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SCHEDULING COAST GUARD
DISTRICT CUTTERS

by

Robert A. Farmer

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Thesis Advisor: Dr. Robert F. Dell

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Scheduling Coast Guard District Cutters

by

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ABSTRACT

The United States Coast Guard is organized by Atlantic and Pacific areas, which are further subdivided into districts. Each district assigns cutters (ships) of length 180 feet or less into weekly statuses. The resulting cutter schedules reflect the district's level of readiness to respond to such emergencies as search and rescue, law enforcement, and pollution response. The First Coast Guard District has one of the largest scheduling problems, assigning each of 16 cutters to one of six weekly statuses. The First District's quarterly schedules must adhere to a number of guidelines which ensure patrol coverage, enforce equitable distribution of patrols, and restrict consecutive cutter statuses. This thesis formulates and solves the quarterly scheduling problem as an elastic mixed integer linear program. Face valid schedules, which are superior to actual schedules for all measures of effectiveness considered, are obtained within 15 minutes on a 486/33 Mhz personal computer using a commercially available integer programming solver.

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I. INTRODUCTION

A. COAST GUARD DISTRICT CUTTERS

United States Coast Guard (USCG) District Commands schedule cutters of length 180 feet or less into weekly statuses. The First Coast Guard District has one of the largest scheduling problems, assigning each of 16 cutters to one of six statuses. The First District's quarterly schedules must adhere to a number of guidelines which ensure patrol coverage, enforce equitable distribution of patrols, and restrict consecutive cutter statuses.

Each cutter is scheduled by week to be either in an operational or maintenance status. The operational statuses are referred to as "bravo statuses". The most common bravo statuses used by the districts are:

- Bravo-24 (B-24) - The cutter must be underway within 24 hours of notification to sail,
- Bravo-12 (B-12) - Within 12 hours,
- Bravo-6 (B-6) - Six hours,
- Bravo-2 (B-2) - Two hours.

Cutters are also assigned various maintenance statuses, of which the most commonly used is "C" for "charlie periods".

Bravo-2 and Bravo-6 statuses are used by the district for cutters which are designated as the first response vessels, or cutters which are required to patrol a certain area. Bravo-24 and Bravo-12 statuses are assigned to allow a cutter to achieve routine maintenance or training. A charlie status is assigned to allow for more in-depth maintenance on the mechanical plant of the cutter and indicates the vessel will not be called upon to respond to anything but the gravest emergencies.

In addition to the operational statuses, the cutter schedules also include yard and dockside availabilities. These availabilities are maintenance periods of longer duration than charlie periods, and are generally planned in advance through the USCG's Maintenance and Logistics Command.

Since Bravo-2 and Bravo-6 statuses fatigue both the crew and the cutter, the district scheduler attempts to rotate these statuses evenly among all available cutters. The scheduler also attempts to interrupt these statuses with less demanding statuses such as Bravo-12 and Bravo-24. The scheduler's job is further complicated by the fact each class of cutter is required to have a certain number of weeks dedicated for maintenance, either charlie periods or dockside availabilities. There are also other demands on a cutter's time, such as public appearances and patrolling special events.

B. CUTTER SCHEDULES AND THE FIRST DISTRICT

We define a "schedule" as a specification of the weekly status for all 16 cutters, which includes a specific patrol area with a patrol status. A quarterly (yearly) schedule is defined as a schedule for 13 (52) consecutive weeks. A "rough" schedule is defined as a schedule that does not indicate a specific patrol area with a patrol status.

1. First District Cutters and Patrols

The USCG's First District stretches from Maine to halfway down New Jersey, and the district boundaries extend seaward to cover the ocean areas claimed by the United States. The district office is located in Boston, Massachusetts.

The district scheduler is responsible for scheduling 16 cutters from the following classes:

- 140 WTGB (icebreaking tug),
- 110 WPB (patrol boat),
- 82 WPB (patrol boat).

These cutters can be scheduled to four different patrol statuses. Each patrol status represents a different geographical area in the district which are designated: B-2NY, B-2G, B-2M, and B-2SAR. Not all of the cutter classes are eligible for every type of patrol year round.

The 82 foot patrol boats cannot be deployed for search and rescue (SAR) during the winter months. This is because severe winter weather and icing conditions can cause stability problems for the cutters. The 140 foot WTGB cutters are also not available during the winter for patrols, because they are used to clear navigable harbors and rivers of ice.

2. Current Manual Scheduling Practices

Currently the district scheduler creates a rough annual schedule in September with paper and pencil. The scheduler then inputs the rough schedule to a spreadsheet. This process takes approximately two to three working days, and only indicates if a cutter will have a patrol status.

Using this as a guide, the scheduler's office subsequently assigns patrol areas (B-2NY, B-2G, B-2M, B-2SAR) to the designated patrol cutters, usually on a monthly basis. The job of creating an annual schedule has heretofore been considered too difficult for the scheduler to attempt.

The rough annual schedule is constantly changing, because ships suffer casualties (break down) or requirements change. This makes the rough schedule developed in September less applicable the further into the future it is projected. Towards the end of each quarter, or more frequently should the need arise, the First District generates a new rough schedule for the remaining quarters. This is a very labor intensive practice with no clear measure of whether one rough schedule is better than another. Essentially, if the scheduler and his assistant can fill the majority of the required patrols, the rough schedule is approved.

C. OBJECTIVE OF CURRENT RESEARCH

The objective of this thesis is to develop an optimization-based model to produce an annual schedule for the

First Coast Guard District. Since the scheduler evaluates schedules quarterly, the problem is formulated on a quarterly basis. This allows the scheduler to generate an annual schedule, yet the individual quarterly schedules can easily be updated.

