Optimal Allocation of Resources at U.S. Coast Guard Boat Stations

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The Office of Boat Forces (OBF) of the United States Coast Guard (USCG) has recently implemented an optimization model and software application – the Boat Allocation Tool (also called the BAT Model), which was used to optimize the allocation of its entire fleet of boats among the USCG boat stations nationwide. The model accommodates various types of supply requirements at the stations and different capabilities of the boats. The main objectives of the BAT Model are to minimize the mismatch between the stations' demand of hours and supply of boat hours, reduce the number of stations with more than two boat types (for maintenance considerations), and minimize the total fleet operating cost. The BAT Model implementation led to a significant reduction in the number of stations with either shortages or excess of boat capacity, decrease in the number of boat types per station, and reduction of the total fleet operating cost.

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I. INTRODUCTION

The U.S. Coast Guard (USCG), a part of the U.S. Department of Homeland Security, is the nation's leading agency in maritime security. The USCG is responsible for safety and security of more than 300 ports, 3,700 marine terminals, 25,000 miles of coastal waterway, and 95,000 miles of combined coastline belonging to the United States (Allen, 2009b). The agency also maintains aids to navigation throughout the coastal and internal waterways, and responds to some 50,000 distress calls a year, saving many lives. According to the former USCG Commandant, Admiral Thad Allen, "Over the past several years, the Coast Guard has faced increasing demands for our services, a deteriorating fleet of operational assets and the need to streamline, simplify and integrate our command and control and mission support structures" (Allen, 2009a).

The three main USCG missions are maritime safety, security, and stewardship for the U.S. coastal areas and internal waterways. These three main missions can be further subdivided into a variety of homeland security and non-homeland security mission categories, including ports/waterways/coastal security, defense readiness, drug and migrant interdiction, marine safety, search and rescue, aids to navigation, fisheries law enforcement, marine environmental protection, and ice operations. The USCG missions are carried out by the three principal USCG forces: (1) cutters – vessels with a length of more than 65 feet, (2) aircraft (airplanes and helicopters), and (3) boats – vessels under 65 feet in length.

In this paper, we concentrate on the USCG boats and their allocation among the USCG stations.

We have developed and implemented at the USCG Office of Boat Forces (OBF) an optimization model and software application, denoted the Boat Allocation Tool (BAT) Model, which identifies an optimal allocation of boat resources among the USCG boat stations. In the *Boat Allocation Problem* section of this paper we briefly describe the USCG boat operations, and present problems that existed in allocating boat resources to the stations. In the *BAT Model Formulation and Solution* section, we discuss the BAT Model in terms of its inputs, formulation, implementation steps, and also provide a description of the associated Excel-based software. The BAT Model performance metrics, resulting benefits and their effect on the USCG boat allocations are described in the *Model Impact* section. Next, we provide the *Conclusion* section with a summary of our contributions to Operations Research practice and perspectives for further model development.

II. BOAT ALLOCATION PROBLEM

The USCG boats operate near shore and on inland waterways, and are organized under the supervision of the OBF into nine districts in the Atlantic and Pacific areas of the coastal U.S. Each district is divided into sectors, which include a total of 178 boat stations for all nine districts.

An allocation of boats to a station is defined by the station's missions, described in the *Introduction* section, and also by specific maritime conditions in which the station boats operate. Accordingly, the USCG classifies boat stations into nine categories: Surf, Heavy Weather, Tactical, Pursuit, Shallow Water, Ice Rescue Long Haul, Ice Rescue Short Haul, Flood, and Auxiliary. For example, "Surf" stations operate in high surf ocean areas and "Shallow Water" stations patrol in low depth water areas. Based on the station category, each station requires certain amount of overall boat supply hours that are necessary to fulfill station-specific missions and maritime conditions. These boat hours can be defined as a *station's demand* for hours, which can range widely from 250 to over 5,000 annual hours with an average of approximately 2,206 hours per station. In addition to the overall station demand of hours, the USCG established, for many stations, specific demand of boat hours relevant to certain station categories, i.e., Heavy Weather, Tactical, Pursuit, Shallow Water, and Ice Rescue (both long and short haul). In other words, each station will have demands for generic boat hours as well as specific hours, which can only be fulfilled by certain boat types.

At the stations, the USCG maintains approximately 800 boats of 11 different types. The usage of a boat type at a given station depends on the required missions and maritime conditions at the station. For example, the 47-foot Motor Lifeboat (MLB) type is employed as a first response rescue resource in high seas, surf and heavy weather environments (USCG Data Sheet, 2008). At the same time, the 45-foot Response Boat Medium (RB-M) type is a speedy universal boat type used at a variety of stations for various missions (USCG Acquisition Directorate, 2010). The calmer waters of shipping ports demand a quicker responding, more maneuverable boat like the 25-foot Response Boat Small (RB-S) type for law enforcement and reaching shallow areas (USCG Data Sheet, 2008). The other eight boat types are mostly specialized for deployment in various maritime missions and weather conditions like heavy weather, ice rescue, flood, towing, and others; all 11 boat types are defined in the model formulation in the Appendix to this paper. Each boat type is budgeted with a *standard annual supply* (capacity) of hours. For example, the MLB and RB-M boat types have a standard supply of 600 hours each annually, whereas the RB-S boat type has only 500 hours.

