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W. K. V. Chan, A. D'Ambrogio, G. Zacharewicz, N. Mustafee, G. Wainer, and E. Page, eds

SIMULATION BASED MULTI-MISSION CUTTER SCHEDULING EVALUATION FOR THE UNITED STATES COAST GUARD

Gregory E. Higgins

United States Coast Guard
2703 Martin Luther King Jr Ave SE
Washington, DC 20593, USA

Sercan Demir
Nurcin Celik

University of Miami
1320 S Dixie Hwy
Coral Gables, FL 33124, USA

ABSTRACT

The United States Coast Guard (USCG) plans the world-wide operations of its ships, referred to as cutters. Rule-based decision making mechanisms, the primary planning tools, are aimed at ensuring adequate time inport for maintenance, stand-by, and generalized assignments for at-sea deployments to geographic regions. This approach is problematic. Stochastic events are becoming increasingly costly. In 2013, Coast Guard cutters suffered nearly four times the normally allocated amount of operational days lost to unplanned repairs. Additionally, the predominant metric used by schedulers is the amount of time a cutter is focused on a single, primary mission. The reality of multi-mission operations is that unplanned emergency missions often supersede planned, routine missions. Furthermore, mission results contribute to multiple strategic goals, though to varying extents based on geographic area. We propose a comprehensive multi-mission schedule evaluation mechanism that measures productivity, given limited Coast Guard resources, across a spectrum of current and future scenarios.

1 INTRODUCTION

The United States Coast Guard, a branch of the U.S. Armed Forces, is responsible for ensuring maritime safety, security and stewardship throughout domestic and international waters. These responsibilities are further sub-divided into 11 statutory missions: (1) Drug Interdiction, (2) Search and Rescue (SAR), (3) Living Marine Resources (LMR) which is the protection and of fisheries, (4) Marine Safety, (5) Migrant Interdiction (Alien Migrant Interdiction Operations abbreviated as AMIO), (6) Other Law Enforcement (OLE) which is predominantly the enforcement of international fishing agreements and foreign fishing vessels incursions into the U.S. Exclusive Economic Zone (EEZ), (7) Marine Environmental Protection including oil and pollution prevention and response, (8) Ice Operations, (9) Ports and Waterways Coastal Security (PWCS), (10) Aids to Navigation (AtoN), and (11) Defense Readiness, which is predominantly assisting the Department of Defense. The United States Coast Guard has developed organizational strategies, i.e. goals focused on these missions at the national (strategic) level. Metrics associated with each strategic mission are well understood. At the National (strategic) level, they are in the form of effort as time, and results. For example, as reported by the U.S. Department of Transportation, in 2013 the USCG conducted approximately 54,000 hours of Search and Rescue which resulted in 3768 lives saved. Table 1 shows the relationship between how strategic missions obligate tactical effort (currently measured as cutter hours) which then has outcomes which simultaneously affect multiple strategic missions/goals.

Regional headquarters such as the Eighth Coast Guard District in New Orleans, LA., responsible for the Gulf of Mexico and Mississippi River system, plan and allocate resources to local USCG units. Along the gulf coast these are: Sector Corpus Christi, TX., Houston-Galveston, TX., Sector New Orleans, LA., and Sector Mobile, AL. These sectors then execute day-to-day, tactical operations throughout their local area of responsibility (AOR) by employing USCG small boats, aircraft, and ships which are referred to as cutters by the USCG.

Table 1**:** Relationship between USCG statutory missions and multi-mission outcome metrics (as pertains to this study).

Statutory (Strategic) Missions	Tactical Mission Events Executed by USCG Patrol Boats	Multi-Mission Outcome Metrics
Drug Interdiction	Counter-Drug Boarding	drug seizure (marijuana)
		drug seizure (cocaine)
Search and Rescue (SAR)	Search and Rescue Case and Post-SAR boarding	lives saved
		property saved
		lives assisted
		property assisted
		safety citation
Living Marine Resources (LMR): Fisheries	Boarding of Commercial Fishing Vessel	fisheries citation
		safety citation
		termination of unsafe voyage
Marine Safety	Boarding of Recreational Vessel	safety citation
		fisheries citation
		termination of unsafe voyage
Migrant Interdiction (Alien Migrant Interdiction Operations: AMIO)	AMIO interdiction, boarding, and repatriation	migrants interdicted
Other Law Enforcement (OLE)	Boarding of Non-U.S. fishing vessel in U.S. Exclusive Economic Zone (EEZ)	OLE fisheries citation
Marine Environmental Protection		Not considered
Ice Operations		Not considered
Ports and Waterways Coastal Security (PWCS)		Not considered
Aids to Navigation		Not considered
Defense Readiness		Not considered