Another goal of this thesis is to formulate and solve the model using GAMS (Brooke et al. (1988)) and XA (Byer (1987)). The use of commercially available software and a standard personal computer will allow the Coast Guard to quickly implement the model for a reasonable cost. Further, each Coast Guard District has its own constraints for scheduling cutters. Using commercially available software allows better support for the Coast Guard, and rapid adaptation of the basic model to the unique characteristics of the individual district's own problems.

D. THESIS OUTLINE

Chapter II surveys related ship scheduling models. In Chapter III, a mixed integer linear program is developed with detailed discussion of the costs, penalties and measures of effectiveness used. Using the model of Chapter III, computational performance for a year's worth of actual data from the First District is presented in Chapter IV. Conclusions are provided in Chapter V. Appendix A contains a face valid annual schedule produced by the model, and Appendix B provides the GAMS program used to generate the model.

II. PREVIOUS SHIP SCHEDULING RESEARCH

A. GENERAL SHIP SCHEDULING MODELS

Most ship scheduling models reported in the operations research literature address problems faced by commercial shipping companies. Ronen (1983) provides an excellent review of the models which have been proposed. He discusses the variety and complexity of ship scheduling problems and proposes a model classification scheme.

The models Ronen discusses are essentially concerned with a fleet of ships moving goods from one or more supply points to various demand points where the objective either minimizes the number of ships required in the fleet or minimizes transportation costs. It is clear the objectives and constraints used for commercial shipping companies are not directly applicable to the problem faced by the USCG districts.

B. MILITARY SHIP SCHEDULING MODELS

1. SeaLift Models

Few military ship scheduling models have been developed. Of these, the most commonly seen formulations are similar to the problems addressed for commercial purposes. Lally (1987) and Lima (1988) formulate problems for the Emergency Deployment Agency. The main objective of these models is to move as much material from several embarkation ports to disembarkation ports in as little time as possible.

2. U.S. Navy Atlantic Fleet Scheduling Problem

Ratliff (1981) first explored the possibilities of using an integer program for scheduling the Navy's Atlantic Fleet. This work was later extended in Ratliff and Nulty (1986) where a network-based model is developed for scheduling the Navy's Atlantic Fleet. In Ratliff and Nulty (1986) each individual ship's schedule is viewed as a network and solved as a longest path problem. These longest path problems are solved repeatedly, changing certain parameters, until all of the specified requirements are satisfied. Computational results are reported that indicate sample problems can be solved to near optimal with between five to twenty iterations of the algorithm; however, no indications of the computation requirements are provided.

Goodman (1985), followed by Brown et al. (1990), develop an extremely efficient algorithm for scheduling surface combatants of the Atlantic Fleet, which they entitle CPSKED. The CPSKED model uses a column generation technique that includes all possible feasible schedules. It then uses an elastic set partitioning model to select the best set of candidate schedules. The authors report solutions to the full scale 111-ship annual scheduling problem in under 2 minutes on an IBM 3033 AP computer. While conceptually the problem of scheduling combatants for the Atlantic Fleet is similar to that faced by USCG cutters, CPSKED is concerned with matching ship capabilities (armament, communication) with missions of varied durations. These considerations are not applicable to this thesis.

3. Quadratic Assignment/Linear Programming Model

Sibre (1977) developed the only model found in the literature which specifically addresses a Coast Guard scheduling problem. Sibre's Naval Postgraduate School thesis contains a mathematical model to schedule the Pacific Area's Hamilton Class High Endurance Cutters. The model is solved using a variation of the Quadratic Assignment/Linear Programming model developed by Geoffrion and Graves (1976). The Quadratic Assignment model contains the guidelines for the number of cutters needed in a patrol area, the cutters available for a specific assignment, the transition cost of cutters shifting from one type of assignment to another, and the costs for violating starting and completion dates. The linear programming model is used primarily to determine the length of the patrols. The model develops a schedule and then uses a heuristic approach to alter the schedule to ascertain if any improvement can be achieved.

Sibre's model cannot be easily adapted to the district cutter scheduling problem because of fundamental differences between the Area scheduling problem and the district scheduling problem. The Area scheduling problem has patrol lengths of variable duration. In contrast, the district schedules patrols of exactly one week. A major concern of Sibre's model is the extensive transit times faced by the High Endurance Cutters between patrol areas. Since the High Endurance Cutters transit to patrol areas far away from their homeport, days away from homeport became a good measure of effectiveness. In the problem under consideration in this thesis, neither of these factors are applicable.

4. Area Scheduling Model In Development

Currently the Coast Guard's Research and Development Center in Groton, Connecticut, has a project to develop an optimization based model to create annual schedules for the Atlantic Area. The R&D Center contracted a group from Brunel University in London, England, led by Dr. G. Mitra to formulate and solve the problem. The problem is to schedule Coast Guard Medium and High Endurance Cutters to various assignments on the East Coast of the United States. The problem calls for daily time resolution in the schedule produced, accounting for transit time, and certain constraints imposed by the Atlantic Area Command. While this research has not been published (see Darby-Dowman et al. (1992)), the problem is similar to that addressed by Brown et al. (1990) and Sibre (1977) and therefore possessed many characteristics which make it not directly applicable to this thesis.

III. FIRST DISTRICT SCHEDULING MODEL

A. PROBLEM DESCRIPTION AND FORMULATION

The problem of creating a quarterly schedule for the First Coast Guard District is formulated as an elastic mixed integer linear program. The formulation ensures all patrol requirements are satisfied. The elastic portion of the model ensures that requirements are minimally violated when they cannot be feasibly satisfied. The model assigns 16 cutters to one of the following statuses every week of the quarter:

- B-2M - The cutter must be within the geographic boundaries of the northern patrol area designated by the letter M,
- B-2G - The cutter must be within the central patrol area G,
- B-2NY - The cutter must be within the southern patrol area NY,
- B-2SAR - A patrol status indicating the cutter is a designated search and rescue vessel,
- B-12 - The First District uses this status for any week a cutter is not scheduled for a specific patrol or maintenance period,
- C - This status indicates a cutter is assigned a charlie period,
- UNAVAL - This status is assigned when a cutter is not available for patrol assignments.

