft one hour to transit from KB Docks to the Dabob range, one day to transit from KB Docks to the Nanoose range and half a day to transit from KB Docks to the Keyport range.

The YTT is the principal craft operated by NUWC Keyport to launch torpedoes. The YTT's cranes allow it to deploy and recover a wide variety of objects into the water.

Figure 2. YTT-10 Leaving Nanoose Range April 2009.
Source: Real Lachance (2009).

The TWR is the principal craft operated by NUWC Keyport to recover torpedoes. Swimmers jump into the water and attach a collar to the torpedo. The torpedo is then hauled onto the rear deck of the craft, which is outfitted with rollers.

Figure 3. TWR-7 en Route to Naval Submarine Base Bangor from Dabob Bay June 2014. Source: Rob Royer (2014).

NUWC Division Keyport schedules days on the one of the six ranges at the request of customers to meet their test requirements. Ministry of Defence customers from Canada and Department of Defense (DoD) customers from the United States are the primary range users at Nanoose, Canada, while DoD customers are the primary range users at Dabob Bay, WA.

B. RANGE SCHEDULING

Range events are scheduled by a customer requesting a period of days to conduct a range event using a range craft on a certain range. The range scheduler looks at the range event calendar and checks to see if the range and range craft are available. If both the range dates and range craft are available, then the event is scheduled. If not, then the customer will either pick another set of days or try to negotiate with the customer that is already scheduled for those days.

Range schedules almost always include a backup day to allow for delays due to material failures of the range craft or the experiment, or due to adverse weather. This conservative approach promotes underutilization of the ranges, the range craft, and crews, but is efficient and economical for the customer sponsoring the event because it increases the likelihood of the customer being able to complete the range event. Range schedules also reflect cancellations and/or reschedules if the customer's experiment is not ready for the range when originally scheduled. These cancellations and/or reschedules usually result in lost opportunities to conduct other range events.

1. Nanoose Test Range

The Canadian Forces Maritime Experimental and Test Ranges (CFMETR), also called the Nanoose Range, is a joint Canadian and United States operated range established by an international treaty in 1965 and governed by a memorandum of understanding (MOU). It is located on Nanoose Bay in the Straits of Georgia off the east coast of Vancouver Island. It is the largest fixed tracking range operated by NUWC Division Keyport covering 60 square nautical miles. Per the MOU, Canada provides the physical facilities such as buildings, piers, and range operations center, while NUWC Keyport provides the equipment to support testing such as radios, tracking towers, underwater communications equipment, radars, and tracking computers. Both Canada and NUWC Keyport supply range craft as needed.

The Canadians have implemented the following rules that affect range availability for use by NUWC Keyport customers:

- Range days are limited to 10 hours long.
- No ranging occurs on Mondays.
- No ranging occurs on days after Canadian holidays.
- The second Tuesday of each month is a non-ranging day to allow for maintenance and training.

- Ranging on Fridays and weekends requires permission of the Commanding Officer of CFMETR.
- Canadians have priority on the range. Exceptions are made for occasions when NUWC Keyport has a United States Navy (USN) ship scheduled to be on the range.

Canada requires the use of NUWC Keyport range craft to support Canadian torpedo exercises or tactical exercises that require the firing of test vehicles.

2. Dabob Bay Test Range

The Dabob Bay test range covers 9 square nautical miles and is about one sixth the size of the Nanoose Range. When feasible, customers prefer conducting T&E events at Dabob's smaller water space because it avoids transiting the range craft and crews up to Nanoose, equipment does not have to clear customs, and it is less expensive to operate on a per-day basis. Dabob Bay is available Monday through Friday, with weekend operations allowed with the NUWC Keyport Commander's approval.

3. Other Ranges

Besides the Nanoose and Dabob test ranges, which provide for fixed underwater tracking, NUWC Keyport operates ranges in the Hood Canal, off of Keyport range, and off the coast of Washington state in the Pacific Ocean. These ranges are well suited to testing and evaluating systems that are relatively benign compared to a heavyweight torpedo and widen the variety of relevant test environments. These other ranges have seen an increase in use due to the proliferation of unmanned surface vehicles (USVs) and UUVs T&E events.

C. OTHER SCHEDULING DEMANDS

Besides range operations, range craft crews support mobilization and demobilization of experiments, equipment, and stores onto and off the range crafts, and conduct routine maintenance of the crafts, periodic refueling of the crafts, craft certifications and inspections, and training. The craft and crews also support maintenance of the underwater tracking and communications equipment. This involves deploying a remotely operated vehicle (ROV) that swims down to the underwater equipment and attaches a rope. The YTT crane hoists the equipment onboard the YTT, and then deploys the replacement equipment using its crane.

D. CRAFT MANNING AND RANGE CRAFT BRANCH MANNING

The range craft at NUWC Keyport are government owned, and the personnel operating them do not have to adhere to U.S. Coast Guard requirements licensing and qualification requirements, although as a matter of policy NUWC Keyport chooses to do so. This requirement may be relaxed if Coast Guard qualified personnel are not available to be hired. Table 1 lists the various vessels operated by NUWC Keyport, manning levels, and licensing requirements for daily operations. There may be exceptions on YTT manning up in Canada if the assistant craft master, assistant engineer, or one of the deck hands became incapacitated prior to underway and the underway is expected to be less than eight hours.

Range craft minimum manning levels are driven by the requirements to: i) Steer and navigate the boat, to include startup, monitor, and shutdown running equipment. ii) Conduct operations on deck such as line handling and launch and retrieval of equipment. iii) Damage control effects such as firefighting, where the four deckhands and two engineers on the YTT provide for two three-man fire teams. The YTT is configured with a galley and berthing and can support around the clock operations. In this case, the YTT manning increases to 11 personnel to allow for rotation of watchstanders.

Other personnel embark on the TWR and YTT to support different types of operations. For a TWR conducting torpedo retrieval operations, navy swimmers embark the boat and jump in the water to install a retrieval collar on the torpedo. For a YTT launching torpedoes, fire control personnel and weapons technicians embark the boat to prepare the torpedoes for launch, and for underwater recovery operations, ROV pilots embark the boat to operate the ROV for recovery of underwater objects.

Table 1. NUWC Keyport Range Craft Manning Requirements and Qualification Levels

TWR	
Position	Certification
Craft master	100 ton master
Engineer	Unlimited 3rd Mate or Designated Duty Engineer (DDE) 1600 Horsepower (HP)
Deckhand	Able Seaman
YTT	
Position	Certification
Craft master	1600 ton master
Assistant Craft master	1600 ton mate
Chief Engineer	DDE 1600 HP
Assistant Chief Engineer	DDE 1600 HP
Deckhands (4)	Able Seaman (AB)
OTHER SMALL CRAFT	
YP-701	Same as for a TWR
IX-536	One Craft master and four AB
NS-9, NS-50, MHS-1, HS-205	Two AB
Dive Boat	One AB

Keyport range craft is manned by crews of sufficient size, and who hold craft specific Coast Guard licenses to provide for safe and efficient operation of the vessel.

The NUWC Keyport range craft branch provides qualified personnel to man the range craft. The range craft branch has 33 personnel listed by position in Table 2. In addition to being responsible for manning of the range craft, the range craft branch oversees repairs, preventative maintenance, shipyard overhauls, and certification of ships systems.

Table 2. NUWC Keyport Range Craft Branch Manning

Administrative Positions	**Operational Positions**
Branch Head	YTT Masters (3)
Port Captain	YTT Assistant Craft Masters (2)
Port Engineer	TWR Masters (2)
Ship's Surveyor/Maintenance Manager	Chief Engineers (2)
Ship's Electrician	Assistant Chief Engineers (3)
Secretary	Able Seaman (15)

The range craft branch operates and maintains all range craft owned by NUWC Keyport.

E. PROBLEM STATEMENT

The current practice of scheduling customers on the range does not consider customer preference. It treats all customer events equally, that is, the relative preferences of a customer's individual preference for alternative range and training period choices and, the relative preferences across all customers who may wish to use a range during a scheduling period are ignored. Similarly, the current practice of scheduling able seamen (AB) does not provide a consistent manner that maximizes the employee's preference for working a particular schedule. It currently consists of writing employee names and dates on a white board and using an ad-hoc selection method to determine their work assignment.

This thesis presents an approach and the results that answer two questions simultaneously. It determines the weekly range schedule that best meets customer's preferences for range and training periods and it provides an employee work schedule that addresses the able seaman's workday and location preferences while resourcing the weekly maintenance and training schedule.

This thesis contributes to the literature by presenting a model that solves a difficult multiple objective scheduling problem with time periods. It also provides a sponsor an approach to address a difficult practical application.

In addressing the above problem, this paper provides a summary of relevant literature in Chapter II, the modeling methodology and formulation in Chapter III, results and analysis in Chapter IV, and conclusions and suggested follow-on research in Chapter V.