The total amount of *all boats' standard supply hours* at a station would ideally need to match the *station's demand* for the overall hours and specific category/mission hours, and thus ensure normal operational capabilities of the boat station to meet its missions and maritime requirements. However, starting from the early 2000s, the USCG recognized the existing disparity between the stations' demand hours and actual supply of hours provided by the boats at those stations.

The allocation of boats to stations is a rather complex issue. The intricacy of boat assignments to the stations stems from the fact that it involves a large variety of stations with their respective missions and maritime conditions, the corresponding different types of demand hours, different boat types and their respective capabilities and quantities. In addition, the USCG follows an extensive set of operational restrictions, called Business Rules, which establish specific boat assignment requirements. For example, these rules require the assignment of certain boat types, such as an MLB, in predetermined minimum quantities to stations with various missions. Another example of a Business Rule is the establishment of a minimum of at least two boats per station. These Business Rules, discussed in more detail in the next section, further increase the complexity of the boat allocation problem.

Traditionally, each station's allocation of boats was based on historical and geographical requirements. The boat allocations were adjusted over the years by ad hoc decisions based on station or regional commander's requests and asset availability. These actions resulted in a significant deviation between the station's demanded hours and actual supply of boats resources, which led to an excess of boat resources at some stations and a shortage of boat hours at other stations. Table 1 displays these significant mismatches for the overall demand; there are even more mismatches for specific mission demands. Unfortunately, due to the different types of boat supplies and station demands, simple boat movements between the USCG stations do not suffice to better match supply and demand, and a more sophisticated approach is necessary.

TABLE 1. RESULTS OF THE ORIGINAL BOAT ALLOCATION

Statistic	*Value*
Average demand hours per station	2,206.2 hours
Average supply hours per station	2,321.2 hours
Percentage of stations with excess hours	61.2%
Average excess hours per station with excess	556.3 hours
Percentage of average excess hours vs. average demand hours per station	25.2%
Percentage of stations with shortage hours	38.8%
Average shortage hours per station with shortage	563.1 hours
Percentage of average shortage hours vs. average demand hours per station	25.5%

As can be seen from Table 1, at 61.2% of all stations the total supply of boat hours exceeded the stations' demand by an average of 25.2% per station. At the same time, even with a nationwide excess of the boat supply over stations' demand hours (2,321.2 of supply hours vs. 2,206.2 of demand hours, on average), 38.8% of all stations experienced a shortage of boat resources, with an average of 25.5% per station. The excesses at certain stations led to a significant underutilization of the boat resources. Conversely, shortages of boat resources at many stations adversely affected their ability to fulfill the required maritime missions in various weather conditions. Therefore, the primary USCG objective was to improve the matching of supply and demand.

In addition, the USCG determined that more than two boat types at a station drastically increased both training and maintenance requirements without adding proportional benefit to a station's capability. This also led to higher boat maintenance costs. Besides the excess and shortage of boat supplies, 37.6% of the boat stations maintained more than the USCG-desired maximum of two boat types. Thus, the USCG also desired to minimize the number of stations with more than two boat types. Finally, the USCG was also interested in minimizing the cost of operating the USCG boat feet.

The mismatch of boat resource assignments versus stations' demand hours necessitated a new optimization approach for the efficient allocation of those resources. This approach would need to minimize the deviation between the demand and supply of boat hours, significantly reduce the number of stations with more than two boat types, and minimize the total cost of boat operations.

The examination of existing literature sources on military resource allocation and USCG boat allocation, in particular Everingham et al. (2008), Radovilsky and Koermer (2007), Deshpande et al. (2006), Billing (2005), Bhatia and Crawley (2004), Zarybnisky (2003), Brown et al. (1996), and Malyankar et al. (1992), reveals that only one paper by Radovilsky and Koermer (2007) directly addresses the need to fix the boat allocation mismatch. This paper describes an attempt to solve the USCG boat allocation problem in 2005-2006 by analyzing an optimal boat allocation model for the USCG stations on the Pacific coast of the U.S. However, their model considered boat allocations for only a portion of all USCG boat stations. Furthermore, this precursor model did not incorporate most of the USCG requirements associated with the boat allocation Business Rules.