The model allows cutters to be manually specified as unavailable and makes sure the required number of "charlie periods" for each cutter are assigned. Additionally, the model enforces all of the First District's policies regarding cutter scheduling, which include:

- Charlie periods should be in two-week blocks,
- Cutter's cannot have more than two consecutive patrol statuses,
- Cutter's cannot be assigned consecutive SAR statuses,
- 82 WPBs cannot be assigned SAR patrols during the Fall and Winter Quarters,
- WTGB class cannot be assigned SAR patrols,
- Patrols should be assigned to cutters equitably.

B. CutS (CUTTER SCHEDULER)

The formulation of CutS (Cutter Scheduler) is presented below after the introduction of appropriate notation.

Indices:

i = cutter;

k = statuses (B-2M, B-2G, B-2NY, B-2SAR, C);

t = week the cutter assumes the patrol status.

Data:

$COST_{ik}$ = cost of scheduling cutter i to patrol k;

$$SHIPAVAL_{it} = \begin{cases} 1 \text{ if ship } i \text{ is available for patrol during week } t; \\ 0 \text{ otherwise;} \end{cases}$$

REQ_k = required number of cutters for status k excluding "C";

$CHARLIE_i$ = minimum number of weeks of charlie status required for cutter i;

$RPEN_k$ = penalty for not meeting the required number of cutters (REQ_K) for patrol status k;

CPEN = penalty for violating charlie status constraints;

FPEN = penalty for violating fairness constraints;

$FAIRLO_i$ = minimum number of patrols for cutter i;

$FAIRHI_i$ = maximum number of patrols for cutter i.

<u>VARIABLES</u>:

$$X_{ikt} = \begin{cases} 1 & \text{if cutter i is assigned status k in week t;} \\ 0 & \text{otherwise;} \end{cases}$$

$DREQ_{kt}$ = elastic variable measuring deviation from required patrol statuses;

$DCON_{it}$ = elastic variable for violating the consecutive charlie period requirement;

$D2C_{it}$ = elastic variable for violating limit on no more than two consecutive charlie periods;

DF_i = elastic variable for violating fairness constraints.

EQUATIONS:

$$Minimize \sum_i \sum_k \sum_t (X_{ikt} \times COST_{ik} + DREQ_{kt} \times RPEN_k + DCON_{it} \times CPEN +$$

$$D2C_{it} \times CPEN + DF_i \times FPEN)$$

Subject to:

(1) $\sum_i X_{ikt} = REQ_k - DREQ_{kt} \quad \forall \quad (k \neq C,\ t)$

(2) $\sum_k X_{ikt} \leq 1.0 \quad \forall \quad (i,\ t)$

(3) $\sum_t X_{ict} \geq CHARLIE_i \quad \forall \quad i$

(4) $X_{ict} - X_{ict-1} - X_{ict+1} \leq 0 + DCON_{it} \quad \forall \quad (i,\ t > 1)$

(5) $X_{ict} + X_{ict-1} + X_{ict-2} \leq 2 + D2C_{it} \quad \forall \quad (i,\ t > 2)$

(6) $\sum_{k \neq c} \sum_t X_{ikt} \geq FAIRLO_i - DF_i \quad \forall \quad i$

(7) $\sum_{k \neq c} \sum_t X_{ikt} \leq FAIRHI_i + DF_i \quad \forall \quad i$

(8) $\sum_{k \neq c} (X_{ikt} + X_{ikt-1} + X_{ikt-2}) \leq 2.0 \quad \forall \quad (i,\ t > 2)$

(9) $X_{iB\text{-}2SARt} + X_{iB\text{-}2SARt-1} \leq 1.0 \quad \forall \quad (i,\ t > 1)$

CONSTRAINT EXPLANATION:

(1) A minimum number of cutters must be assigned to patrol status k.

(2) Each cutter cannot be assigned more than one status for each week. Any cutter not assigned a status is placed in B-12.

(3) Each cutter must have at least a minimum number of required charlie periods.

(4) Charlie periods must be consecutive.

(5) Consecutive charlie periods should not exceed two weeks.

(6) Each cutter must have a minimum number of patrols.

(7) Each cutter cannot exceed a maximum number of patrols.

(8) A cutter cannot be assigned more than two consecutive patrol statuses.

(9) A cutter cannot be assigned consecutive B-2SAR statuses.

C. CONSTRAINT DESCRIPTION

Constraints (4) and (5) require charlie periods to be assigned in two-week blocks. The First District Scheduler has not effectively been able to manually assign charlie periods in this manner due to the complexity of the task.

One of the goals of CutS is to create quarterly schedules which distribute the number of patrols between the cutters equitably; constraints (7) and (8) are designed to achieve this goal. The parameters $FAIRHI_i$ and $FAIRLO_i$ are calculated based on a number, FAIR, which is the total number of required patrols divided by the number of cutters. $FAIRHI_i$ is established by simply adding two to the number FAIR. Allowing the number of patrols assigned to each cutter to deviate by two empirically gives the model flexibility, while still adhering to the First District Scheduler's requirement to equitably distribute the patrol statuses. $FAIRLO_i$ is the minimum of FAIR and the maximum number of patrol assignments possible for each cutter. The maximum is easily determined by summing the number of weeks the cutter is available and subtracting the number of required charlie periods.

The last two constraints, (8) and (9), express First District policy, requiring that no cutter have more than two consecutive patrol periods. The District's policy also dictates cutters should not have consecutive SAR statuses.