Supports Strategic Mission	Metric (units)
Drug Interdiction	pounds cocaine interdicted
	pounds marijuana interdicted
	pounds other drugs interdicted
Search and Rescue (SAR)	number of lives saved
	number of lives assisted
	dollar value of property saved
Living Marine Resources (LMR)	number of fisheries citations(s) issued
Marine Safety	number of safety citation(s) issued
AMIO	number of migrants interdicted
Other Law Enforcement (OLE)	number of OLE fisheries citation(s) issued

A significant aspect of USCG resource planning and allocation is the scheduling of cutters. Regional (USCG Districts) and local (USCG Sectors) units collaboratively conduct this practice manually utilizing Excel, due to frequent unplanned changes to cutter statuses. Each day there may be multiple nuanced changes such as equipment failures necessitating an at-sea cutter's brief return to port to retrieve a part for repairs, and operational changes (e.g. a cutter encumbered with migrants aboard may be able to conduct some, but not all, other missions). Scheduling follows business rules to allocating ensure adequate inport time for maintenance "Charlie" status, with generalized assignments for when each of the cutters should be either at-sea " Alpha" status, or on inport stand-by "Bravo" status, for each of the four subordinate gulf coast sectors, (in the example of the Eighth District). Alpha time is further allocated to the Coast Guard's strategic missions. For example, of a cutter's 1200 hours of at-sea Alpha time, 50% may be allocated to fisheries enforcement resulting in a metric of 600 cutter hours in support of LMR (i.e. fisheries). Normally, each sector has a minimum of one cutter in Alpha status in order to quickly respond to emergencies far out at-sea that near-shore assets such as boats or helicopters cannot. Gaps in coverage due to a (planned) Alpha cutter's unplanned return to port or mission-limiting status are normally covered by another cutter shifted out of Bravo status.

For the purposes of this study, cutter operations can be summarized into cyclical processes. At the start of each day, cutters assume their planned daily status, either Alpha (at-sea), Bravo (inport stand-by), or Charlie (inport maintenance). In the case that a cutter is assigned to Alpha status, the applicable USCG sector assigns the cutter to a general geographic area at-sea. If the cutter is inport, it will depart at a designated time, and transit to an assigned patrol area. If already at-sea, the cutter will transit to the newly assigned location. Upon reaching that location the cutter will either patrol (thus creating deterrence as would a police patrol) or conduct missions of opportunity, normally boarding and inspecting commercial fishing vessels or recreational vessels (also creating deterrence). At any time a mission of high priority may arise, such as the report of a vessel or person in distress (referred to as a Search and Rescue case), thus causing the cutter to transit, (if within reasonable distance/time) to the best known or approximated location of vessel/person. The cutter will then execute the mission. After the mission's duration, the cutter will resume patrolling as assigned and conduct planned missions (e.g. boarding commercial fishing vessels to enforce fisheries and safety regulations). While at-sea, the crew of a cutter monitors fuel state and for critical equipment failure, both potentially necessitating an unscheduled return to port. A cutter will also return to port when scheduled to assume Bravo standby or planned Charlie maintenance.

2 LITERATURE REVIEW

Christensen, Fagerholt and Ronen (2004) provides an overview of maritime transport optimization work; classifying the papers in the literature by their focus on either strategic commercial shipping systems (fleet size and mix) or tactical shipping routing and scheduling. His work also includes the specialized case of naval and coast guard applications. Pesenti (1995) presents heuristics methods to optimize the resource allocation of large-scale strategic commercial shipping systems with the aim to maximize profit. Fagerholt (1999) continues this line of study by focusing on optimal fleet design and size employing dynamic and integer programming to minimize cost.

There are numerous studies focused on tactical routing and scheduling of commercial vessels. Mitra and Darby-Dowman (1985) studies set-covering integer programming method with the aim of the shortest route(s) to achieve minimum cost by addressing the problem of routing, scheduling of transportation vehicles while incorporating staffing personnel assignment pick-ups as well. Fagerholt and Christiansen (2000) advances this work, still employing the set-covering integer programming method, by applying it to commercial maritime shipping routing and scheduling with the addition of cargo-hold allocation and partitioning. They utilize integer programming coupled with heuristics to minimize the total cost.

With real-world applications and pragmatism in mind, Fagerholt (2004) offers a computer based, user friendly, decision support system (DDS), to be used in conjunction with manual scheduling methods; this allows for the evaluation of multiple objectives (e.g. quickest time or minimum cost).