II. LITERATURE REVIEW

Many problems that require scheduling solutions over multiple periods are solved using mathematical programing techniques, such as linear and integer programs. This chapter reviews relevant literature concerning the integer linear program (ILP), and its use in scheduling. It also presents some frameworks for decomposing employee scheduling problems.

In the context of this thesis, personnel scheduling, facilities scheduling, and ship scheduling are germane, all of which are interdependent to the success of the enterprise. Weather impacts facility availability, material failures cripple ships, and medical and personnel issues reduce manning. The stochastic nature of these events increase the computational complexity of an optimization problem in such a way that a tractable solution may not be attainable. Fortunately, this “schedule risk” may be mitigated by other means, for example, redundancy in equipment, adjustments to training events, and on-call manning requirements. Therefore, all data for this problem are treated as deterministic.

A. PERSONNEL SCHEDULING FRAMEWORKS

One assumption is that there is an adequate number of personnel to satisfy some level of customer demand. Personnel scheduling must start with shaping the size of the work force to meet the aggregate demand over a set period T. This strategic planning considers historical demand, projected demand, and expected work force attrition over the time period T. This long-term demand is further decomposed into skill set demand S and location demand D. Without such a personnel framework, any month-to-month, week-to-week, or day-to-day scheduling may be futile or inefficient. Abernathy et al. (1973) point out that even with an optimally sized strategic framework, a sub-optimal short-term scheduling methodology will undermine the benefits of the strategic framework.

1. Strategic Personnel Planning Framework

Strategic personnel planning starts with aggregate planning methodology to determine appropriate staffing levels in the manufacturing or service sectors. In the aggregate planning method, personnel demand is forecast for a specified time into the future to determine required staffing levels. Worker related expenses such as cost to hire a worker, cost to fire a worker, overtime cost, and cost to idle a worker are balanced against inventory costs, and shortage costs to determine the optimum level of staffing (Nahimas and Olsen 2015, 145).

Part of the consideration of the strategic personnel-planning framework must account for planned and unplanned losses on the organization, especially for those staff positions requiring experience and a high degree of skill. It must also account for the various skills required.

Abernathy et al. propose a three-stage model for staffing a hospital, most of which applies to other staffing models. The three steps are organizational policy decisions, staff allocations, and short-term scheduling (Abernathy et al. 1973, 695). Policy decisions concern areas such as the staffing structure, hiring and firing policies, operations scheduling, and services levels. Staff allocations concern areas such as a fixed level of staffing, a variable level of staffing, or use of temporary workers. Short-term scheduling is discussed in the next section.

Warner (1976) uses a similar three-step process called “the staffing decision,” “the scheduling decision,” and “the allocation decision” (842). In this construct staffing represents the number of nurses to have on the staff and is an annual decision, scheduling is when each staff member will work and will have days off and is made about monthly, and allocation is made daily and accounts for variability in the demand. Warner’s “scheduling decision” definition is similar to Abernathy’s et al. short term scheduling definition.

2. Temporal Personnel Planning Framework

The goal of temporal personnel scheduling is to get the right amount of people, with the right amount of skills, in the right place, at the right time to complete a task or a project. Temporal personnel scheduling reacts to demand on a time scale of weeks to hours. A task may only require one person with multiple skills, or dozens of people each with a unique skill that complements those skills of the other people assigned to the same task. The job of making the schedule may fall on the shoulders of the manager or may have a dedicated scheduler whose sole job is to put together the schedule. The schedule maker may need to consider company policies granting assignments by seniority, government regulations limiting the number of hours a person can work, or employee preferences on desired shifts.

De Causmaeker et al. (2004) surveyed 11 companies in Belgium ranging in size from 20 employees to over 1,000 employees and arrived at the following conclusions: a lot of time and effort is spent on creating schedules, the scheduler is expected to know everything about anything, and companies desire efficiency gains by minimizing staffing and overtime. De Causmaeker et al. also noted that very few of the companies utilized any sort of optimization software.

Ernst et al. broke the scheduling problem down into modules as follows:

1. Model the demand: Determine the level of staffing required over the period that the schedule is valid for. This level of staffing may be determined from expected steady state tasking or from a variable work schedule.
2. Schedule off days: Determine how many days personnel work prior to getting a day off.
3. Schedule shifts: Determine who works what shifts.
4. Integrate demand, days off, and shifts: Determine feasible lines of effort that meet organization and governmental rules.
5. Assign tasks: Determine what tasks will be accomplished when.
6. Assign staff: Personnel are assigned to lines of effort. (2004, 5–6)

Steps may be omitted depending on the type of organization involved. Knowing what type of organization involved allows a focus on the particular algorithms or practices that may be of most benefit.

De Causmaeker et al. (2004) break down the types of personnel scheduling into four types: permanence, where an around the clock presence must be maintained such as police, emergency services, and hospitals; mobility, where the personnel travel to various locations to perform their jobs such as housing inspectors, and home health care; fluctuation, where demand varies such as restaurants, and call centers; and project centered, where given tasks are assigned to one or more staff to execute within a certain time frame such as engineering firms.

Whereas Ernst et al. suggested breaking down the personnel schedule problems using a series of modules, De Causmaeker, et al. decompose the problem dimensions of "personnel (P), time (T), and the task or duty to be carried out (D)" (De Causmaeker et al. 2004, 185). Table 3 presents the De Causmaeker et al. decomposition. It provides a framework for decomposing the personnel-scheduling problem into an initial set of variables and constraints needed to formulate the problem as will be discussed in the next section.

In their survey of literature on personnel scheduling, Bradley and Martin (1990) compare the cyclic schedules versus non-cyclic schedules. Cyclic schedules provide stability and allow personnel to plan for days off, but its rigidity allows it to be easily perturbed by non-routine events such as staff absences due to health reasons or training requirements.

Table 3. Parameters for the Classification of Personnel Scheduling Problems. Source: De Causmaeker et al. (2004, 186).

P	Division of personnel into groups
D	Division of different tasks
(D,T)	Duty D has to be executed by time T
(P,T)	Employee P has to work at time T
(P,D)	Employee P has to perform duty D
(P,D,T)	Employee P has to perform duty D at time T (the actual schedule)

By decomposing from the general, groups (P) and division of tasks (D), and adding a temporal aspect time (T) the who, what, and when of personnel scheduled can be specified.

B. SOLUTION METHODS FOR SOLVING PERSONNEL SCHEDULING PROBLEMS

Many methods have been employed to solve personnel scheduling problems. Ernest et al. (2004) classify these methods as demand modeling, artificial intelligence, constraint programming, metaheuristics, and mathematical programming, e.g., linear programming, approaches. Of the approaches listed, only mathematical programming offers solutions that guarantee optimality. Most other solution methods only offer feasible solutions with no indication of how good a solution is. When a problem is computationally too complex to solve using mathematical programming approaches or only a feasible solution is desired, or optimality is not required, the methods listed above are often employed. Specifically, most scheduling problems involve trying to achieve many conflicting goals. For example, an organization would like to minimize the number of required staff to reduce costs without sacrificing service, morale, or work force stability while the staff would like to maintain a schedule that fits their individual needs for time off (Warner 1976).

1. Linear Programming

The advent of computers promoted the use of mathematical programs to optimize the use of resources, material, employees, time, or dollars to achieve better decisions for the person or company, but as Ragsdale points out, “good decisions do not always result in good outcomes” (2018, 11, 17). The need for optimization is not a new problem and many network problems can be solved graphically or in closed form (Dantzig and Fulkerson 1954, 217).

Ragsdale lays out the steps of formulating a linear programming model in four steps (2018, 21–22). The first step is to understand the problem that is being solved. In this paper, the problem is how to schedule T&E customers for a time period on the range to maximize customer value and how to schedule employees to support the customer range events while meeting the employee’s work preferences. The second step is to determine the decision variables, which are what customers’ range events occur on what day and which employees work at a particular range each day. The third step is to write the objective function in terms of the decision variables. The last step is to write the constraints in terms of the decision variables. In order for this to be a linear program the objective function and constraints must be linear combinations of the decision variables, where the decision variables can take on continuous values greater than zero, positive integer values, or binary values (0, 1) (Della Croce 2014, 103–104).

2. Integer Linear Programming

Integer linear programming (ILP) is a subset of linear programming where the decision variables can be integers. In this paper, an integral number of employees are assigned to a work schedule. Similarly, a customer is allocated an integral number of range events. Taking this further an employee is either assigned to a work schedule or not assigned to a work schedule and a customer is either assigned a range event or not assigned a range event. A binary variable is use to represent this logic of a 1 for selection and a 0 for non-selection. Problems of this type are termed combinatorial optimization problems or 0–1 Integer Programs (IPs) (Nemhauser and Wolsey 1999, 4).