D. COSTS, PENALTIES, AND MEASURES OF EFFECTIVENESS

The difficulty establishing meaningful measures of effectiveness for ship scheduling problems is well documented by Soland (1982). The measures of effectiveness used for CutS are essentially the same as those employed by the First District Scheduler:

- Minimize the transit time to cutter's patrol areas,
- Minimize the number of required patrol statuses missed,
- Equitably distribute the patrol statuses among cutters.

In addition to the above measures of effectiveness, the amount of time necessary to create quarterly and annual schedules is considered in the computational results reported in Chapter IV.

The costs and penalties for CutS stem from the measures of effectiveness and from discussions with the First District Scheduler. The cost of assigning a cutter to a patrol is the transit time of the cutter to the patrol area. Accordingly, the transit time matrix shown in Table 1 was developed. The entries in Table 1 indicate the hours required to transit from a cutter's homeport to the patrol area at the cutter's normal cruising speed. For example, it takes the ADAK 17 hours to transit from its homeport to the B-2M patrol area. Even though cutters generally remain in their homeport for their charlie periods, a transit time of two is used for any cutter assigned to "C". The number two is used because it is less than the smallest transit time in Table 1, but it is greater than the zero used for the B-12 status. This relationship ensures that only the minimum number of charlie periods are assigned to each cutter.

CutS uses the following penalties, which are derived from the transit time matrix:

- 40 for missing a B-2M, B-2NY, or B-2SAR status,
- 30 for missing a B-2G status,
- 25 for each unit of violation from the fairness constraints,
- 40 for violating charlie requirements.

The scheduler desires all patrol requirements to be satisfied, regardless of the transit time for a cutter. This results in the penalty of 40 for missing a required status (a value slightly greater than any of the values in Table 1). Failing to fill a B-2G status is penalized less than the other patrol statuses, because two cutters are normally assigned to this patrol area. If the scheduler is unable to meet all of the required patrol statuses, the first status to be unfilled will likely be one of the B-2G patrols. A penalty of 25 is used for violating the fairness constraints, since the scheduler indicates it is better to assign a cutter extra patrols than to leave an area uncovered. However, the scheduler would not assign an extra patrol to a cutter which is very far away from the cutter's homeport. The penalty of 25 allows CutS numerous alternatives to reasonably violate the fairness constraint prior to exceeding the penalty for missing a B-2G status.

TABLE 1

TRANSIT TIME MATRIX

The values in this table represent the transit time in hours for a cutter to reach a patrol area. These values are used in the objective function of CutS. CutS' objective function minimizes the total quarterly transit time used by cutters to reach patrol areas.

	B-2M	B-2G	B-2NY	B-2SAR
ADAK	17	9	3	9
WRANGEL	3	6	17	6
SANIBEL	6	3	6	3
MONOMOY	6	3	6	3
JEFF-ISL	3	6	17	6
GRAND-ISL	3	3	11	3
BAIN-ISL	17	9	3	9
PT-BONITA	18	7	4	7
PT-FRANCIS	14	4	4	4
PT-JACKSON	18	5	5	5
PT-HANNON	4	11	21	11
PT-TURNER	11	4	7	4
PT-WELLS	14	5	4	5
PENOBSCOT	36	18	6	18
STURGEON	36	18	6	18
THUNDER	6	18	36	18

IV. COMPUTATIONAL EXPERIENCE

A. TEST PROBLEMS

The First District Scheduler provided the District's rough quarterly schedules for the last two quarters of fiscal year 1991 and the first two quarters of fiscal year 1992. The rough quarterly schedules yielded the following information, which is summarized in Table 2:

- the weeks cutters were not available to be assigned any statuses,
- the number of charlie periods each cutter was assigned,
- the number of required patrol statuses which were missed during the quarter,
- the number of patrol statuses assigned to each cutter.

The First District also provided a 12 week schedule for the second quarter of fiscal year 1992.

The quarterly versions of CutS were run with the information shown in the first two columns of Table 3. While the total number of charlie periods per quarter were virtually the same between CutS and the provided rough quarterly schedules, some of the individual cutter's charlie periods were modified by the addition or subtraction of one period. These modifications were conducted to establish an even charlie period requirement for each cutter and thereby more applicably model constraints (4) and (5).

TABLE 2

SUMMARIZED INFORMATION FROM FIRST DISTRICT'S SCHEDULES

"Weeks of unavailable" represent the total number of weeks cutters were not available to receive patrol assignments. "Weeks of charlie" is the number of charlie periods given to the cutters during the quarter. "Missed statuses" is the number of required patrols the manually created schedule was unable to fill.

	Weeks of Unavailable	Weeks of Charlie	Missed Statuses
Fall Quarter	58	70	6
Winter Quarter	75	64	[illegible]
Spring Quarter	46	68	1
Summer Quarter	53	63	4

TABLE 3

SUMMARIZED TEST PROBLEM DATA INPUT

Using essentially the same initial conditions as Table 2, CutS had significantly fewer missed statuses.

	Weeks of Unavailable	Weeks of Charlie	Missed Statuses
Fall Quarter	58	70	0
Winter Quarter	75	64	3
Spring Quarter	46	68	0
Summer Quarter	53	62	0

All computational results reported in this thesis were obtained using a 486/33 Mhz personal computer and the commercial linear/integer programming solver XA.

B. SOLUTION TIMES

A basic measure of effectiveness is the time required to obtain feasible quarterly schedules. The schedules generated each quarter using the information of Table 3 are included in Appendix A. These quarterly schedules were shown to the First District Scheduler for his critique. The scheduler and his assistant reported the schedules are feasible and of good quality.

1. Time Necessary to Develop Schedules

The scheduler and his assistant take approximately two to three working days to develop a rough annual schedule. The amount of time CutS requires to develop each quarterly schedule within specified tolerances of optimality are shown in Table 4. Generation of an annual schedule within 5% of optimal by running the quarterly versions of CutS consecutively, including the required inputs for each model, can easily be accomplished in under two hours. This is a vast improvement over the two to three days required by the district scheduler.