Extensive work has been done on the routing and scheduling of United States Coast Guard vessels and aircraft. Cline, King and Meyering (1992) focus on the routing and scheduling of USCG buoy tenders, a class of ship primarily designed for the single-mission of repairing and maintaining aids-to-navigation buoys. They utilize heuristics to minimize transit distances with penalties for late scheduling. The basis for modeling multi-mission USCG cutter schedules is Brown, Dell and Farmer (1996), which introduces Cutter Scheduler (CutS). This model employs elastic mixed integer linear programming focused on minimizing an objective function's "cost" by assigning penalties for violating business rules. Our study is heavily influenced by Brown, Dell and Farmer's work. Additional deterministic and stochastic concepts come from Wagner and Radovilsky's (2012) study on Coast Guard small boats (< 65 ft), which models constrained resources, coupled with user defined risk tolerances, and is highly applicable to our work's scheduling of cutters across multiple missions and performance metrics.

More recent United States Coast Guard scheduling studies have focused on planning and scheduling aircraft. Hahn and Newman (2008) utilizes mixed integer programming to optimize the scheduling of helicopter maintenance and operational deployments at the USCG's Air Station Clearwater, FL. Vigus (2003) conducts a discrete event simulation study in order to minimize cost, by determining the optimal mix of in-sourced and out-source labor at the United States Coast Guard's Aviation Logistics Center (ALC) in Elizabeth City, NC. Though not recent, yet highly applicable to our study, is Armacost's (1992) strategically focused model of fisheries law enforcement aircraft patrols, which identifies an optimal level of patrol effort (i.e. pareto optimal) for effective deterrence of illegal fishing. This is the first quantifiable estimate of USCG deterrence and serves as the basis for numerous follow-on work.

Related, but not directly applicable are concepts from non-naval, police studies with access to "big data". Zhang and Brown (2012) provides concepts for developing an advanced geographic information system (GIS) based set-covering programming model and associated simulation based on the sizing of police patrol districts. However, it should be stated that there are critical distinctions between naval and community police systems, as naval forces have relatively few patrol resources, and must contend with vast distances and slow transit times. Thus there are additional challenges and relatively fewer data for naval and coast guard applications.

The United States Coast Guard has begun to better understand and developing strategies focused on deterrence. Influential concepts incorporating the mathematical quantification of deterrence are provided by Taquechel and Lewis (2012). Recommendations for implementing a United States Coast Guard strategy focused on deterrence, including performance measures, a model for domestic fisheries law enforcement compliance, and the role of "big-data" are provided by Palin et al. (2012). Sweigart and Taquechel (2015) complement this work with a simulation of USCG patrol efforts to detect of foreign fishing vessels illegally fishing in US waters. An et al. (2013), focused on the distinct USCG mission of Ports, Waterways and Coastal Security (PWCS) by presenting Port Resilience Operational/Tactical Enforcement to Combat Terrorism (PROTECT), a novel logical and illogical quantal response (QR) Stackelberg leader-follower model.

Table 2: Summary of the related literature work reviewed.

Author	**Title**	**Objective**	**Scheduling Methodology**	**Marine/ Naval**	**Scope**	**Deterministic or Stochastic**	**Incorporates Deterrence**
Mitra and Darby-Dowman (1985)	A Extension of Set Partitioning with Application to Scheduling Problems	Shortest route (cost)	IP		Tactical		
Cline, King and Meyering (1992)	Routing and Scheduling Coast Guard Buoy Tenders	Shortest route(s) with scheduleing (time) penalites	Heuristics		Tactical	D	
Bailey, Glazebrook and Dell (1994)	Optimization Based Dynamic Optimization: Planning USCG Law Enforcement Patrols	Maximize utility (counter-drug law enforcement patrols)	DP		Tactical	Both	
Pesenti (1995)	Hierarchical Resource Planning for Shipping Companies	Maximize profit	Heuristics		Strategic	D	
Darby-Dowman et al. (1995)	An Intelligent System for US Coast Guard Cutter Scheduling	Meet goals	Discrete optimization model		Both	D	
Brown, Dell and Farmer (1996)	Scheduling Coast Guard District Cutters	Minimum cost	Elastic MIP		Tactical	D	
Fagerholt (1999)	Optimal Fleet Design in a Ship Routing Problem	Minimum cost	IP & DP		Strategic	D	
Fagerholt and Christiansen (2000)	A Combined Ship Scheduling and Allocation Problem	Minimum cost	IP & heuristics		Tactical	D	
Fagerholt (2002)	A Computer-Based Decision Support System for Vessel Fleet Scheduling - Experience and Future Research	Multi-objective decision support system (DSS)	n/a		Both	D	
Taquechel and Lewis (2012)	How to Quantify and Reduce Risk to Critical Infrastructure	Minimize cost, maximize utility	n/a		Both	S	
Wagner and Radovilsky (2012)	Optimizing Boat Resources at the U.S. Coast Guard: Deterministic and Stochastic Models	Maximize resources (boats) in order to minimize cost	LP		Tactical	Both	
Zang and Brown (2012)	Police Patrol Districting and Scheduling Method and Simulation Evaluation Using GIS Simulation	Maximize utility (patrol effectiveness)			Tactical	S	
An et al. (2013)	A Deployed Quantal Response-Based Patrol Planning System for the U.S. Coast Guard	Maximize utility (counter-terrorism patrols)	Heuristics		Tactical	Both	
This study	Simulation Based Multi-Mission Schedule Evaluation for the Coast Guard	User Defined	Evaluates schedule		Both	Both	Potentially