The case of employee scheduling is called an assignment problem. Using the formulation of Nemhauser and Wolsey, there are *n* employees are assigned to *m* tasks and each employee *j* can only be assigned to one task *i*. In this case $n \geq m$ and the cost for employee *j* to be assigned to task *i* is c_{ij}. The goal is to minimize the cost. The objective function is min $\sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij}\, x_{ij}$ where x_{ij} is 1 if employee *j* is assigned to task *i* and 0 otherwise (Nemhauser and Wolsey 1999, 5 - 6). The constraints are $\sum_{j=1}^{n} x_{ij} = 1$ for *i* = 1, …m, which ensures that each task *i* has only one employee *j* assigned and $\sum_{i=1}^{m} x_{ij} \leq 1$ for j = 1, …n, which ensures each employee *j* is assigned to at most one task *i*. In this problem the cost is the employee’s total preference value (lower is better) to being assigned to certain work schedule.

Similarly, the customer allocation of a range event is called a knapsack problem where *n* things with value v_i are placed into a knapsack. The objective function is max

$\sum_{i=1}^{n} v_i y_i$ where y_i is 1 if customer i is assigned to range event i and 0 otherwise (Nemhauser and Wolsey 1999, 5). The constraints take the general form of $\sum_{i=1}^{n} a_i y_i \leq b$ where a_i may represent a TWR, YTT, range location or day on the range and b is the amount of that asset that is available.

The knapsack problem is termed a nondeterministic polynomial time (NP) – complete problem which means that a NP problem could be solved on a nondeterministic Turing machine in polynomial time (Nemhauser and Wolsey 1999, 133–137). NP-complete problems must be solved using other methods. One such method is approximation using the branch and bound method where the integrality conditions in the ILP are relaxed and the problem is solved. For the maximization problem, this relaxation gives an upper bound to the objective function. The branch and bound algorithm picks a decision variable that has is not an exact integer and rounds it up and down and then solves the problem with a less than or equal to the lower value and a greater than and equal to the upper value. It checks the value of the next decision variable and repeats the branch and bound process with that decision variable. Infeasible solutions are eliminated (Ragsdale 2016, 293 – 300). Feasible solutions to this problem may also be found by using several different heuristics (Nemhauser and Wolsey 1999, 440–443), but optimality is not guaranteed.

Ryan (1992) uses a set partitioning method with bound and branch to reduce complexity and argues that "rostering problems can be usually broken down into smaller independent subproblems corresponding to groups of crew members of the same rank" (460). Dawid, Konig, and Strauss (2001) argue that using Ryan's approach might result in not finding a feasible solution and propose that greater flexibility can be gained by downgrading assignments which is where a more qualified or senior crew members may fill the assignment in a position requiring less qualification or filled by a junior crew member (675).

Brucker, Qu, and Burke (2011) present several formulations for the personnel scheduling models proposed by De Causmaecker, depending on whether employees are only qualified for one task or any task can be performed by any employee, etc. Brucker, Qu, and Burke conclude that most of the problems for small scheduling tasks can be formulated as an integer linear program, while heuristics may be required for more computationally complex problems (473).

III. METHODOLOGY

A. BACKGROUND

Range crew scheduling for NUWC Keyport boat crews can be divided into spatial assignments and into non-spatial assignments. In a spatial assignment the crew overnights at the geographic region of the assigned duty, while in a non-spatial assignment, the crew returns to their home base each night. Due to the distance required to get to a spatial assignment, it is highly desirable for the same crew to be used for the duration of the assignment, even though the tasking may change each day. Examples of spatial assignments are operations at Nanoose, Canada or in San Diego, and escort duty for Puget Sound Naval Shipyard high-value, material transits. For non-spatial assignments, the crew members may be changed out daily, although doing so may reduce the benefits of the task's learning curve. To facilitate this restriction in the model, we use a construct that we call Options. Valid options are made up of groupings of days which represent feasible or allowable day groupings that satisfy the spatial crew assignment restrictions.

The formulation for the optimization model follows. For ease of explanation, the model is presented in two parts, ILP (1) and ILP (2). Common to both parts are the sets, indices, and parameters that follow. An explanation of all equations used follow the algebraic formulation.

B. SETS

E	Employee crew for boats
T	Time periods
L	Range locations
B	Boat Type
O	Options
C	Customers
$PO \subseteq O \times T$	Time period and Option tuples
$OLE \subseteq O \times L \times E$	Option, Location, and Employee tuples

C. INDICES

$e \in E$	Employees $\{e1,\ \cdots,\ e15\}$
$t \in T$	Time Periods $\{M, T, W, Th, F, Sa, Su\}$
$l \in L$	Locations $\{Nanoose, Keyport\}$
$b \in B$	Boat Types $\{YTT, TWR\}$
$o \in O$	Options $\{1a, 1b, \cdots, 1e, 2a, 2b, 2c, 2d, 3a, 3b, 3c, 3d, 4a, 4b, 4c, 4d, 5a, 5b, 5c\}$
$c \in C$	Customers $\{A, B, C, D\}$
$(t,o) \in PO$	Time period and Option tuples
$(o,l,e) \in OLE$	Specific Option, Location, and Employee tuples: $PO \cup (e,l,t)$

D. PARAMETERS [UNITS]

$noncon_{t,o}$	Table of indicators [1 if day is included in an option, 0 otherwise]
$pri_{o,b,l,c}$	Customer's preference for an Option [Higher is better]
$empOptPref_{e,l,o}$	Employee's preference for working a particular Option [Lower is better]
req_b	The number of employee's required to crew boat b [number of people]
$\overline{Y}_{o,b,l,c}$	Stores the solution from ILP(1) for use in ILP(2)

E. DECISION VARIABLES

$Y_{o,b,l,c}$	1 if Object o is choosen for Customer c using Boat b at Location l, 0 otherwise
$X_{o,b,l,e}$	1 if Employee e is choosen for Option o using Boat b at Location l, 0 otherwise

F. ILP-1

$$MAX \sum_{o \in O} \sum_{b \in B} \sum_{l \in L} \sum_{c \in C} pri_{o,b,l,c} Y_{o,b,l,c} \tag{1}$$

$$s.t. \quad \sum_{o \in O | (t,o) \in PO_{t,o}} \ \sum_{b \in B | b = \{YTT\}} \ \sum_{l \in L} \sum_{c \in C} Y_{o,b,l,c} \le 2 \quad \forall t \in T \tag{2}$$

$$\sum_{o \in O | (t,o) \in PO_{t,o}} \ \sum_{b \in B | b = \{TWR\}} \ \sum_{l \in L} \sum_{c \in C} Y_{o,b,l,c} \le 2 \quad \forall t \in T \tag{3}$$

$$\sum_{b\in B}\sum_{l\in L}\sum_{o\in O} Y_{o,b,l,c} \leq 1 \quad \forall c \in C \tag{4}$$

$$Y_{o,b,l,c} \in binary \quad \forall o \in O, b \in B, l \in L, c \in C \tag{5}$$

G. ILP-2

$$MIN \sum_{o\in O}\sum_{b\in B}\sum_{l\in L}\sum_{e\in E} empOptPref_{e,l,o}\, X_{o,b,l,e} \tag{6}$$

$$s.t. \quad \sum_{l\in L}\sum_{b\in B} X_{o,b,l,e} \leq 1 \quad \forall e \in E, o \in O \tag{7}$$

$$\sum_{e\in E|(o,l,e)\in OLE_{o,l,e}} X_{o,b,l,e} \geq req_b \cdot \overline{Y}_{o,b,l,c} \quad \forall o \in O, b \in B, l \in L, c \in C \mid pri_{o,b,l,c} \tag{8}$$

$$X_{o,b,l,e} \in binary \forall o \in O, b \in B, l \in L, e \in E \tag{9}$$

H. FORMULATION DISCUSSION

This multiple objective integer linear program (ILP) is solved preemptively, where ILP-1 is first solved, the solution stored, and then using the solution obtained from ILP-1, the second program, ILP-2, is solved. Solving this program preemptively has two primary benefits. It removes the need to determine the tradeoff, that is, weights on the objective function coefficients, between the total customer and total employee preferences. Also by partitioning the problem, computation is much easier which should allow for the use of open source IP solvers if the need arises. The primary assumption that allows this problem to be solved preemptively is that the customer preferences completely dominate the employee preferences.

The ILP-1 objective function (1) maximizes the customer's total preference value (higher is better). The first two constraints, (2) and (3), ensure that no more than two boats of each type, YTT and TWR, respectively, are deployed on any given day. The next constraint (4) ensures that a customer will never be given more than one range option. The domain restriction for ILP-1's decision variable is given in (5).