In 2009, the USCG's interest in a complete and optimized boat allocation model led to the project described in this paper. In particular, the USCG desired to extend the coverage of the boat allocation model to all USCG stations on the east and west coasts of U.S., as well as Alaska, Hawaii, and stations in U.S. territories. In addition, the USCG increased the complexity of the project significantly by introducing different types of hours, both from the supply and demand sides, as well as a multitude of other required operational restrictions. To address all these issues, we develop a new optimization model called the Boat Allocation Tool (BAT) Model. The mathematical properties of the BAT Model and its theoretical extensions are discussed in Wagner and Radovilsky (2012). In this paper we exclusively focus on the actual BAT Model application, its practical implementation and significant impact to the USCG, which are discussed in the next two sections, *BAT Model Formulation and Solution*, and *Model Impact*.

III. BAT MODEL FORMULATION AND SOLUTION

3.1. Model Inputs

The need for improved boat assignments to stations was mandated and spearheaded by the Platform Division (PD) of the Office of Boat Forces (OBF), which controls boat allocations to the stations. We were provided with the necessary input information for boat types and boat stations. For each of the 11 boat types this information included the number of boats, standard supply of annual hours per boat, and fixed annual and variable costs per boat hour.

The OBF also provided us with the boat station data that incorporated an overall demand for hours per station as well as specific demands for "big boats", tactical, pursuit, shallow water, and ice haul rescue hours. In addition, the OBF also established a set of *24 Business Rules (BRs)*, which represented written *operational requirements* for assigning boat resources. These BRs can be summarized in the following groups of rules:

- Assign specific boat types in predetermined minimum quantities to stations with various missions (tactical, pursuit, flood and ice haul rescue) and maritime conditions (heavy weather, surf, and shallow water).
- Provide an opportunity for stations to share an MLB, a critical boat type in short supply, required by many stations. More precisely, if two stations are close enough, and one of the stations does not have an MLB, but needs one, then the adjacent station, that has this boat, covers the area of responsibility for both stations when sea and weather conditions exceed the capability of other boat types at the stations.
- Allocate boat resources to non-mission station purposes including maintenance and training.
- Establish a minimum requirement for the number of boats per station of at least two boats.
- Meet mission requirements with no shortages for critical boat demands at certain stations, for which the OBF provided the number of demand hours required at a station for a specific type of supply.

In addition to the above rules, the OBF also requested that the amount of boat hours supplied by each boat to each station should be relaxed from the standard values. By varying individual boat supply hours, the OBF hoped to provide a better match between the station demand and boat supplied hours, and also to better meet specific stations' mission requirements with no shortages. For the amount of supply hours assigned per boat, the OBF established upper and lower limits, as a proportion of the standard hours per boat type. However, there was a strict requirement to conserve the total amount of supply hours; in other words, if a boat at one station was assigned more hours than the standard amount, then some other boat of the same type must necessarily be assigned less than the standard. All these requirements and Business Rules were incorporated into the optimization modeling.

3.2. Optimization Model – Boat Allocation Tool (BAT)

The OBF's initial inputs and operational requirements enabled us to formulate and then implement a mathematical model defined as the Boat Allocation Tool (BAT) Model. A mathematical formulation of this optimization model is presented below. For further details and a complete theoretical analysis of the model formulation, we refer the reader to the paper by Wagner and Radovilsky (2012). In Table 2 we describe the main sets used in the mixed integer program, in Table 3 we provide the main parameters, and in Table 4 we present the main variables.

TABLE 2. SETS USED IN THE BAT MODEL

Set Notation	***Description***
$t \in T$	Set of boat types
$s \in S$	Set of stations
$m \in M$	Set of specialized station missions
$s \in S_m$	Set of stations that are assigned mission, $m \in M$
$t \in T_m$	Set of boat types that are appropriate for mission, $m \in M$
$t \in T_s$	Set of boat types allowed at station, $s \in S$
$t \in T_c$	Set of critical boat types, whose presence requires the presence of another boat type

TABLE 3. PARAMETERS USED IN THE BAT MODEL

Parameter	***Description***
B_t	Available number of boats of type t
d_t	Yearly default capacity, in hours, of a type t boat
H_s	Yearly demand, in hours, of station s
f_t	Yearly fixed cost of utilizing one boat of type t
v_t	Variable cost of utilizing one boat of type t for one hour
b_m	Minimum number of boats required to satisfy mission m at a station
H_{As}	Yearly demand for a class $A \subseteq T$ of boats at station s, in hours
m_t	Multiplier (for d_t) to provide minimum allowable hours assigned
M_t	Multiplier (for d_t) to provide maximum allowable hours assigned
$d_{s,s'}$	Distance between stations s and s'
γ	Distance threshold to allow MLB sharing
$R = \{(s, s') \in S \text{ x } S\text{: } s<s' \wedge d_{s,s'} \leq \gamma\}$	Set of pairs of stations eligible to share MLB boats