Legend:
D: Deterministic — LP: Linear Programming — IP: Integer Programming
S: Stochastic — DP: Dynamic Programming — USCG: United States Coast Guard

Portions of the above table excerpted from Christiansen, Fagerholt and Ronen (2004), Ship Routing and Scheduling: Status and Perspectives.

Most similar and influential to our study are two works. Bailey, Glazebrook and Dell's (1994) study of USCG counter smuggling (i.e. counter drug) law enforcement patrols' effectiveness by utilizing dynamic programming with Monte Carlo Simulation and Stackelberg Game concepts. This approach includes both deterministic and stochastic elements, however it evaluates only a single tactical activity, the patrolling against smuggling, which exists within a much larger USCG process. Darby-Dowman et al. (1995) provides a model for the deployment and scheduling of multi-mission cutters. It incorporates a discrete optimization model and includes a decision support application, realizing the necessity of allowing manual schedule changes due to real-world complexities. Our study offers a novel approach to the problems presented by previous work. The scheduler (human, computer, or hybrid – as recommended) is not replaced, rather the effects of this schedule are evaluated in a complex simulation. Additionally, unlike previous studies, there is now a significant amount of real-world "big-data" available since the USCG began intensively collecting data in the early 2000's. This data enables a stochastic simulation to evaluate the quantifiable effects of a given schedule across all, not only a single, United States Coast Guard's mission.

3 PROBLEM SETTING

Cutters are a critical resource. They are (relatively) slow moving and must transit vast geographic distances. Due to their long endurance, and operational capabilities they are necessary for the majority of USCG operations far off shore (>30 Nautical Miles). To effectively support the USCG's national strategic missions, and make effective resource planning decisions, the cutter scheduling process must be able to estimate not only resources dedicated to each mission (i.e. cutter hours) but also results. Due the amount of stochastic events such as cutter break-downs and the different amount of USCG missions in each region, no method currently exists. This study's approach includes both modeling and simulation. Based on stochastic data for each cutter class and each geographic area, multi-mission results are predicted to inform USCG decision makers their return on investment.

3.1 Considered Case: Cutter Schedule for USCG Sector Corpus Christi, TX.

USCG Sector Corpus Christi conducts the majority of USCG missions, including Other Law Enforcement (OLE) along the United States – Mexico international border. There are normally a total of four 87 foot coastal patrol boats assigned to Sector Corpus Christi. Sector Corpus Christi is an ideal case to model because only one class of cutter, 87 ft patrol boats are normally utilized in this area of responsibility. Additionally, there is the need to analyze the UCSG's ability to respond to potential shift increase in maritime migration and/or smuggling due to increased land-side border enforcement or the construction of a boarder wall.

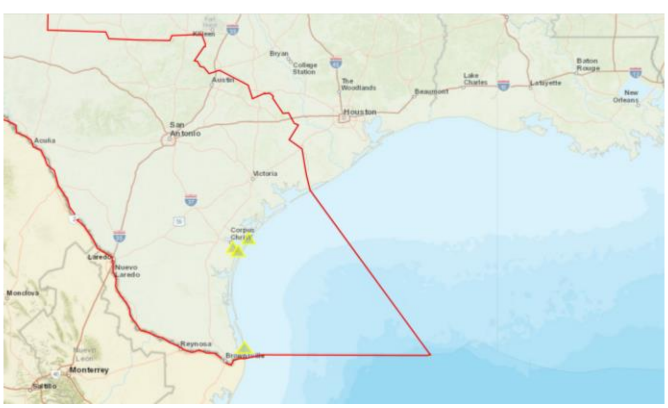


Figure 1: Map of USCG Sector Corpus Christi's seaward Area of Responsibility (AOR).

Figure 2: USCG 87' Coastal Patrol Boat (CPB).