The ILP-2 objective function (6) minimizes the employee’s total work preference value (lower is better). The first constraint for ILP-2 (7) ensures that an employee in assigned to no more than one option. The next constraint (8) determines the employee crew assignment based on the customer range schedule. The final constraint (9) is the domain restriction for ILP-2’s decision variable.

Discussion of how ILP-1 and ILP-2 are implemented, data instances, and the analysis of the results are discussed in the next chapter.

IV. DATA AND RESULTS

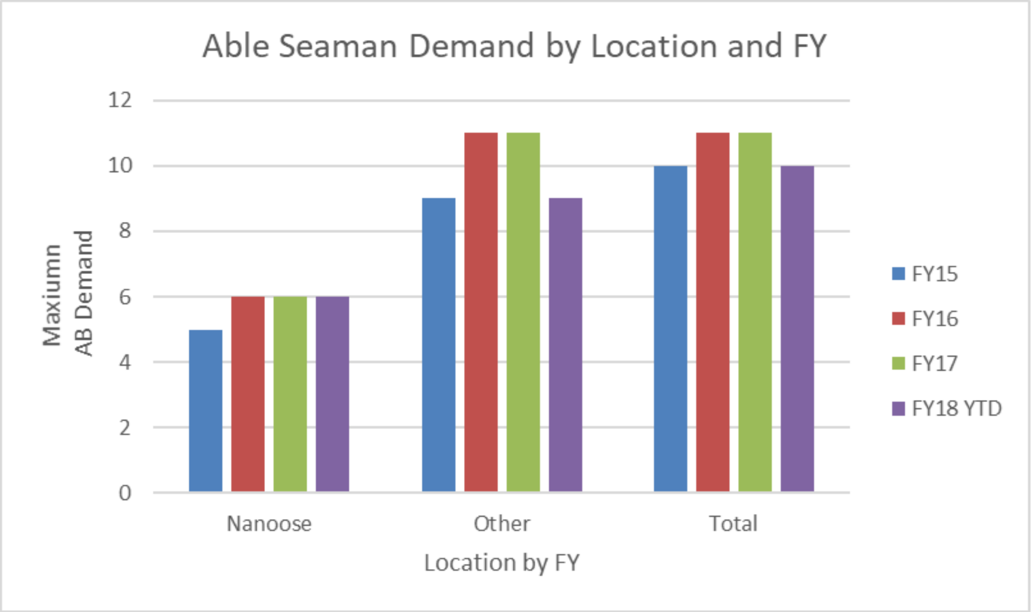
A. HISTORICAL ABLE SEAMAN TEMPORAL MANNING REQUIREMENTS

The crews available to man vessels consists of several subgroups of employees as shown in Chapter I, Section D, Table 1. For this thesis the most numerous subgroup of employees, the able seaman, are used in the optimization scenarios presented later in this chapter. The other sub-groups of employees, such as YTT masters or DDEs, are too few in number to warrant the need of an optimization model.

Historical AB demand is inferred from NUWC Keyport's monthly range usage report that details the dates, locations and purposes of all Keyport range operations. For each range operation, the monthly report lists the types and numbers of boats employed. This list and the required AB manning from Table 1 informs the total number of AB required on any one day for range operations.

The monthly range reports allow one to infer total daily AB demand, but it contains no information on the numbers of AB available on a particular day. It is unknown if the number of available AB on a particular day was less than, equal to, or greater than customer demand.

Figure 4 breaks out the number of days at a given total daily AB demand level for a given FY year. The maximum total AB demand across fiscal years does not vary by more than 10%.

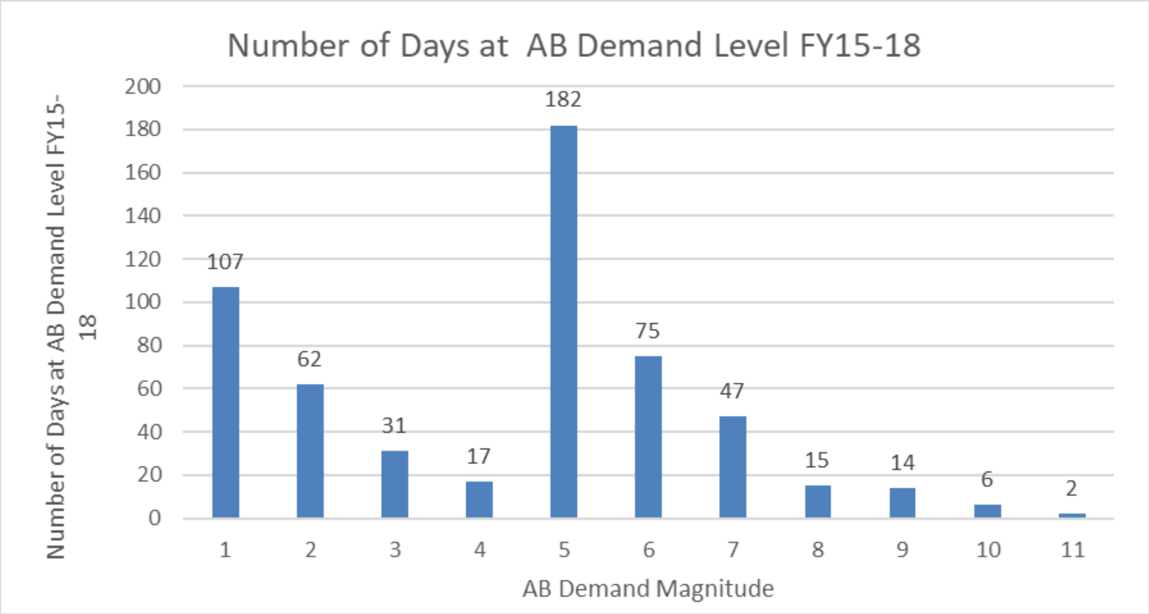


For each fiscal year from FY15 to FY18YTD, the maximum number of AB demand for range events at Nanoose, for range events at locations other than Nanoose, and total AB demand is graphed.

Figure 4. Total Daily Able Seaman Demand by Location and Fiscal Year

Figure 5 is the cumulative number of days from FY15 through May FY18 of daily total AB demand, where the mean number of AB per event is 4.3 persons, the mode is 5 AB persons per event and the median is 5 AB seaman per event. Days where there are no range events, either due to no customer demand, cancellation of range events due to equipment failure, or scheduled range down times are omitted from the figure.

This section presented historical AB demand going back to FY15 that demonstrated maximum AB demand, while infrequent, was 11 and did not vary by more than 10% across fiscal years. Given an AB pool of 15, this represents a minimum load factor of 73%, calculated by dividing 11 by 15, provided every AB is available. Unavailability of even 20% of the AB pool drives the load factor up to almost 92%, and warrants the use of an optimization model to maximize employee work preferences.



The image shows the cumulative number of days from FY15 to FY18YTD for AB of daily demand levels for all range events. The mode is 5 AB per day, the median is 5 AB per day, and the mean is 4.3 AB per day when ranging occurred.

Figure 5. Cumulative Number of Days at AB Daily Demand Level from FY15-FY18 YTD

B. OPTIMIZING CUSTOMER DEMAND AND AB PREFERENCE

The formulation presented in the previous chapter discusses two parameters used to capture customer and employee preferences. Development of the data associated with these parameters are discussed.

Customer priorities are applied to the selection of a boat type, TWR or YTT, a range, Nanoose or Keyport, and an operation schedule. In the optimization model presented in the previous chapter the customer priority parameter, *pri*, is used to capture the customer priority (bigger is better) for each operation schedule, customer, location and boat type. For the scenarios examined in this thesis, 100 is used for the least desirable option while a maximum of 500 is used for the most desirable. An operation schedule consists of a set of feasible options in which a training event can occur. The feasible set of options used in this thesis are listed in Table 4.

Table 4. Set of Time Periods and Options *PO* (*t*, *o*)

	1a	1b	1c	1d	1e	2a	2b	2c	2d	3a	3b	3c	3d	4a	4b	4c	4d	5a	5b	5c
Mo	1					1				1				1				1		
Tu		1				1	1			1	1			1	1			1	1	
We			1				1	1		1	1	1		1	1	1		1	1	1
Th				1				1	1		1	1	1	1	1	1	1	1	1	1
Fr					1				1			1	1		1	1	1	1	1	1
Sa													1			1	1		1	1
Su																	1			1

The numeric part of the operation schedule *o* denotes the length of the range operation in days, and the letter part of the schedule denotes the day of the week the operation schedule *o* begins on. The letter a starts on Monday, b starts on Tuesday, c starts on Wednesday, and d starts on Thursday.

Employee work preferences (lower values are better) are accounted for using the parameter, *empOptPref*, where a value of 5 is least desirable and a value of 1 is most desirable. A penalty of 100 is given to an employee particular option if the employee is not available for duty. An example of data for this parameter is shown in Table 6.