TABLE 4. VARIABLES USED IN THE BAT MODEL

Variable	***Description***
x_{st}	Integer number of boats of type t allocated to station *s*, ∀*s*, *t*
y_{st}	Binary variable indicating whether or not boat type *t* is utilized at station *s*, ∀*s*, *t*
h_{st}	Number of hours of boat type *t* assigned to station *s*, ∀*s*, *t*
$q_{s,s'}$	Binary variable indicating whether or not stations *s* and *s'* share an MLB boat that is hosted by station *s'* (station *s* has no MLBs), ∀ *(s, s')* ϵ *R*.
$r_{s',s}$	Binary variable indicating whether or not stations *s'* and s share an MLB boat that is hosted by station *s'* (station *s* has no MLBs), ∀ *(s', s)* ϵ *R*

Finally, we present the integer program that underlies the BAT Model, which minimizes the weighted combination of the three objectives discussed in our paper (deviation of supply and demand, number of types of boats at each station and fleet operating cost), subject to a variety of logical and operational constraints (Business Rules).

Objective Function:

$$\min\ w_1 \sum_{s\epsilon S}\left|\sum_{t\epsilon T} h_{st} - H_s\right| + w_2 \sum_{s\epsilon S}\sum_{t\epsilon T} y_{st} + w_3 \sum_{s\epsilon S}\sum_{t\epsilon T}(f_t x_{st} + v_t h_{st}) \quad (1)$$

Boat Capacity Constraints:

$$\sum_{s\epsilon S} x_{st} \le B_t, \forall t \in T \quad (2)$$

Variable y_{st} Definition Constraints:

$$x_{st} \le B_t y_{st}, \forall s \in S, t \in T \quad (3)$$

Mission Sufficiency Constraints:

$$\sum_{t\epsilon T_m} x_{st} \ge b_m, \forall s \in S_m, m \in M \quad (4)$$

Appropriate Boat Constraints:

$$\sum_{t\epsilon T\setminus T_s} x_{st} = 0, \forall s \in S \quad (5)$$

Minimal Boat Constraints:

$$\sum_{t\epsilon T} x_{st} \ge 2, \forall s \in S \quad (6)$$

Critical Boat Constraints:

$$\sum_{t\epsilon T\setminus T_s} x_{st} \ge \frac{x_{st}}{B_t}, \forall s \in S, t \in T_c \quad (7)$$

Conservation of Supply Constraints:

$$h_{st} \le d_t B_t x_{st}, \forall s \in S, t \in T, \quad \sum_{s\epsilon S} h_{st} \le d_t B_t, \forall t \in T \quad (8)$$

Flexible Hours Limit Constraints:

$$m_t d_t x_{st} \le h_{st} \le M_t d_t x_{st}, \forall s \in S, t \in T \quad (9)$$

Critical Demand Constraints:

$$\sum_{t\epsilon A_i} h_{st} \ge H_{A_i s}, \forall s \in S, i = 1, \ldots, 6 \quad (10)$$

MLB Sharing Constraints:

$$x_{s0} \ge 1 - \sum_{s':(s,s')\epsilon R} q_{s,s'} - \sum_{s':(s',s)\epsilon R} r_{s',s}, s \in S \quad (11)$$

MLB Sharing Constraints:

$$\sum_{s':(s,s')\epsilon R} \left(q_{s,s'} + r_{s,s'}\right) + \sum_{s':(s',s)\epsilon R} \left(q_{s's} + r_{s',s}\right) \leq 1, s \epsilon S \quad (12)$$

The BAT Model provides a user-optimal allocation of boats to the stations. The main decisions that the BAT Model needs to make are to identify the number of boats of specific types, and their respective supply hours, to be allocated to the boat stations. These allocations are done in such a way that minimizes the following three criteria representing the BAT Model objectives:

1. The total deviation of demanded station hours and boat supply hours for all stations.
2. The total number of types of boats at each station.
3. The total fleet operating cost.

The BAT formulation combined these criteria in one formula by weighing each criterion depending on its level of importance for the allocation of boat resources, with the total weight equal to 1. We also formulated mathematically the above-mentioned operational requirements (BRs), and other USCG restrictions, presented in the previous *Model Inputs* section, as model constraints. For sharing MLB boats, the concept of *optimally sharing* the supply of this limited resource was incorporated into the model. In particular, we derived that 28 miles is the minimum threshold to allow sharing of the MLB boats. In other words, the sharing is only allowed if the coast-line distance between two stations is less than or equal to 28 miles.

The BAT Model is an integer linear program, which contained a significant number of stations with different missions, various types and quantities of boats available for allocation, and a noteworthy set of operational requirements. All these made the BAT Model a fairly large-scale application with approximately 6,500 decision variables and 17,000 constraints.

3.3. BAT Decision Support System

The USCG requested that we implement the BAT Model in Excel, which is the Coast Guard's standard tool for managing and planning boat resources and their allocations. Therefore, we utilized Excel-enabled optimization software from *Frontline Systems*, in particular, its *Premium Solver Platform for Excel V9.5* and *Standard Large-Scale LP Solver Engine V9.0 Windows*. The solution of the BAT Model can be derived in one minute or less.