3.2 Characteristics of Data

Our proposed approach utilized three sources of input data. First, pre-determined scheduling data (a quarterly cutter schedule in Excel), which included which cutters would patrol in what locations on a given day, and the various statuses for the cutters scheduled to remain inport. Second, subject Matter Experts (SMEs) provided extensive information in regards to processes, cutter specifics (e.g. speeds and fuel consumption), and clarified weak historical data, (e.g. planning for a minimum of one alien-migrant interdiction operations mission per year even though there is little historical data). SME guidance also influenced the elimination of outlier data suspected of bad user input into database computer systems. Third, the majority of data is from the Coast Guard's databases. The Aviation Logistics Management Information System (ALMIS) provided failure rates and durations of 87' Patrol Boats. ALMIS originally served only aviation units, it's use has been expanded to nearly all USCG platforms including cutters and small-boats. The Marine Information for Safety and Law Enforcement (MISLE), a "Big-Data" system which captures virtually all the Coast Guard's operational activities (note that this database's poor user interface is the cause of many bad data). This "big-data" provided by MISLE was curated to provide interarrival times between missions, mission location, duration, and results. Analysis of the data's distributions, error and number of data points is shown below in Table 3. Table 4, (on the following page) shows the percentage of mission occurrence by geographic zone, the geographic zones (as arbitrarily created for this study) are also shows, with search and rescues (SAR) cases shown, overlaid in red, as an example.

Table 3: Results of input analysis for the considered case study missions' interarrival times and duration, and cutter mechanical failures. 2012-2017.

Event	Interarrival (hrs)	ChiSqr (p value)	Duration (hrs)	ChiSqr (p value)	# Data pts
SAR	EXPO(320)	< 0.005	-0.5 + LOGN(3.75, 2.69)	< 0.005	394
Drug	DISC ((12/16),NORM(1.01e+003, 635), (2/16), 4.39e+003 + 504 * BETA(0.112, 0.11), (2/16), 9.24e+003 + 840 * BETA(0.112, 0.112))	n/a	0.5 + LOGN(6.38, 12.4)	< 0.005	17, 70**
AMIO	DISC(8/13,WEIB(151, 0.46) , 2/13,NORM(2.9e+003, 384), (2/13),NORM(5.66e+003, 360) , (1/13),16800)	n/a	0.999 + WEIB(0.811, 0.701)	< 0.005	14, 92**
OLE	EXPO(102)	< 0.005	0.999 + WEIB(0.0581, 0.719)	< 0.005	1157
LMR	WEIB(84.1, 0.448)	0.0579	0.999 + WEIB(1.99, 1.06)	< 0.005	133
RecVsl Boardings	EXPO(487)	< 0.005	TRIA(0.999, 1.23, 2)	< 0.005	53
Cutter Mechanical Failure	142 * BETA(0.506, 2.04)*	0.34	EXPO(9.51)*	0.138	139

* Units are days.

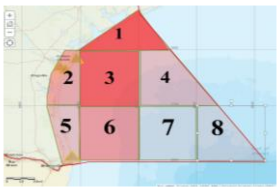
** All Eighth District data vice only for Sector Corpus Christi. Duration and results assumed to be similar as this mission is performed similarly throughout gulf coast.

Infrequently performed missions have minimal historical data. For example, from 2012 to 2016, in Sector Corpus Christi's area of responsibility, only 17 counter drug missions have occurred at-sea. In order to increase the number of data points analyzed, based on input from subject matter experts, a larger data sample of the entire Gulf of Mexico (USCG Eighth District) was used for certain mission's duration as they are performed similarly. Conversely, frequently preformed missions such as safety and law enforcement boardings of commercial fishing vessels (Living Marine Resources: LMR) have very large amounts of historical data.

3.3 Discrete-Event Multi-Mission Cutter Schedule-Results Model

The discrete-event multi-mission cutter simulation model contains four primary phases: (1) creation of cutters, missions, and cutter-casualties, (2) daily status assignment process, (3) cutter-mission pairing (or rejection), and (4) post-mission checks and tallies. Cutters are defined as entities, vice resources, to allow for priority based pairing with missions, thus simulating the real-world mission assignment process. A cutter's and mission's location is assigned as attribute based on the same geographic zones as represented in Table 4.

Table 4: Percentage of mission occurrence by region.



Geographic zones used to sort mission events. Frequency of SAR is overlaid in red.