The relative tradeoff or *weights* of customer priority preference versus employee work preference are not relevant in this thesis since the optimization is executed in a preemptive manner, that is, the customer priority objective is first met and once the optimal operational schedule is solved, then the optimal employee schedule is found that will execute the operational schedule. If a feasible solution is found for both objectives, this preemptive method is guaranteed to find a Pareto optimal solution, that is, another solution cannot be found without making one or both objectives worse off.

This thesis examines four different scenarios typically encountered during the planning and scheduling of range events at NUWC Keyport.

1. Scenario 1

The first situation is where two customers want to range on the same day. This is a frequent occurrence and the optimization model deals explicitly with this by maximizing customer preference and allowing for different boat types to be used by different customers on the same day at the same range. It also deals with a customer that wants to book multiple operations during an entire week while only needing a portion of the week. This tactic of overbooking prevents other customers from using the range that week. In Chapter III, Section F, the constraint in Equation (4), limits the customer to no more than one operation schedule. Scenario 1's customer preferences are shown in Table 5 and employee work preferences are shown in Table 6.

Table 5. Scenario 1 Customer Preferences

Customer	Location	Boat	Schedule	Day(s)	Value
A	Nanoose	TWR	1a	M	100
B	Keyport	YTT	4a	M-Th	400
B	Keyport	YTT	4d	Th-Su	300
C	Nanoose	YTT	3a	M-W	500

This table shows inputs (customer, range location to conduct the event, boat type for the range event, schedule option and value) used for scenario 1. The column of days is not a direct input but is implied by the Option assignment.

Table 6. Scenario 1 Employee Work Preferences

Employee	Nanoose Employee Preferences					Keyport Employee Preferences				
	M	Tu	We	Th	Fr	M	Tu	We	Th	Fr
e1	1	1	1	1	1	5	5	5	5	5
e2	2	2	2	2	2	4	4	4	4	4
e3	3	3	3	3	3	3	3	3	3	3
e4	4	4	4	4	4	2	2	2	2	2
e5	5	5	5	5	5	1	1	1	1	1
e6	1	1	1	1	1	5	5	5	5	5
e7	2	2	2	2	2	4	4	4	4	4
e8	3	3	3	3	3	3	3	3	3	3
e9	4	4	4	4	4	2	2	2	2	2
e10	100	100	100	100	100	1	100	1	100	1
e11	100	100	100	100	100	100	5	5	5	100
e12	100	100	100	100	100	100	4	4	100	100
e13	100	100	100	100	100	3	100	3	3	100
e14	100	100	100	100	100	2	100	2	100	2
e15	100	100	100	100	100	100	4	100	100	100

Employee work schedule preferences in scenario 1 list each employee and his preference for working at a particular range on a particular day. Preferences range from 1 to 5 where 1 is better. A value of 100 means that the employee is available for work on that day at that range, but incurs a penalty due to disrupting his schedule.

Table 7 is the solution of the optimization model assigning customers and employees to the operational schedule shown in Table 5.

Table 7. Scenario 1 Solution

	Customer	Option	Location	Boat Type
	A	1a	Nanoose	TWR
Employees	e8			
	C	3a	Nanoose	YTT
Employees	e1	e2	e6	e7
	B	4a	Keyport	YTT
Employees	e3	e4	e5	e9

The solution for scenario 1 is grouped by customer, location and boat type and the employees are presented in the row below each customer. For example, customer B was assigned Option 3a located in Nanoose using a YTT with employees, e1, e2, e6, and e7.

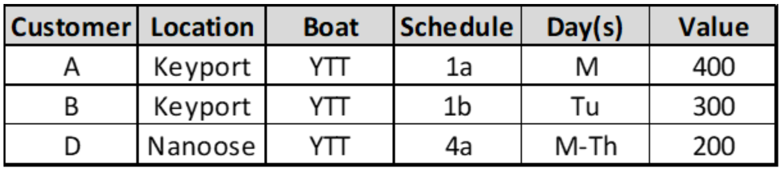
The solution presented in Table 7 selects customer C’s Nanoose YTT request, customer B’s Keyport YTT request, and customer A’s Nanoose TWR request. Customer B’s Keyport YTT M-Th option (value of 400) is selected over customer B’s Keyport YTT Th-Su option (value of 300) as the constraint in equation (4) limits customer B to one option for the week. With the customer options selected the optimization model minimizes employee work preferences and selects employees e1, e2, e6, and e7 to man the Nanoose YTT, employees e3, e4, e5, and e9 to man the Keyport YTT, and employee e8 to man the Nanoose TWR.

As the results in Table 7 illustrate, the optimization model selects the employees that provide the most value over the entire operation schedule, which are not necessarily the same employees the provide the best value for a particular day and customer. In this scenario, the optimization model selects for the Keyport YTT employees with daily values of 1, 2, and 3, and for the Nanoose YTT, employees with daily values of 1 and 2. The optimization model then selects the employee for the Nanoose TWR with a daily value of 3 for the single day operation schedule.

2. Scenario 2

In the second scenario, two YTT range events are scheduled back to back at the Keyport range. This involves two different range customers and hence two different operation schedules. The optimization model is not restricted by the constraint in equation (8) to have the same crew for each operation schedule. Scenario 2's customer preferences are shown in Table 8 and employee work preferences are shown in Table 9.

Table 8. Scenario 2 Back to Back YTT Operation Schedules at Keyport



Customer	Location	Boat	Schedule	Day(s)	Value
A	Keyport	YTT	1a	M	400
B	Keyport	YTT	1b	Tu	300
D	Nanoose	YTT	4a	M-Th	200

This table shows inputs (customer, range location to conduct the event, boat type for the range event, schedule option and value) used for scenario 2. The column of days is not a direct input, but is implied by the Option assignment.

Table 9. Scenario 2 Employee Preferences for Back to Back YTT Operation Schedules at Keyport

Employee	Nanoose Employee Preferences					Keyport Employee Preferences				
	M	Tu	We	Th	Fr	M	Tu	We	Th	Fr
e1	1	1	1	1	1	5	5	5	5	5
e2	2	2	2	2	2	4	4	4	4	4
e3	3	3	3	3	3	3	3	3	3	3
e4	4	4	4	4	4	2	2	2	2	2
e5	5	5	5	5	5	1	1	1	1	1
e6	1	1	1	1	1	5	5	5	5	5
e7	2	2	2	2	2	4	4	4	4	4
e8	3	3	3	3	3	3	3	3	3	3
e9	4	4	4	4	4	2	2	2	2	2
e10	100	100	100	100	100	1	100	1	100	1
e11	100	100	100	100	100	100	5	5	5	100
e12	100	100	100	100	100	100	4	4	100	100
e13	100	100	100	100	100	3	100	3	3	100
e14	100	100	100	100	100	2	100	2	100	2
e15	100	100	100	100	100	100	4	100	100	100

Employee work schedule preferences in scenario 2 list each employee and his preference for working at a particular range on a particular day. Preferences range from 1 to 5 where 1 is better. A value of 100 means that the employee is available for work on that day at that range, but incurs a penalty due to disrupting his schedule.

Table 10 is the solution of the optimization model assigning customers and employees to the operational schedule shown in Table 8.

Table 10. Scenario 2 Solution

	Customer	Option	Location	Boat Type
	D	4a	Nanoose	YTT
Employees	e1	e2	e6	e7
	A	1a	Keyport	YTT
Employees	e4	e5	e9	e10
	B	1b	Keyport	YTT
Employees	e4	e5	e8	e9

The solution for scenario 2 is grouped by customer, location and boat type and the employees are presented in the row below each customer. For example, customer D was assigned Option 4a located in Nanoose using a YTT with employees, e1, e2, e6, and e7.