To streamline and ease the implementation and utilization of the BAT Model, we developed an Excel-based decision support system (DSS) that consists of four main spreadsheets: *Input*, *Model*, *Output*, and *Performance*. The *Input* spreadsheet provides the stations' input parameters such as initial hourly demands and boat supply resources with their respective costs. A USCG user working with the BAT Model can input and modify a variety of parameters in order to see and analyze the implications of the input deviations on the BAT optimization results. A representative screenshot of the *Input* worksheet is presented in Figure 1, which depicts most of the levers that a user of the BAT Model can input and, if necessary, modify.

Boat types	MLB	SPC-NLB	SPC-HWX	RB-M	RB-S	RBS-AUX	SPC-LE
Number of Boats	106	2	4	167	335	13	41
Default hours per boat	600	350	350	600	500	500	1000
Fixed cost per boat	$36,951	$15,000	$15,000	$36,000	$5,657	$5,657	$9,217
Variable cost of one hour	$120.00	$60.00	$120.00	$120.00	$47.00	$47.00	$87.00

Optimize!

Show Model

Go to Output

Station	Total Hours	Big Boat Hours	Tactical Hours	Pursuit Hours	Shallow Water Hours	Ice Long Haul Hours
STA ALEXANDRIA BAY	1877	1187	690			
STA ALPENA	2615	1164			319	
STA ANNAPOLIS	1701	580			430	
STA APRA HARBOR	1269	618				12
STA ASHTABULA	1316	607				
STA ATLANTIC CITY	1838	748				
STA BARNEGAT LIGHT	5161	1090	2361	1710		
STA BAYFIELD	2012	696			319	
STA BELLE ISLE	5299	1764		1757		
STA BELLINGHAM	3036	590		959		
STA BODEGA BAY	1641	597				25

FIGURE 1. A PORTION OF THE BAT INPUT SPREADSHEET

(For confidentially purposes, the data in this Figure is just an input example and does not represent real USCG inputs.)

A BAT Model user is required to provide general and specific hourly demands for all stations (at the request of the USCG, the actual hours used in the model are not shown in Figure 1). For each boat type, the user can easily modify the available number of boats, the default boat hourly capacity, as well as fixed and variable hourly costs of the boat. The user can also modify the importance of each optimization criteria (minimum deviation of demanded and supplied hours, minimum number of boat types per station, and total allocation cost) by varying their respective weights in the BAT Model objective function in the *Model* spreadsheet.

Clicking on the *Optimize!* button in the *Input* spreadsheet (see Figure 1) will run the BAT model in the background, and then switch to the *Output* spreadsheet to show the optimization results, which consist of the optimal number of boats of various types assigned to the stations, and respective amount of boat hours to be allocated to each boat. See Figures 2-3 for a representative screenshots of the *Output* spreadsheet. The *Performance* spreadsheet will show the performance-metric results of the BAT optimization discussed in the *Model Impact* section of this paper.

For training the users on how to utilize the BAT Model and its Excel-based DSS, we have developed a technical manual called the *BAT User's Guide*. This guide provides a detailed description of the BAT Model and its input/output data, presents a step-by-step implementation process, and offers in-depth instruction on using each described DSS spreadsheet. The guide is widely used by OBF employees to understand the BAT Model features, examine the USCG Business Rules incorporated in the model, and also to train OBF and district personnel.

	MLB	SPC-NLB	SPC-HWX	RB-M	RB-S	RBS-AUX	SPC-LE	SPC-SW	SPC-AIR	SPC-ICE	SPC-SKF
Station	**Boat Allocation**										
STA ALEXANDRIA BAY	0	0	2	0	0	0	0	0	0	0	0
STA ALPENA	0	0	2	0	0	0	0	0	0	0	0
STA ANNAPOLIS	0	0	0	0	0	2	1	0	0	0	0
STA APRA HARBOR	0	0	2	0	0	0	1	0	0	0	0
STA ASHTABULA	0	0	0	1	1	0	0	0	0	0	0
STA ATLANTIC CITY	0	0	0	1	0	0	0	1	1	0	0
STA BARNEGAT LIGHT	0	0	0	1	2	0	0	1	1	0	0
STA BAYFIELD	0	0	0	0	0	0	0	0	0	1	0
STA BELLE ISLE	2	0	0	1	1	0	0	1	0	1	0
STA BELLINGHAM	0	0	0	1	3	0	0	0	0	0	0
STA BODEGA BAY	0	0	0	1	1	1	0	0	1	0	0
STA BOOTHBAY HARBOR	2	0	0	0	1	0	0	0	0	1	0
STA BOSTON	2	0	0	0	1	0	0	0	0	0	0
STA BRANDT POINT	2	0	0	0	0	0	0	0	0	0	1
STA BRUNSWICK	0	0	0	0	0	2	1	0	0	0	0
STA BUFFALO	0	0	2	0	0	0	2	0	0	0	0

FIGURE 2. A PORTION OF THE BAT OUTPUT SPREADSHEET WHICH SHOWS OPTIMAL BOAT ASSIGNMENTS TO STATIONS

(For confidentially purposes, the data in this Figure is just a randomized output example and does not represent real USCG inputs.)