The Fall and Winter versions of CutS consistently take longer to solve than the Spring and Summer versions of the model. This is partly because of the restrictions imposed on using the WTGB and 82 WPB class of cutters. It is also the result of the information provided by the First District, which was used as the initial inputs for CutS. The number of free weeks cutters had available for patrols during the Fall and Winter are significantly less than the weeks available for the Spring and Summer, as can be seen in Table 2. These two factors make the Fall and Winter models have comparatively less scheduling flexibility than the Spring and Summer.

The solution times required to guarantee an optimal solution, or a solution within 1% of optimal, dramatically increase for more restrictive quarters as compared to solving within 5% of optimal. However, the quality of the quarterly schedules, as indicated by the objective function values shown in Table 5, do not display dramatic improvement for the test problem considered. For example, the time necessary for the Fall version of CutS to create a quarterly schedule guaranteed within 5% and 1% of optimal was 13.4 and 157.0 minutes respectively. The objective function value for the model, however, actually increased from 386 to 387.

The model produces face valid quarterly schedules for anything within 10% of optimal. For solutions within 5% of optimal, CutS usually creates schedules which have not violated any of the constraints. The changes in the quarterly schedules above the 5% level are the result of CutS switching patrol statuses, which reduce the integer objective function value only slightly.

TABLE 4

SOLUTION TIMES OF THE QUARTERLY MODELS

The solution times are obtained using a 486/33 Mhz P.C. and show at any setting the ability of CutS to quickly obtain schedules which took more than two days to manually develop.

Quarter	Time in minutes to obtain solution within percentage from optimal			
	10%	5%	1%	0%
FALL	8.9	13.4	157.0	367.4
WINTER	5.9	8.8	16.4	85.7
SPRING	3.0	2.9	3.0	3.0
SUMMER	1.6	3.0	2.6	4.4

TABLE 5

OBJECTIVE FUNCTION VALUES

This table demonstrates that objective function values guaranteed to be between 5% and 1% of the optimal do not change appreciably, whereas Table 4 shows a significant increase in time. The 5% setting is therefore recommended. The linear program (LP) objective function value is an easily obtained bound of the best possible solution.

Quarter	Objective function value for guaranteed within percentage from optimal				Objective of LP Solution
	10%	5%	1%	0%	
FALL	418	386	387	384	381
WINTER	498	464	464	463	460
SPRING	458	458	458	458	458
SUMMER	454	427	427	427	427

2. Computational Difficulties Imposed by Constraints

The requirement for charlie periods to be in two-week blocks (CutS constraints (4) and (5)) greatly increases the computational difficulty, and hence the amount of time necessary to obtain a solution. Because these constraints force CutS to assign charlie periods in two-week blocks, entering odd numbers for the minimum required charlie periods empirically makes it more difficult, if not impossible, for the model to solve within 10% of optimal.

Test runs of CutS to investigate how much computational difficulty constraints (4) and (5) add are shown in Table 6, where a 14-hour time limit was imposed. Table 6 compares computational performance with all cutters having requirements for an even number of charlie periods, 25% of the charlie requirements being odd numbers, and with constraints (4) and (5) removed. Table 6 dramatically portrays the computational difficulty imposed by these constraints and by entering an odd number of charlie periods.

Note that requiring the total number of charlie periods to be an even number is not a limiting assumption. The scheduler is given some flexibility when setting these requirements, and the total number is large enough that the addition or subtraction of one period is only a slight alteration.

C. UNFILLED PATROL STATUSES

The most important measure of effectiveness is the number of required patrols missed. This criteria is essentially how the district scheduler compares the various rough quarterly schedules developed by hand; consequently, it is a logical

TABLE 6

CONSECUTIVE CHARLIE CONSTRAINTS AND COMPUTATIONAL REQUIREMENTS

The computational difficulty imposed by the constraints on consecutive charlie periods is evident from the large increase in the solution times with the constraints added. The effect of using an odd number of required charlie periods is also demonstrated.

Quarter	Time in minutes to obtain solution within 10% from optimal or exceed time limit.		
	All Even Number Charlie Periods	25% of Charlie Periods Odd	Constraints Removed
FALL	8.9	840.0	0.3
WINTER	5.9	840.0	0.1
SPRING	3.0	18.4	0.2
SUMMER	1.6	8.8	0.2

measure of how well CutS performs. The rough annual schedule developed by the First District leaves 19 statuses unfilled, shown in Table 2. CutS annual schedule leaves only three statuses unfilled, shown in Table 3, a marked improvement.

D. EQUITABLE DISTRIBUTION OF PATROL STATUSES

Another measure of effectiveness is how equitably the patrol statuses are distributed among the cutters. CutS is required to develop quarterly schedules which fairly distribute the number of patrol statuses assigned to each cutter. (This is also a goal which the district scheduler uses.) The number of patrols assigned to each cutter per quarter, along with the yearly totals, are shown in Table 7 for the rough quarterly schedules of the First District. Table 8 displays the same information for the quarterly schedules generated by CutS. It is difficult to determine any significant differences between the schedules by looking at the respective tables; consequently, the standard deviations are calculated. The standard deviation for yearly number of patrols assigned by the First District (the WTGB class is not included in the calculations) is 2.55 patrols, while the standard deviation for the CutS' schedule is 2.40 patrols. A more impressive result is noted in the third and fourth quarters. These two quarters have the greatest number of cutters available for patrols, hence there is more flexibility in scheduling cutters to meet the requirements. The standard deviation for the First District's third quarter schedule (including the WTGB class) is 1.41 patrols, while that of CutS is .77 patrols. The fourth quarter's schedules display similar standard deviations with the district's schedule being 1.83 patrols, while the schedule proposed by CutS has a standard deviation of .57 patrols. CutS is able to generate schedules which more evenly distribute patrol statuses among the cutters.