The solution presented in Table 10 selects all of the customer’s priorities. The employee assignments at Nanoose are similar to the previous employee assignments in scenario 1 and the solution selects employees e1, e2, e6, and e7. Those employees all have employee work preference values of 1 and 2 for each day of the operation schedule. The Keyport YTT assignments are for two different customers and the employee assignments are not constrained to be the same for each customer, but are optimized for each operation schedule. For operation schedule 1a, the solution selects employees e4, e5, e9, e10 who all have work preference values of 1 and 2 for Monday. On Tuesday for operation schedule 1b, the solution selects employees e4, e5, and e9 with employee work preferences of 1 and 2, but drops employee e10 who has a penalty of 100 in favor of employee e8 instead who has an employee work preference of 3

3. Scenario 3

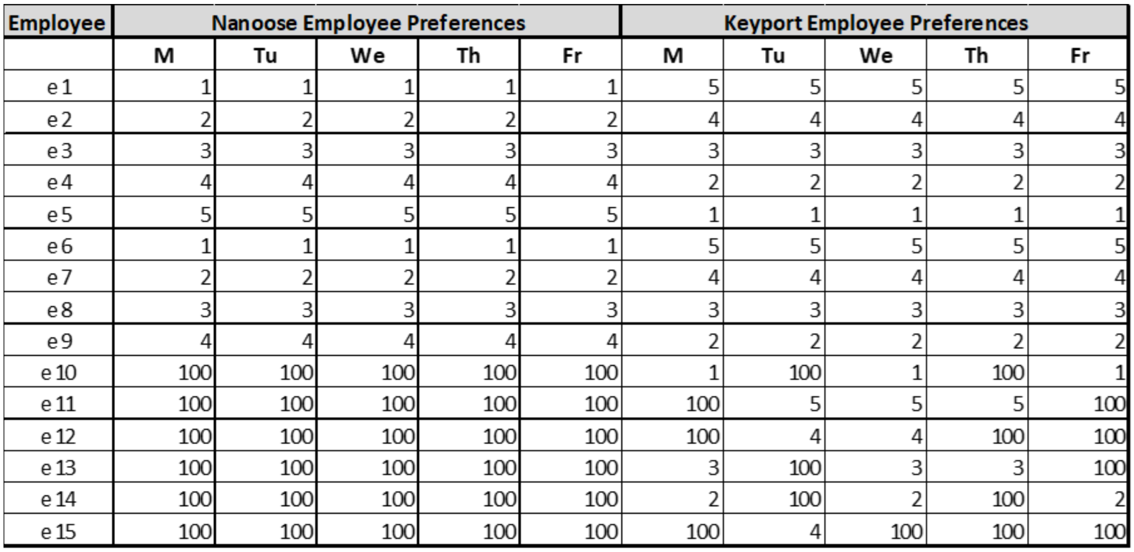
This scenario is a modification of the previous scenario except that back-to-back operations on TWRs occur up at Nanoose over four operation schedules. Scenario 3’s customer preferences are shown in Table 11 and employee work preferences are shown in Table 12.

Table 11. Scenario 3 Consecutive TWR Operational Periods at Nanoose

Customer	Location	Boat	Schedule	Day(s)	Value
A	Nanoose	TWR	1a	M	400
B	Nanoose	TWR	1b	Tu	300
C	Nanoose	TWR	1c	W	200
D	Nanoose	TWR	1d	Th	100

This table shows inputs (customer, range location to conduct the event, boat type for the range event, schedule option and value) used for scenario 3. The column of days is not a direct input, but is implied by the Option assignment.

Table 12. Scenario 3 Employee Preferences for Consecutive TWR Operation Schedules at Nanoose

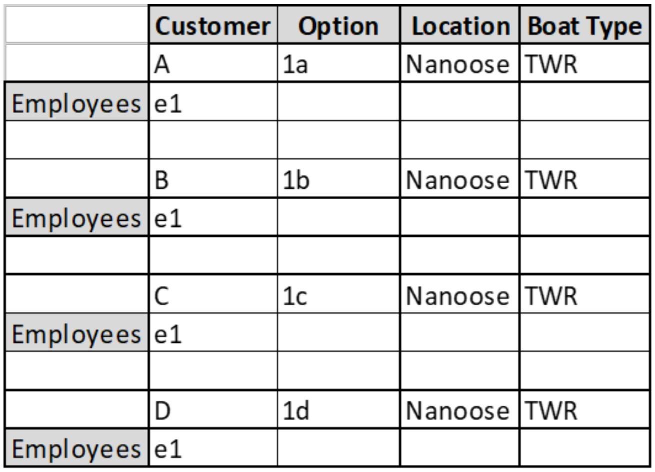


Employee	Nanoose Employee Preferences					Keyport Employee Preferences				
	M	Tu	We	Th	Fr	M	Tu	We	Th	Fr
e1	1	1	1	1	1	5	5	5	5	5
e2	2	2	2	2	2	4	4	4	4	4
e3	3	3	3	3	3	3	3	3	3	3
e4	4	4	4	4	4	2	2	2	2	2
e5	5	5	5	5	5	1	1	1	1	1
e6	1	1	1	1	1	5	5	5	5	5
e7	2	2	2	2	2	4	4	4	4	4
e8	3	3	3	3	3	3	3	3	3	3
e9	4	4	4	4	4	2	2	2	2	2
e10	100	100	100	100	100	1	100	1	100	1
e11	100	100	100	100	100	100	5	5	5	100
e12	100	100	100	100	100	100	4	4	100	100
e13	100	100	100	100	100	3	100	3	3	100
e14	100	100	100	100	100	2	100	2	100	2
e15	100	100	100	100	100	100	4	100	100	100

Employee work schedule preferences in scenario 3 list each employee and his preference for working at a particular range on a particular day. Preferences range from 1 to 5 where 1 is better. A value of 100 means that the employee is available for work on that day at that range, but incurs a penalty due to disrupting his schedule

Table 13 is the solution of the optimization model assigning customers and employees to the operational schedule shown in Table 11.

Table 13. Scenario 3 Solution



	Customer	Option	Location	Boat Type
	A	1a	Nanoose	TWR
Employees	e1			
	B	1b	Nanoose	TWR
Employees	e1			
	C	1c	Nanoose	TWR
Employees	e1			
	D	1d	Nanoose	TWR
Employees	e1			

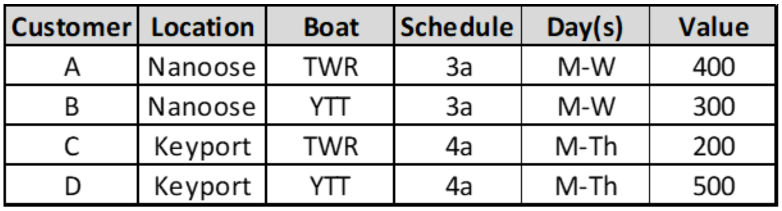
The solution for scenario 3 is grouped by customer, location and boat type and the employees are presented in the row below each customer. For example, customer D was assigned Option 1d located in Nanoose using a TWR with employee e1.

In this scenario, the solution selects all of the customer's preferences. The solution selects the same employee, e1 for all four operation schedules. The employee work preference for employee e1 is 1 for all four days, but so is the employee work preference for employee e6. Though not constrained to produce this outcome, this is the best outcome as far as minimizing employee travel time and per diem costs, since it takes a day to transit up to Nanoose for operations and a day to transit back. Swapping out employees at Nanoose increases ranging costs. Employee costs are not part of the optimization model.

4. Scenario 4

Scenario 4 examines the situation where there are insufficient employees to meet the customer's desired operational schedule without incurring a penalty. Some of the most common reasons for employee unavailability are annual leave, training, and sickness. Leave and training may be cancelled to meet customer AB demand when other employees are not available as denoted in the employee preference table with a penalty value of 100. Because of the disincentive of receiving such a penalty, the optimization model will always select an available employee when possible. In the cases of sickness, injury or a lack of employees to meet customer demand, then the problem is infeasible and another operational schedule must be found that can be properly resourced. Scenario 4's customer preferences are shown in Table 14 and employee work preferences are shown in Table 15.

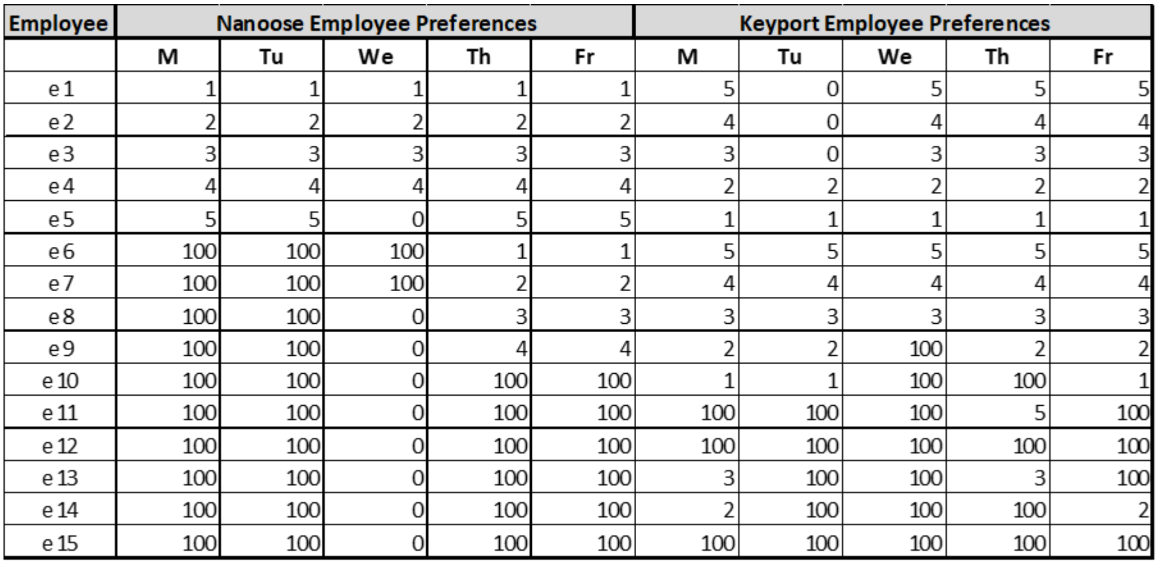
Table 14. Scenario 4 Limited Employee Availability



Customer	Location	Boat	Schedule	Day(s)	Value
A	Nanoose	TWR	3a	M-W	400
B	Nanoose	YTT	3a	M-W	300
C	Keyport	TWR	4a	M-Th	200
D	Keyport	YTT	4a	M-Th	500

This table shows inputs (customer, range location to conduct the event, boat type for the range event, schedule option and value) used for scenario 4. The column of days is not a direct input, but is implied by the Option assignment.