	MLB	SPC-NLB	SPC-HWX	RB-M	RB-S	RBS-AUX	SPC-LE	SPC-SW	SPC-AIR	SPC-ICE	SPC-SKF
Station	**Hours per Boat**										
STA ALEXANDRIA BAY	0	0	750	0	0	0	0	0	0	0	0
STA ALPENA	0	0	340	0	0	0	0	0	0	0	0
STA ANNAPOLIS	0	0	0	0	0	300	800	0	0	0	0
STA APRA HARBOR	0	0	600	0	0	0	300	0	0	0	0
STA ASHTABULA	0	0	0	390	800	0	0	0	0	0	0
STA ATLANTIC CITY	0	0	0	850	0	0	0	700	750	0	0
STA BARNEGAT LIGHT	0	0	0	400	450	0	0	650	300	0	0
STA BAYFIELD	700	0	0	0	0	0	0	0	0	400	0
STA BELLE ISLE	0	0	0	200	750	0	0	300	0	200	0
STA BELLINGHAM	0	0	0	650	300	0	0	0	0	0	0
STA BODEGA BAY	0	0	0	550	320	700	0	0	400	0	0
STA BOOTHBAY HARBOR	300	0	0	0	400	0	0	0	0	200	0
STA BOSTON	500	0	0	0	580	0	0	0	0	0	0
STA BRANDT POINT	850	0	0	0	0	0	0	0	0	0	200
STA BRUNSWICK	0	0	0	0	0	650	200	0	0	0	0
STA BUFFALO	0	0	730	0	0	0	100	0	0	0	0

FIGURE 3. A PORTION OF THE BAT OUTPUT SPREADSHEET WHICH SHOWS OPTIMAL BOAT ASSIGNMENTS TO STATIONS

(For confidentially purposes, the data in this Figure is just a randomized output example and does not represent real USCG inputs.)

IV. MODEL IMPACT

The implementation of the BAT Model has had a significant positive effect on the allocation of boats among the USCG stations. According to the OBF, the model allowed them to "align boat resources in the best possible way." The operational part of the ongoing boat allocations, i.e., the boat allowances and reallocations plans for each station, is directly derived from the model's recommendations. In addition, the OBF observed that the new implemented allocations efficiently met the mission requirements in terms of significant reductions of boat shortages and overages. Indeed, there was not a single instance of a boat station with its mission requirements being reduced due the new boat allocations. Finally, the implementation is firmly based on the USCG Business Rules that were directly incorporated in the BAT Model's optimal recommendations. Despite the fact that there are some differences between the BAT Model recommendations and actual implementation (see the next two sections), the OBF stated that "the spirit of the model is being implemented."

4.1. Model Implementation

The primary user and coordinator of the BAT Model implementation is the Platform Division (PD) group of the OBF, which is directly responsible for boat allocations among all USCG stations. This PD group directly communicates with district managers, who are in charge of boat allocations in their own districts. The PD group is also responsible for developing the actual plans for boat allowances in the districts, coordinating the rearrangement of boats with district managers and station offices, and delivering new boats to the districts and stations.

The PD group, based on boat allocations created by the BAT Model, developed a six-year implementation plan that started in 2010, and will continue through 2015. For each year, this plan laid out, based on the BAT Model, allocation allowances for a specific portion of the USCG stations. This plan is also associated with the delivery of new RB-M boats that will replace the old UTB boats coming out of more than 40 years of service. In 2010-2012, the USCG received 30 new RB-M boats each year, which were delivered to stations according to the implementation plan. For the other boat types, the USCG is combining the reallocation of existing boats with the deliveries of new RB-M boats. By the end of 2012, approximately 95% of all BAT Model related allocations will be implemented. In the next 3 years, 30 new RB-M boats will be delivered each year to the USCG, and they will also be allocated according to the same implementation plan.

The OBF, and its PD group, provided detailed information to the districts and boat stations on the upcoming boat allocations. This information thoroughly explained that the boat allocations/reallocations are derived from a scientifically-based algorithm and optimization tool (the BAT Model). The OBF also explained to the district and station personnel that the allocations must follow the USCG Business Rules that were incorporated into the BAT Model. These efforts resulted in minimal negative feedback from the districts and stations on the planned changes.

Out of nine district managers, only one manager had concerns with the allocation of certain boat types at three stations in his district. According to the OBF, resistance to change drove these particular concerns. In addition, several station officers wanted to have both an MLB and RB-M at the same station, which is precluded by the established USCG Business Rules. At the same time, a very small portion of the negative feedback from the stations was due to the fact that not all business requirements were incorporated in the BAT Model and associated implementation plan. For example, some station managers requested a larger type of boat due to their “trailering" requirements, which were not a part of the BAT Model. These requirements mean that a boat will be towed by a truck over land and put in the water near the station. The OBF was willing to consider well-reasoned requests from districts and stations, and incorporate them into the implementation plan.