	Geographic Zone							
Mission	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
SAR	0.255	0.109	0.24	0.0699	0.0791	0.167	0.0274	0.0517
Drug	0.529	0.0588	0	0	0.353	0.0588	0	0
AMIO	0.286	0.0714	0	0	0.357	0.143	0	0.143
OLE	0.0061	0.0199	0.0017	0.0009	0.228	0.721	0	0.0224
LMR	0.102	0.117	0.141	0	0.0938	0.508	0	0.039
RecVsl Boardings	0	0.755	0.0816	0	0.163	0	0	0

Creation of cutters, missions, and cutter casualties: At time zero, all cutters are created as entities and assigned (an attribute) for planned daily status: Alpha, Bravo or Charlie based on an Excel cutter schedule. Additional attributes are assigned for fuel state, location, and if the cutter is fully mission capable (i.e. it does not have a major equipment failure, also referred to as a cutter casualty). Missions entities are created based on each mission type's interarrival time, and assigned attributes for location, duration, and potential results (if completed). Each type of mission queues individually. Entities representing the occurrence of an equipment failure (cutter casualty) are also created based on interarrival time. Missions and casualties, and their attributes, are created based on historical data.

Daily assignment process: Cutters assigned to Alpha status, i.e. patrolling at-sea, are addressed first (via a Decide block). The process of departing port to an assigned patrol location is simulated with a delay and fuel decrease commensurate with the distance transited from a cutter's homeport to the scheduled patrol location at cruise speed (maximum efficiency, which for 87ft patrol boat is approximately 12 knots). In Figure 3, the red box encloses the routing logic for the different daily statuses (Alpha, Bravo, Charlie). To indicate a cutter has left port and is now at-sea, a counter variable for "Cutter Coverage" is updated. Charlie (maintenance) status cutters remains inport in a Hold block through the completion of their scheduled maintenance period (often multiple days based on a casualty duration attribute). The Bravo (stand-by) cutter remain inport in a Hold blocks until its scheduled change in status or the Cutter Coverage variable drops below 1, thus indicating the planned Alpha cutter is no longer at-sea and a back-up is needed. The now previously Bravo cutter is thus reassigned to be in Alpha status and rerouted through the logic to update the counter variable. The number of times a Bravo cutter is needed ("recalled" in USCG terminology) is tallied.

Cutter-Mission Pairing: Cutters are assigned missions, via a Qpick block, from the respective mission queues based on priority order reference (POR). Unplanned/emergency missions have highest priority: (1) SAR, (2) Drug Interdiction, (3) Migrant Interdiction (AMIO), (4) Foreign Fishing Vessel Incursion (OLE); then lower priority, planned routine missions: (5) Boarding of a (domestic US flagged) commercial fishing vessel, and (6) Boarding of a recreational vessel. Both cutter and mission are paired with Match and Batch blocks (as shown in Figure 3's blue box) in order to retain attributes of both. Immediately after the pairing, high priority missions are evaluated, via a Decide block, to determine if the cutter can be on-scene to begin the mission in a reasonable time, which is approximated to be within 3 hours (based on subject matter expert input). Note that this time to be on-scene includes both the mission's wait time in queue, plus the cutter's potential transit time to the mission location, (based on the 87ft patrol boat's top speed of 25 knots). In reality, another better suited Coast Guard asset, e.g. a helicopter, would likely have responded. If the mission is accepted, there is a delay, an update in fuel state, and cutter location commensurate with the transit actually being performed. Then, to account for the cutters time on-scene accomplishing the mission, there is another delay and fuel consumption update corresponding to the mission duration. For low priority missions, as in reality, cutters do not transit (outside of their geographic patrol zone) searching for commercial and/or recreational vessels to board, these are rejected if not in the same location (i.e. zone) as the cutter. All missions that exceed the three hour mission expiration time limit are removed from their queues, tallied as not completed, and disposed of, thus preventing old missions from "clogging" the mission queues. Rejected mission are tallied and disposed in the same manner.

Post mission checks/tallies: Following both acceptance and completion, or mission rejection, cutters and missions are separated. The cutter passes thru logic to check if low fuel (less than 20%) requires a return to port to refuel or if there is a cutter casualty (i.e. equipment failure). The creation of a cutter casualty entity increments a counter variable which is the criteria a Decide block uses to route the cutter to port to assume Charlie status (the duration of which is assigned as a cutter attribute). If still the same day, the cutter is re-routed back to the cutter's assigned patrol area for another pairing with a prospective mission. If the next day, and thus the cutter may be assigned to a different status (i.e. Bravo inport standby), the cutter is routed back through the daily assignment process logic. Completed missions are sorted by mission type, and mission completion and specific mission results are tallied (e.g. a SAR case's lives saved and value of property saved, a counter drug mission's pounds of cocaine seized).