Table 15. Scenario 4 Employee Preferences for Limited Employee Availability

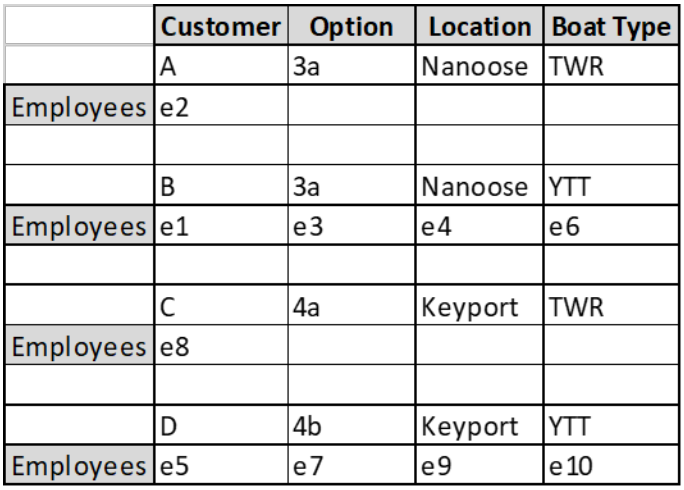


Employee	Nanoose Employee Preferences					Keyport Employee Preferences				
	M	Tu	We	Th	Fr	M	Tu	We	Th	Fr
e 1	1	1	1	1	1	5	0	5	5	5
e 2	2	2	2	2	2	4	0	4	4	4
e 3	3	3	3	3	3	3	0	3	3	3
e 4	4	4	4	4	4	2	2	2	2	2
e 5	5	5	0	5	5	1	1	1	1	1
e 6	100	100	100	1	1	5	5	5	5	5
e 7	100	100	100	2	2	4	4	4	4	4
e 8	100	100	0	3	3	3	3	3	3	3
e 9	100	100	0	4	4	2	2	100	2	2
e 10	100	100	0	100	100	1	1	100	100	1
e 11	100	100	0	100	100	100	100	100	5	100
e 12	100	100	0	100	100	100	100	100	100	100
e 13	100	100	0	100	100	3	100	100	3	100
e 14	100	100	0	100	100	2	100	100	100	2
e 15	100	100	0	100	100	100	100	100	100	100

Employee work schedule preferences in scenario 4 list each employee and his preference for working at a particular range on a particular day. Preferences range from 1 to 5 where 1 is better. A value of 100 means that the employee is available for work on that day at that range, but incurs a penalty due to disrupting his schedule.

Table 16 is the solution of the optimization model assigning customers and employees to the operational schedule shown in Table 14.

Table 16. Scenario 4 Solution



	Customer	Option	Location	Boat Type
	A	3a	Nanoose	TWR
Employees	e2			
	B	3a	Nanoose	YTT
Employees	e1	e3	e4	e6
	C	4a	Keyport	TWR
Employees	e8			
	D	4b	Keyport	YTT
Employees	e5	e7	e9	e10

The solution for scenario 4 is grouped by customer, location and boat type and the employees are presented in the row below each customer. For example, customer D was assigned Option 4b located in Keyport using a YTT with employees e5, e7, e9, and e10.

In scenario 4, the solution selects all of the customer preferences. Only six employees are available for operations at Nanoose from Monday through Wednesday. The solution selects employee e2 for the TWR with a daily employee work preference of 2, and selects employees e1, e3, and e4 for the YTT with daily employee work preferences of 1, 3, and 4, respectively. Both of the two remaining employees at Nanoose have a penalty of 100 for each day of the operation schedule. The solution selects e6 over e7, which allows employee e7 with Keyport employee work preference of 4 to be selected over e6 with a Keyport employee work preference of 5. Many more employees are available for range craft duties at Keyport, but only 3 employees, e5, e7, and e8, are available for the operation schedule who have no penalties. Of the last two employees needed to round out the Keyport manning, the solution selects employees e9 and e10, who have the least amount of penalties of the available employees remaining.

C. OPTIMIZATION MODEL IMPLEMENTATION AND COMPUTATION

The GAMS implementation is found in Appendix B of this thesis (Paul L. Ewing, personal communication, July 31, 2018). For this thesis, GAMS software version 25.1.1

uses the IBM ILOG CPLEX optimizer to solve the ILP (GAMS, 2018). All solutions found in this thesis used an optimality gap of 0.0 and the pre-solve function of CPLEX found solutions for all the scenarios within 2 seconds.

V. CONCLUSIONS AND AREAS FOR FURTHER STUDY

A. CONCLUSIONS

This paper presents an algorithm that balances the demands of the customers with the preferences of the employees by solving an integer linear program, referred to as the optimization model, in a preemptive manner. Four scenarios are used to test the optimization model, using the priorities of four hypothetical customers and the preferences of 15 able seamen for a hypothetical employee work schedule. The objective function for customer priorities maximized the values of the customers' priorities with respect to operation schedule. Another objective function for employee preferences minimized total employee work preference, where lower is better with being assigned to a location and operation schedule on a per day basis. For employees a penalty could be assigned to a day if having the employee work that day meant disrupting leave, cancelling training or missing a medical appointment.

For the four scenarios, the optimization model's solutions modeled actual range operations such as the following: allows two customers to share a range day (scenario 1); keeps employees together for an operational schedule (scenario 1); allows employee change outs between operation schedules (scenario 2); assigns the same employee to the consecutive operation schedules given that employee has the lowest employee work preference (scenario 3); alerts management to disruptive employee schedules (scenario 4); assigns employees with the lowest employee's total preference value (lower is better) values to the longer operation schedules first, and then the assignment of employees with least preferred work schedules to shorter operation schedules second (all scenarios).

Finally, historical AB demand going back to FY15 demonstrates that maximum AB demand, while infrequent, was 11 and unavailability of even 20% of the AB pool would drive the AB load factor up to almost 92%, which indicates that the use of an optimization model to maximize employee work preferences may be warranted.

B. AREAS FOR FURTHER STUDY

The optimization formulation covers the basics of range scheduling and crew rostering at NUWC Keyport. There are many other enhancements and complexities that could be added to both as outlined below.

1. Additional Constraints

The optimization formulation could add constraints to reflect NUWC Keyport policies and rules as is typically done in more complex formulations in crew rostering. Examples of additional constraints are:

- Number of days in a row an employee works
- Number of work assignments an employee completes to maintain proficiency
- Parity of assignments between Keyport and Nanoose for employees and between employees for all assignments to prevent burnout
- Number of hours of overtime an employee works

Besides adding constraints to reflect policy goals and improve employee performance, current constraints could be modified to allow two boats of one type to operate at the same range location on the same day, or to allow a customer to request more boats than just one.

2. Expansion of the Set of Options

The options in the formulation are purposely limited in scope in several ways. The number of elements in each set could be increased to reflect the actual complexity of range operations. For example:

- *E* — set of employees *e* {1…15} could be increased as the AB population grows. Additionally, other sets of employees could be added to account for other range craft positions such as craft master and DDE.
- *T* — days of the week {Monday…Sunday} could be increased to a month or longer to even out range operational assignments and workload.
- *L* — set of locations *l* {Nanoose, Keyport} could be increased to add other operational areas such as Hood Canal, Dabob Bay, Brownsville, and off the coast of Washington state.

- *B* — set of boat types *b* {YTT, TWR} could be increased to reflect other boat types listed in Table 1.
- *C* — set of customers *c* {A…D} could be increased along with the increase in *T* to 20 or 30 customers.

3. Additional Model Complexity

Complexity to the model could also be added by allowing for the use of downgrading methodology proposed by Dawid, Konig, and Strauss (2001), where a more skilled employee can be slotted to do a job requiring less skill, thereby increasing the pool of available employees. Indeed, this seems to be essential to the range craft workforce given the small number of certain positions such as YTT assistant craft master.

Finally, instead of solving the problem preemptively, the problem could be solved in the monolith, where ILP1 and ILP2 are combined in a single objective function with the appropriate weighting of the objective function coefficients (Paul L. Ewing, personal communication, August 14, 2018). This problem would be ideal for a high-performance solver such as CPLEX.