4.2. Implementation Results

To identify the real and quantifiable impact of the BAT Model on boat allocations, we compare several sets of boat allocation results. First, we utilize the data provided by the USCG-defined boat allocation plan for 2010-2015, called the *Original Allocation*, which was introduced in September of 2009, prior to the BAT Model development. We apply the BAT Model’s recommendations that we submitted to the USCG, called the *BAT Allocation,* as another comparison benchmark.

Finally, we evaluate the actual implemented boat allocation, derived from the BAT Model and some subsequent adjustments to it, denoted the *Implemented Allocation*.

We summarize for each allocation in Table 5 the total size of the boat fleet and boat quantities for all 11boat types.

Comparing the Original and BAT Allocations, we see a number of striking differences: (1) The total fleet size is reduced from 804 to 622 boats, a 22.6% reduction; (2) the number of RB-S boats is reduced by 42.2% from 360 to 208; and (3) the number of SPC-SKF boats is reduced from 67 to 29, a 56.7% reduction. The decreases in the number of boats for various boat types are primarily associated with the BAT Model's optimal assignments of boat supply hours to satisfy stations' demands. Using flexible supply hours, rather than default standard hours, increases the boats' ability to better match more demand hours, and, thus, reduces the required number of boats.

Comparing the BAT and Implemented Allocation columns in Table 5, we see that the total fleet increases by 15.1%, from 622 to 716 units. This is due to the fact that the OBF, while implementing the BAT Model, modified the boat allocations for approximately 25% of its stations. Most of these changes in the Implemented Allocation were minor and resulted from station specific conditions that the BAT Model did not incorporate. For example, at certain stations MLBs were replaced with RB-Ms, and at other stations the opposite occurred. These changes were mostly "human considerations" associated with the *degree* of heavy weather or sea roughness a station receives, which the BAT Model did not incorporate.

TABLE 5. SUMMARY OF BOAT FLEET COMPOSITION IN ORIGINAL, BAT, AND IMPLEMENTED ALLOCATIONS

Boat Type	*Original Allocation*	*BAT Allocation*	*Implemented Allocation*
Motor Lifeboat (MLB)	106	102	102
Special Purpose Craft – Near shore Life Boat (SPC-NLB)	3	2	3
Special Purpose Craft – Heavy Weather (SPC-HWX)	4	0	4
Response Boat – Medium (RB-M)	166	166	158
Response Boat – Small (RB-S)	360	208	318
Response Boat – Small Auxiliary (RBS-AUX)	10	10	10
Special Purpose Craft – Law Enforcement (SPC-LE)	33	26	20
Special Purpose Craft – Shallow Water (SPC-SW)	47	47	47
Special Purpose Craft – Air (SPC-AIR)	8	8	12
Special Purpose Craft – Ice (SPC-ICE)	0	24	0
Special Purpose Craft – Skiff (SPC-SKF)	67	29	42
Total	804	622	716

At the same time, several major changes in the fleet composition were due to a substantial increase in the number of RB-S and SPC-SKF boats, and the elimination of the SPC-ICE boats in the Implemented vs. BAT Allocations. The growth in the RB-S boats at some stations is related to a USCG readiness rule that required increasing the operational readiness of this boat type to a significantly higher level (close to 100%), due to substantial variations of mission demands at these stations, which necessitated more boats per station. This rule was introduced after the completion of the BAT Model, and the USCG decided, in order to avoid any further increase in the model complexity, to manually adjust the boat allocations. In addition, the USCG chose to manually adjust the number of SPC-SKF boats, primarily used for the flooding-related missions, because flooding occurrences are rather unpredictable. Also, the USCG made a decision to completely eliminate the SPC-ICE boat type due to the fact that the ice rescue short haul missions, for which the SPC-ICE boats were used, are now satisfied by non-boat resources.

In addition to analyzing the boat fleet composition, we introduced to the USCG *new performance metrics* for quantifying the improvements achieved by the BAT Model over the original boat allocations. The performance metrics include measurements that reflect the main objectives used in the BAT Model, i.e., matching the supply of boats' hours with the stations' demand of hours, reducing the number of boat types per station, and decreasing the fleet operating cost. In addition, we introduce capacity utilization of the boat supply hours and shortfall demand rate.