TABLE 7

NUMBER OF PATROLS MANUALLY ASSIGNED PER CUTTER,

FIRST DISTRICT

This table displays the number of patrols per quarter each cutter was assigned by the First District Scheduler. The table shows how equitably the manually developed schedule distributed the patrols by comparing entries within the same column.

	1st	2nd	3rd	4th	Total
ADAK	4	4	4	4	16
WRANGEL	5	6	4	1	16
SANIBEL	5	5	6	5	21
MONOMOY	3	5	3	6	17
JEFF-ISL	5	4	5	4	18
GRAND-ISL	5	2	5	3	15
BAIN-ISL	5	7	5	6	23
PT-BONITA	5	0	2	7	14
PT-FRANCIS	3	6	5	2	16
PT-JACKSON	6	4	2	3	15
PT-HANNON	4	6	5	4	19
PT-TURNER	4	4	2	6	16
PT-WELLS	5	4	6	3	18
PENOBSCOT	0	0	4	2	6
STURGEON	0	0	4	1	5
THUNDER	0	0	2	4	6

TABLE 8

NUMBER OF PATROLS ASSIGNED PER CUTTER, OPTIMIZATION MODEL

This table shows the number of patrols assigned to each cutter per quarter by CutS. This table indicates how equitably CutS was able to distribute the patrols by comparing entries within the same column. Any value below 4 was a result of limited cutter availability and should not be considered as inequitable. Contrasting these results to Table 7 shows CutS' superiority to equitably distribute patrol assignments.

	1st	2nd	3rd	4th	Total
ADAK	4	3	4	4	15
WRANGEL	6	6	4	4	20
SANIBEL	6	5	5	4	20
MONOMOY	3	6	4	4	17
JEFF-ISL	6	6	4	4	20
GRAND-ISL	6	3	6	6	21
BAIN-ISL	6	6	4	4	20
PT-BONITA	4	1	4	4	13
PT-FRANCIS	6	6	4	4	20
PT-JACKSON	4	5	4	3	16
PT-HANNON	4	6	4	4	18
PT-TURNER	6	4	4	4	18
PT-WELLS	4	5	4	4	17
PENOBSCOT	0	0	4	4	8
STURGEON	0	0	4	4	8
THUNDER	0	0	2	4	6

E. ASSIGNMENT OF PATROL STATUSES

The final measure of effectiveness is the ability to assign patrols to cutters within the geographic area of the cutter's homeport. While the district scheduler makes patrol assignments with this in mind, the scheduler does not actually calculate the transit times of the cutters. CutS, on the other hand, minimizes the objective function value, which is based on the total transit time of the cutters. The objective function value of the 12-week schedule produced by the First District for the Winter quarter is 458, while the objective function value of the schedule produced by CutS is 310. These objective function values are based on the cost of specific patrol assignments and on penalties incurred for missing required patrols. In order to get a better comparison between the First District and CutS, the four weeks for which no penalties are incurred for missing required patrols are compared. The objective function value associated with the First District's schedule is 105, while that of the schedule produced by CutS is only 83.

V. CONCLUSIONS

CutS produces quarterly schedules in a reasonable amount of time on a personal computer which are superior to manually developed schedules in all areas of concern: schedules developed by CutS miss significantly fewer required patrols, the schedules assign patrols to cutters which are closer to the cutter's homeport, and CutS' schedules more equitably distribute the number of patrols each cutter receives. CutS develops face-valid schedules which can be implemented without any changes; however, the real benefit of the model is that it will assist the district scheduler to quickly develop feasible schedules. This will give the scheduler an opportunity to produce quarterly schedules of a higher quality than has been previously possible.

CutS was demonstrated for the First District Scheduler and members of his staff at the Coast Guard's Research and Development Center. The scheduler brought a quarterly schedule he had spent many hours developing. He was not pleased with his results because of a high number of required patrol statuses missed. He was able to input the data required for CutS and obtain a quarterly schedule, which did not miss any required patrols, in under 30 minutes. This demonstration resulted in a push for immediate implementation.

CutS can be improved by adding the capabilities of a spreadsheet to the model. The Coast Guard's Research and Development Center has developed a spreadsheet and database to be used with the Area scheduling model under development. The Research and Development Center intends to adapt this interface for use with CutS.

APPENDIX A

QUARTERLY SCHEDULES DEVELOPED BY CutS

The following are quarterly schedules created by CutS, solved within 5% of optimal using the initial data listed in Table 3. The left hand margin has the cutter's name, and the top margin lists the week the cutter is to have the assigned status. Week 1 commences on the Monday of the first week of the first quarter of a fiscal year and continues until the following Monday. Each quarterly schedule includes the last two weeks of the previous quarter.

1ST QUARTER

	51	52	1	2	3
ADAK	B-2G	B-2G	C	C	UNAVAL
WRANGEL	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
SANIBEL	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
MONOMOY	C	B-2SAR	UNAVAL	UNAVAL	UNAVAL
JEFF-ISL	C	C	B-2M	B-2SAR	C
GRAND-ISL	C	C	B-2SAR	B-12	B-2SAR
BAIN-ISL	B-2G	C	B-2NY	B-12	B-2NY
PT-BONITA	B-2NY	C	B-2G	B-2NY	C
PT-FRANCIS	B-12	B-2NY	B-12	B-2G	B-2G
PT-JACKSON	C	C	B-2G	C	C
PT-HANNON	B-2M	B-2M	B-12	B-2M	B-2M
PT-TURNER	B-2SAR	B-12	B-12	B-2G	B-2G
PT-WELLS	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
PENOBSCOT	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
STURGEON	B-12	B-12	UNAVAL	UNAVAL	UNAVAL
THUNDER	B-12	B-12	UNAVAL	UNAVAL	UNAVAL