3.4 Results and Conclusion

Based on a three month given (hypothetical, though realistic) daily schedule, we simulate the operations of USCG cutters in USCG Sector Corpus Christi's operational area of responsibility. Table 5 (next page) shows the results of 1000 simulation replications. This comprehensive multi-mission schedule evaluation mechanism is unique in that it measures productivity output given limited Coast Guard resources across a realistic spectrum of stochastic events. The current approach, only measuring effort (hours) planned for an area or mission does not fulfill the need to predict how local tactical-level resources contribute to multiple strategic goals. Nor does it provide an accurate estimate on return on investment, as our method does. This new method of scheduling has far-reaching implications. Not only can schedulers make informed decisions based on how various cutter schedule options support stated strategic goals but deterrence, the act of preventing negative acts simply by being present, can now begin to be estimated due to the predicted quantitative mission results. Lastly, and perhaps most importantly, various missions can be prioritized based on cost and value-added information. For example, the U.S. Food and Drug Administration (FDA) estimates the value of a human life at $7,900,000. The United Nations Office of Drug and Crime estimates the cost to the U.S. government, for a pound of illegally smuggled cocaine to be $38,186. Based on likely results, and the value of each, priorities and strategies should potentially be reexamined based on costs and benefits.

In this paper, a comprehensive multi-mission cutter scheduling and evaluation mechanism is proposed with an aim to measure productivity output given limited Coast Guard resources across a spectrum of current and future scenarios. The current approach used by the USCG, a rule based decision making mechanism and single mission effort-hours, has significant variance between the actual versus desired outputs, and the USCG incurs high costs because of a lack of accurate scheduling mechanisms under highly uncertain circumstances. Some examples of the events posing uncertainty to the system that is being studied are mission occurrences and cutter equipment casualties and breakdowns. Our proposed scheduling mechanism improves cutter scheduling by predicting the tactical outcomes, e.g. lives saved, amount of drug seized, and number of migrant interdicted. Our model helps predict the results across multiple missions where the results could help decision makers effectively plan resources to achieve desired results.

Table 5: USCG Mission Results Output Analysis for 1000 replications

Mission Results	Average	Standard Deviation	90% Confidence Interval Half-Width	Min	Max
Lives Saved	0.54	0.23	0.01	0.00	1.28
Lives Assisted	2.92	1.23	0.06	0.00	6.98
Property Saved (in dollars)	116000	48900	2550	0	277000
Lbs. Cocaine Interdicted	0.00116	0.00152	0.00008	0.00000	0.00882
Lbs. Marijuana Interdicted	505.00	662.00	34.40	0.00	3840.00
Lbs. Other Drugs Interdicted	0.137	0.179	0.009	0.000	1.040
Migrants	2.41	0.56	0.03	1.04	4.57
OLE Citations issued	0.028	0.026	0.001	0.000	0.165
US Fisheries Law (LMR) Citations Issued	0.057	0.053	0.003	0.000	0.331
Vessel Voyage Terminations	1.95	1.73	0.09	0.00	10.90
Safety Citations Issued	1.95	1.73	0.09	0.00	10.90

OLE: Other Law Enforcement (US/MX cross-border illegal fishing)
LMR: Living Marine Resources (US domestic fisheries)

Future work includes expanding the current scheduling model to include all of the USCG Sectors within a region, in this case, adding Sector Houston-Galveston, Sector New Orleans, and Sector Mobile. Additionally, more detailed input data is possible which would create more realistic variation in the mission results.

REFERENCES

An, B., F. Ordóñez, M. Tambe, E. Shieh, R. Yang, C. Baldwin, J. DiRenzo III, K. Moretti, B. Maule, and G. Meyer. 2013. "A Deployed Quantal Response-Based Patrol Planning System for the US Coast Guard." *Interfaces* 43(5):400-420.

Armacost, R. L. 1992. "A 0–1 Nonlinear Programming Model for Coast Guard Fisheries Law Enforcement Aircraft Patrols." *European Journal of Operational Research* 56(2):134-145.

Bailey, M. P., K. Glazebrook, and R. F. Dell. 1994. "Simulation-Based Dynamic Optimization: Planning United States Coast Guard Law Enforcement Patrols." In *Proceedings of the 1994 Winter Simulation Conference*, edited by D. A. Sadowski, A. F. Seila, J. D. Tew, and S. Manivannan, 392-398. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Brown, G. G., R. Dell, and R. Farmer. 1996. "Scheduling Coast Guard District Cutters." *Interfaces* 26(2):59-72.

Brown, G. G., R. Dell, and R. Wood. 1997. "Optimization and Persistence." *Interfaces* 27(5):15-37.

Christiansen, M., K. Fagerholt, and D. Ronen. 2004. "Ship Routing and Scheduling: Status and Perspectives." *Transportation Science* 38(1):1-18.