4.3. Performance Metrics

The performance metric results for the three allocations (Original, BAT, and Implemented) are presented in Table 6. Using these results, we were able to identify and demonstrate a significant practical impact of the BAT Model and its subsequent implementation. In particular, the proportion of stations with an excess supply of boat hours is 1.7% for the BAT Allocation and 41.6% for the Implemented Allocation, the latter of which is significantly lower than the 61.2% in the Original Allocation. The average excess per station dropped from the original 556.3 hours to 209.8 hours in the Implemented Allocation, a reduction of 61.9%. The increase of excess supply in the Implemented vs. BAT Allocations is due to the OBF modification of the BAT Model that led to a growth of the fleet size, and specifically the quantities of RB-S and SPC-SKF boats (see Table 5). However, the remainder of the metrics stayed relatively unchanged. Therefore, the USCG changes did not deteriorate the BAT Model's impact on the boat allocations.

The BAT Allocation eliminated stations with a shortage of boat resources, and reduced this proportion to only 1.1% in the Implemented Allocation, which can be contrasted with the 38.8% of stations with shortages in the Original Allocation (see Table 6). The latter is a noteworthy result that helps the USCG to dramatically improve its ability to fulfill maritime missions without delays or requests for additional boat resources.

As previously mentioned, the fleet size decreased from 804 units in the Original Allocation to 716 units in the Implemented Allocation, a 10.6% reduction. This also led to a 4.6% reduction of the fleet operating cost (see Table 6). However, the cost reduction was not as high as the decrease of the fleet size. This was due to the fact that only a part of the fleet operating cost, i.e., the fixed cost, is directly associated with the number of boats. At the same time, the variable cost, another part of the fleet operating cost, is independent from the fleet size, because it is based on the assigned number of hours. Using the BAT model, the OBF was also able to decrease the average number of boat types per station from 3.1 to 2.2, a 29.0% reduction (see Table 6). Overall, this result ensures a higher efficiency of the USCG personnel training and maintenance operations. However, the BAT Model did not produce a significant reduction of stations with more than two boat types. This was due to several reasons: (a) boat operational requirements (Business Rules) for stations with certain missions and weather conditions necessitated more than two boat types, and (b) the OBF gave a substantially higher priority (weight) to minimizing the deviation of stations' demand hours and boat supply hours, to the detriment of the second objective of minimizing the number of stations with more than two boat types.

Finally, the implementation of the BAT Model led to improvements in capacity utilization of boat supplies. The Original Allocation resulted in a total oversupply of 60,884 hours, which represents a capacity utilization rate of 85.3%. In addition, the Original Allocation led to a total shortage of 38,851 hours, which represents a shortfall rate of 9.9% (a proportion of shortage hours to total demand hours). The Implemented Allocation, based on the BAT Model, increased the capacity utilization rate to 96.2% and reduced the shortfall rate to 0.03% (see Table 6), which substantially increases the USCG's ability to fulfill all required missions with fewer boat resources.

TABLE 6. PERFORMANCE METRICS FOR ORIGINAL, BAT, AND IMPLEMENTED ALLOCATIONS

Performance Metric	*Original Allocation*	*BAT Allocation*	*Implemented Allocation*
Total size of utilized boat fleet	804	622	716
Percentage of stations with excess hours	61.2%	1.7%	41.6%
Percentage of stations with a shortage of hours	38.8%	0.0%	1.1%
Average excess hours per station with an excess	556.3	70.2	209.8
Average shortage hours per stations with a shortage	563.1	0.0	70.0
Percentage of stations with more than two boat types	37.6%	30.9%	30.9%
Average number of boat types per station	3.1	2.3	2.2
Fleet operating cost	45,648,887	43,379,851	43,541,610
Capacity utilization	85.3%	99.0%	96.2%
Demand shortfall rate	9.90%	0.00%	0.03%

V. CONCLUSION

In this paper we demonstrated the valuable contributions of the BAT Model to the U.S. Coast Guard. To the best of our knowledge, we were the first to design a practical optimization model that was used by the USCG to resolve the allocation problem of matching the supply of boats with the demand of stations nationwide. Based on the BAT Model, we have also developed a decision support system that enables the USCG to have an analytical framework for analyzing various managerial decisions related to their boat allocations.

The BAT Model solution successfully resolved one of the most important issues in the USCG's boat resource management and induced a substantial reduction of shortages and excesses of boat supplies at the stations. The model also provides other significant performance improvements, e.g., fleet reduction, lower average number of boat types per station, increased capacity utilization, lower percentage of stations with shortage or excess of capacity, increased capacity utilization, and lower fleet operating cost.

The BAT Model and its successful implementation at the USCG constitute an important motivation for the continued application of this model in practice. The BAT Model can be, with few modifications, adopted to optimize an allocation or re-allocation of various resources with different usages and supply capacities to the organization units that demand those resources. The goals of these allocations will be, like in the USCG case described in this paper, to minimize the excess or shortage of resources at the organization units in conjunction with the minimum total cost of allocated resources. In particular, the need for this optimization may be found in logistics and supply chain decision making, e.g., the allocation of various types of cargo trailers between the distribution centers of a company, or the allocation of different types of rental vehicles to a set of rent-a-car divisions in various parts of the country.

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