C. APPLICATION OF RESULTS TO OTHER AREAS

The customer value and employee preference optimization algorithms could be applied to many everyday applications in the Navy such as creating a watch bill for a ship for both underway operations and in port duty sections, or for watch bills at fleet command centers that must be manned around the clock. It could also be used to create and assign teams of varying engineering disciplines to undertake projects.

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APPENDIX . GAMS FORMULATION

```
$TITLE MFF
*$Offlisting
$set datapath %gams.user1%
*----------GAMS AND DOLLAR CONTROL OPTIONS-------------------------
$OFFUPPER OFFSYMLIST OFFSYMXREF
$inlinecom{ }

OPTIONS
   LIMROW   =  200000
   LIMCOL   =  500
   ITERLIM  =  1000000
   RESLIM   =  100000
   SOLPRINT =  OFF
   DECIMALS =  2
*   LP      =  cplex
*   RMIP    =  cplex
*   MIP     =  cplex
   OPTCR    =  0.000001
   ;
*----------------------------------------------------------------

$ONTEXT
        Authors : Lee Ewing
                Naval Postgraduate School
                Operations Research Dept.
                845–389-1050
                leeewing@hotmail.com

        Original: May 2018, Lee Ewing


        Description: This model makes two assignments for a single period
         weekly schedule: 1. Hightest weighted assignment is for boat assignment
         by type and location.  2. Secondary weighted assignment is for crew
         to boats based on crew member preferences.

         Update1: July 2018, Lee Ewing - Corrected set computation validOLE to
         ensure that employees can cover an assigned option.

         Update2: July 2018, Lee Ewing - Solved the multiobjective problem preemptively
         by first finding the best boat schedule based on MAXIMIZING customer
         preference (HIGHER IS BETTER), then using that solution to
```

```
      find the best employee schedule
      by MINIMIZING total employee preferences (LOWER IS BETTER).

      Update3: July 2018, Lee Ewing - Removed two constraints that were not used
      or where made redundant by running the model preemptively.

$OFFTEXT

*-----Indices------------------------------------------

$ONEMPTY
SETS

 e Employees
   /
   e1 * e15
   /

 t Time period
   /
   M,T,W,Th,F,Sa,Su
   /

 l Locations
   /
   Nanoose, Keyport
   /

 b boat type
   /
   YTT, TWR
   /

 o Options
   /
   1a,1b,1c,1d,1e,2a,2b,2c,2d,3a,3b,3c,3d,4a,4b,4c,4d,5a,5b,5c
   /

 c Customers
   /
   A, B, C, D
   /

 PO(t,o) time periods and options
    /
```

```
$ondelim
$include %datapath%\PO.csv
$offdelim
    /
;

display PO;

Table noncon(t,o)
       1a 1b 1c 1d 1e 2a 2b 2c 2d 3a 3b 3c 3d 4a 4b 4c 4d 5a 5b 5c
M      1  0  0  0  0  1  0  0  0  1  0  0  0  1  0  0  0  1  0  0
T      0  1  0  0  0  1  1  0  0  1  1  0  0  1  1  0  0  1  1  0
W      0  0  1  0  0  0  1  1  0  1  1  1  0  1  1  1  0  1  1  1
Th     0  0  0  1  0  0  0  1  1  0  1  1  1  1  1  1  1  1  1  1
F      0  0  0  0  1  0  0  0  1  0  0  1  1  0  1  1  1  1  1  1
Sa     0  0  0  0  0  0  0  0  0  0  0  0  1  0  0  1  1  0  1  1
Su     0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0  0  1
;

*------Data--------------------------------------------

Parameter pri(o,b,l,c) customer’s priority for different options

/
$ondelim
$include %datapath%\CustomerPriority.csv
$offdelim
/
;

Parameter empPref(e,l,t) employee’s work preferences
/
$ondelim
$include %datapath%\EmployeePref.csv
$offdelim
/
;

display empPref;

Parameter req(b)
/
YTT 4
TWR 1
/
```

```
;

display req;

Parameter validTE(t,e);
validTE(t,e)=YES$ (sum(o,PO(t,o) and sum(l,empPref(e,l,t))));
display validTE;

parameter flag;
Parameter validOLE(o,l,e);
loop (l,
  loop (e,
     loop (o,
       flag = 0;
       loop (t$PO(t,o),
         If( (validTE(t,e)*empPref(e,l,t)) > 0,
             flag = 1;
         Else
             flag = 0;
             Break;
          );
         );
       If (flag eq 1,
          validOLE(o,l,e) = YES;
       );
     );
   );
);

display validOLE;

Parameter empOptPref(e,l,o) ;

loop( (o,l,e)$validOLE(o,l,e),
       empOptPref(e,l,o) = sum(t$PO(t,o),empPref(e,l,t)) ;
);

display empOptPref;


*------variables-------------------------M-------------------
Parameter Ybar(o,b,l,c);

BINARY VARIABLE
   Y(o,b,l,c) 1 if object o is choosen for boat b at location l & 0 otherwise
```

```
   X(o,b,l,e) 1 if employee e is choosen for location l on boat b for option o & 0 otherwise
;


VARIABLE
   ZObj1  Objective function for Customer Schedule
   ZObj2  Objective function for Employee Schedule
;


EQUATIONS
   OBJ1, OBJ2
    c2,c3,c5,c6,c7,c8
;



*------Objective functions------------------------------------------

OBJ1..
          Zobj1
             =E=
                SUM( (o,b,l,c), pri(o,b,l,c)*Y(o,b,l,c) )
          ;

OBJ2..
          Zobj2
             =E=
               SUM( (o,b,l,e), empOptPref(e,l,o)*X(o,b,l,e) )
          ;

*------ Constraints------------------------------------------


*   No more than two YYT boats are available on any one day

c2(t)..
        sum( (o,l,b,c)$(PO(t,o) AND (ord(b)=1)), Y(o,b,l,c) )
           =l=
        2
;

*   No more than two TWR boats are available on any one day

c3(t)..
```

```
        sum( (o,l,b,c)$(PO(t,o) AND (ord(b)=2)), Y(o,b,l,c) )
           =l=
        2
;

*    Customer is assigned to only one option
c5(c)..
        sum( (b,l,o), Y(o,b,l,c) )
          =l=
        1
;


*     Employee can only be assigned to one location per day
c6(e,o)..
        sum( (l,b), X(o,b,l,e) )
           =l=
        1
;

*    Link employees to boat
c7(l,b,c,o)$pri(o,b,l,c)..
        sum(e$validOLE(o,l,e), X(o,b,l,e))
           =g=
        req(b) * Ybar(o,b,l,c)
;

*   Non-concurent options
c8(t,e)..

    sum( (b,l,o)$noncon(t,o), X(o,b,l,e) )
       =l=
    1
;


Model ABS
      /
      OBJ1
      c2, c3, c5
      / ;

*Y.fx(‘1a’,’TWR’,’NANOOSE’,’A’) = 1 ;
*Y.fx(‘3a’,’YTT’,’NANOOSE’,’C’) = 1 ;
*Y.fx(‘4d’,’YTT’,’KEYPORT’,’B’) = 1 ;
```

```
        SOLVE ABS USING MIP MAXIMIZE zOBJ1 ;

display Y.l;

loop((o,b,l,c),
        Ybar(o,b,l,c) = Y.l(o,b,l,c) ;
);

Model ES
      /
      OBJ2
      c6, c7, c8
      / ;

      SOLVE ES USING MIP MINIMIZE zOBJ2 ;

display X.l;


************** Output to Files

Parameters objvalEmpPref, objvalCustPref;

objvalCustPref = SUM( (o,b,l,c), pri(o,b,l,c)*Ybar(o,b,l,c) ) ;
objvalEmpPref = SUM( (o,b,l,e), empOptPref(e,l,o)*X.l(o,b,l,e) ) ;

FILE Xfile/  %datapath%\o_schedule.csv /;
Xfile.lw=0 ;
Xfile.nw=0 ;
Xfile.nd=0 ;
Xfile.pw=32767 ;

Put Xfile;

put”Total Customer Preference Objective Function Value,,”objvalCustPref; put/;
put”Total Employee Preference Objective Function Value,,”objvalEmpPref; put/;

put ,”Customer,Option,Location,Boat Type” ; put/;

loop(o,
 loop(b,
  loop(l,
   loop(c$Ybar(o,b,l,c),
        put ,”,”c.tl,,”,”o.tl,,”,”l.tl,,”,”b.tl;
```

```
         put/;
           put “Employees,” ;
           loop(e$X.l(o,b,l,e),
              put e.tl,,”“;
           );
           put/;
           put/;
    );
  );
 );
);

PUTCLOSE Xfile;
```

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