Cline, A. K., D. King, and J. Meyering. 1992 "Routing and Scheduling Coast Guard Buoy Tenders." *Interfaces* 22(3):56-72.

Darby-Dowman, K., R. Fink, G. Mitra, and J. Smith. 1995. "An Intelligent System for US Coast Guard Cutter Scheduling." *European Journal of Operational Research* 87(3):574-585.

Fagerholt, K. 1999. "Optimal Fleet Design in a Ship Routing Problem." *International Transactions in Operational Research* 6(5):453-464.

Fagerholt, K., and M. Christiansen. 2000. "A Combined Ship Scheduling and Allocation Problem." *Journal of the Operational Research Society* 51(7):834-842.

Fagerholt, K. 2004. "A Computer-Based Decision Support System for Vessel Fleet Scheduling—Experience and Future Research." *Decision Support Systems* 37(1):35-47.

Hahn, R. A., and A. Newman. 2008. "Scheduling United States Coast Guard Helicopter Deployment and Maintenance at Clearwater Air Station, Florida." *Computers & Operations Research* 35(6):1829-1843.

Mitra, G., and K. Darby-Dowman. "CRU-SCHED: A Computer-Based Bus Crew Scheduling System Using Integer Programming." *Computer Scheduling of Public Transport* 2 (1985): 223-232.

Palin, P., S. Hall, C. Baldwin, and T. Lewis. 2012. "Deterrence and the United States Coast Guard: Enhancing Current Practice with Performance Measures." Washington, DC: U.S. Coast Guard.

Pesenti, R. 1995. "Hierarchical Resource Planning for Shipping Companies." *European Journal of Operational Research* 86(1):91-102.

Sweigart, B., and E. Taquechel. 2015. "Modeling/Simulation Efforts: Foreign Fishing Vessel (FFV) Incursions." Powerpoint presentation. Washington, DC: U.S. Coast Guard.

Taquechel, E. F., and T. Lewis. 2012. "How to Quantify Deterrence and Reduce Critical Infrastructure Risk." *Homeland Security Affairs* 8, no. 1. Monterey, California: Naval Postgraduate School Center for Homeland Defense and Security (CHDS). https://www.hsaj.org/articles/12007

U.S. Department of Transportation, Research and Innovative Technology Administration, Bureau of Transportation Statistics, Table 2-49: U.S. *Coast Guard Search and Rescue Statistics, Fiscal Year 2013. 2013.* Washington, DC: U.S. Department of Transportation.

Vigus, S. E. 2003. *A Simulation-Based Analysis of the Impact of In-Sourcing a Major Process Element on the Coast Guard HH-60J Depot Maintenance Process*. Thesis, School of Engineering and Management, Air Force Institute of Technology, Air Force Air University, OH.

Wagner, M. R., and Z. Radovilsky. 2012. "Optimizing Boat Resources at the US Coast Guard: Deterministic and Stochastic Models." *Operations research* 60(5):1035-1049.

Zhang, Y., and D. E. Brown. 2012. "Police Patrol District Design Using Agent-Based Simulation and GIS." In *Proceedings of the 2012 IEEE International Conference on Intelligence and Security Informatics*, pp. 54-59. Heidelberg, Germany: Springer, Inc. https://doi.org/10.1186/2190-8532-2-7

AUTHOR BIOGRAPHIES

GREGORY HIGGINS recently received his Masters of Industrial Engineering from the University of Miami. He received his B.S. in Operations Research and Computer Analysis from the United States Coast Guard Academy in 2004. He is a Lieutenant Commander in the U.S. Coast Guard and has served on board four cutters. Most recently, he served as the Commanding Officer of the 154 foot Patrol Boat, U.S. Coast Guard Cutter KATHLEEN MOORE, homeported in Key West, FL. His email address is gregory.e.higgins@uscg.mil.

SERCAN DEMIR is a Ph.D. candidate in the Department of Industrial Engineering at the University of Miami. He received his M.S. degree in Industrial and Systems Engineering from the University of Southern California. His research interests include coordination of supply chains by contracts and game theory application in supply chain management. His email address is s.demir@umiami.edu.

NURCIN CELIK is an Associate Professor at the Department of Industrial Engineering at the University of Miami. She received her M.S. and Ph.D. degrees in Systems and Industrial Engineering from the University of Arizona. Her research interests include architectural design and application of dynamic data- driven adaptive simulations for distributed systems. She has received several awards, including Presidential Early Career Award for Scientists and Engineers (PECASE) Award (2017), AFOSR Young Investigator Research Award (2013), UM Provost Award (2011, 2016), and IAMOT Outstanding Research Project Award (2011). Her email address is celik@miami.edu.