	4	5	6	7	8
ADAK	C	C	B-2NY	C	C
WRANGEL	B-2M	B-12	B-2SAR	B-2M	C
SANIBEL	B-2SAR	B-2G	C	C	B-2SAR
MONOMOY	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
JEFF-ISL	C	B-2SAR	B-2M	C	C
GRAND-ISL	B-2G	C	C	B-2SAR	C
BAIN-ISL	B-2NY	C	C	B-2NY	C
PT-BONITA	C	B-2NY	C	C	B-2NY
PT-FRANCIS	C	C	B-2G	B-2G	C
PT-JACKSON	B-2G	B-12	C	C	B-2G
PT-HANNON	B-12	B-2M	C	C	B-2M
PT-TURNER	C	C	B-2G	B-2G	C
PT-WELLS	UNAVAL	B-2G	C	C	B-2G
PENOBSCOT	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
STURGEON	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
THUNDER	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL

	9	10	11	12	13
ADAK	B-2NY	B-12	B-2NY	B-2NY	B-12
WRANGEL	C	B-2SAR	B-2M	B-12	B-2M
SANIBEL	B-2G	C	C	B-2G	B-2SAR
MONOMOY	B-2SAR	C	C	B-2SAR	B-2G
JEFF-ISL	B-2M	C	C	B-2M	B-12
GRAND-ISL	C	B-2M	B-2SAR	C	C
BAIN-ISL	C	B-2NY	C	C	B-2NY
PT-BONITA	C	C	B-12	C	C
PT-FRANCIS	C	B-2G	C	C	B-2G
PT-JACKSON	C	C	B-2G	C	C
PT-HANNON	C	C	B-12	C	C
PT-TURNER	C	B-2G	B-2G	C	C
PT-WELLS	B-2G	C	C	B-2G	B-12
PENOBSCOT	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
STURGEON	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
THUNDER	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL

2ND QUARTER

	12	13	14	15	16
ADAK	B-2NY	B-12	C	C	B-2NY
WRANGEL	B-12	B-2M	B-2SAR	B-12	B-2M
SANIBEL	B-2G	B-2SAR	C	C	B-2G
MONOMOY	B-2SAR	B-2G	C	C	B-2SAR
JEFF-ISL	B-2M	B-12	B-2M	B-2SAR	C
GRAND-ISL	C	C	UNAVAL	UNAVAL	UNAVAL
BAIN-ISL	C	B-2NY	B-12	B-2NY	C
PT-BONITA	C	C	B-2NY	UNAVAL	UNAVAL
PT-FRANCIS	C	B-2G	C	C	B-12
PT-JACKSON	C	C	B-2G	B-2G	C
PT-HANNON	C	C	B-12	B-2M	C
PT-TURNER	C	C	B-2G	B-2G	C
PT-WELLS	B-2G	B-12	C	C	B-2G
PENOBSCOT	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
STURGEON	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
THUNDER	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL

	17	18	19	20	21
ADAK	B-2NY	C	C	B-2NY	UNAVAL
WRANGEL	B-2M	C	C	B-2SAR	B-2M
SANIBEL	B-2SAR	C	C	B-2G	C
MONOMOY	C	C	B-2SAR	B-12	B-2SAR
JEFF-ISL	C	B-2M	B-2G	C	C
GRAND-ISL	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
BAIN-ISL	C	B-2SAR	B-2NY	C	C
PT-BONITA	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
PT-FRANCIS	B-2G	B-2NY	C	C	B-2G
PT-JACKSON	C	B-2G	C	C	B-2G
PT-HANNON	C	B-12	B-2M	B-2M	C
PT-TURNER	C	B-2G	B-2G	UNAVAL	UNAVAL
PT-WELLS	B-2G	C	C	B-2G	B-2NY
PENOBSCOT	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
STURGEON	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
THUNDER	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL

	22	23	24	25	26
ADAK	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
WRANGEL	C	C	B-2M	C	C
SANIBEL	C	B-2G	B-2SAR	C	C
MONOMOY	B-2G	C	C	B-2SAR	B-2G
JEFF-ISL	B-2M	B-2SAR	UNAVAL	UNAVAL	UNAVAL
GRAND-ISL	B-2SAR	B-2G	C	C	B-2SAR
BAIN-ISL	B-2NY	B-2NY	C	C	B-2NY
PT-BONITA	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
PT-FRANCIS	B-2G	C	C	B-2NY	B-2G
PT-JACKSON	C	C	B-2G	C	C
PT-HANNON	C	B-2M	B-12	B-2M	B-2M
PT-TURNER	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
PT-WELLS	C	C	B-2NY	C	C
PENOBSCOT	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
STURGEON	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
THUNDER	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL

3RD QUARTER

	25	26	27	28	29
ADAK	UNAVAL	UNAVAL	UNAVAL	B-2NY	B-2NY
WRANGEL	C	C	B-2M	B-2M	B-12
SANIBEL	C	C	B-2G	B-2SAR	C
MONOMOY	B-2SAR	B-2G	B-12	UNAVAL	B-2G
JEFF-ISL	UNAVAL	UNAVAL	UNAVAL	C	C
GRAND-ISL	C	B-2SAR	B-2G	C	C
BAIN-ISL	C	B-2NY	B-2NY	C	C
PT-BONITA	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
PT-FRANCIS	B-2NY	B-2G	C	C	B-2G
PT-JACKSON	C	C	UNAVAL	C	C
PT-HANNON	B-2M	B-2M	C	C	B-2M
PT-TURNER	UNAVAL	UNAVAL	UNAVAL	B-2G	B-2SAR
PT-WELLS	C	C	B-2SAR	B-2G	B-12
PENOBSCOT	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
STURGEON	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
THUNDER	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL

	30	31	32	33	34
ADAK	B-12	B-2G	B-2NY	C	C
WRANGEL	B-12	C	C	B-12	C
SANIBEL	C	B-2SAR	B-12	B-12	B-12
MONOMOY	C	C	B-2G	B-2SAR	B-12
JEFF-ISL	B-12	B-12	C	C	B-2M
GRAND-ISL	B-2G	C	C	B-2G	C
BAIN-ISL	B-2NY	B-12	B-2SAR	B-12	C
PT-BONITA	UNAVAL	UNAVAL	UNAVAL	B-2G	C
PT-FRANCIS	B-2SAR	B-12	C	C	B-2SAR
PT-JACKSON	B-2G	B-2G	B-12	UNAVAL	B-2G
PT-HANNON	B-2M	C	C	B-2M	C
PT-TURNER	C	C	B-2G	C	C
PT-WELLS	B-12	C	C	B-12	B-2G
PENOBSCOT	UNAVAL	B-2NY	B-12	B-2NY	UNAVAL
STURGEON	UNAVAL	C	C	UNAVAL	B-2NY
THUNDER	UNAVAL	B-2M	B-2M	UNAVAL	UNAVAL

	35	36	37	38	39
ADAK	B-12	C	C	UNAVAL	UNAVAL
WRANGEL	C	UNAVAL	B-12	B-2M	B-2M
SANIBEL	B-2G	B-2G	C	C	B-12
MONOMOY	C	C	B-2G	C	C
JEFF-ISL	B-2M	B-12	B-2M	B-2SAR	B-12
GRAND-ISL	C	B-2SAR	B-12	B-2G	B-2SAR
BAIN-ISL	C	B-12	B-2SAR	C	C
PT-BONITA	C	B-2G	B-12	B-2G	B-2G
PT-FRANCIS	B-2G	UNAVAL	UNAVAL	UNAVAL	UNAVAL
PT-JACKSON	B-2SAR	C	C	UNAVAL	UNAVAL
PT-HANNON	C	B-2M	C	C	B-12
PT-TURNER	UNAVAL	UNAVAL	UNAVAL	UNAVAL	B-2G
PT-WELLS	C	C	B-2G	C	C
PENOBSCOT	B-12	B-2NY	B-2NY	C	C
STURGEON	B-2NY	C	C	B-2NY	B-2NY
THUNDER	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL

4TH QUARTER

	38	39	40	41	42
ADAK	UNAVAL	UNAVAL	UNAVAL	B-12	B-12
WRANGEL	B-2M	B-2M	UNAVAL	B-2G	C
SANIBEL	C	B-12	C	C	B-2G
MONOMOY	C	C	B-2G	B-12	B-2G
JEFF-ISL	B-2SAR	B-12	C	C	B-2M
GRAND-ISL	B-2G	B-2SAR	UNAVAL	B-2SAR	B-12
BAIN-ISL	C	C	B-12	B-2NY	B-12
PT-BONITA	B-2G	B-2G	C	C	B-2SAR
PT-FRANCIS	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
PT-JACKSON	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
PT-HANNON	C	B-12	B-2M	B-2M	UNAVAL
PT-TURNER	UNAVAL	B-2G	B-2G	B-12	C
PT-WELLS	C	C	B-2SAR	B-2G	C
PENOBSCOT	C	C	B-2NY	B-12	B-2NY
STURGEON	B-2NY	B-2NY	C	C	UNAVAL
THUNDER	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL

	43	44	45	46	47
ADAK	B-12	B-2NY	B-2NY	B-12	B-2NY
WRANGEL	C	B-2M	B-2M	UNAVAL	UNAVAL
SANIBEL	C	C	B-2SAR	C	C
MONOMOY	B-2SAR	B-12	C	C	B-2G
JEFF-ISL	B-2M	C	C	UNAVAL	UNAVAL
GRAND-ISL	B-2G	B-2G	C	C	B-2SAR
BAIN-ISL	B-2G	C	C	B-2SAR	C
PT-BONITA	B-12	C	C	B-2G	UNAVAL
PT-FRANCIS	UNAVAL	UNAVAL	B-2G	B-2G	B-12
PT-JACKSON	UNAVAL	UNAVAL	UNAVAL	C	C
PT-HANNON	C	C	UNAVAL	UNAVAL	UNAVAL
PT-TURNER	C	B-2SAR	C	C	B-2G
PT-WELLS	C	B-2G	B-2G	UNAVAL	UNAVAL
PENOBSCOT	B-2NY	C	C	B-2NY	C
STURGEON	UNAVAL	UNAVAL	UNAVAL	UNAVAL	B-12
THUNDER	UNAVAL	C	C	B-2M	B-2M

	48	49	50	51	52
ADAK	C	C	B-2NY	C	C
WRANGEL	UNAVAL	B-2G	UNAVAL	UNAVAL	UNAVAL
SANIBEL	B-2G	B-2SAR	UNAVAL	UNAVAL	UNAVAL
MONOMOY	C	C	B-12	C	C
JEFF-ISL	UNAVAL	B-12	B-12	B-2G	B-2SAR
GRAND-ISL	B-2M	B-12	B-2G	C	C
BAIN-ISL	C	B-12	C	C	B-2G
PT-BONITA	B-12	B-12	B-2SAR	B-2G	B-12
PT-FRANCIS	B-12	B-2G	B-2G	C	C
PT-JACKSON	B-2G	C	C	B-2SAR	B-2G
PT-HANNON	UNAVAL	UNAVAL	B-12	B-2M	B-2M
PT-TURNER	B-2SAR	C	C	B-12	B-12
PT-WELLS	UNAVAL	UNAVAL	UNAVAL	UNAVAL	UNAVAL
PENOBSCOT	C	UNAVAL	UNAVAL	UNAVAL	UNAVAL
STURGEON	B-2NY	B-2NY	B-12	B-2NY	B-2NY
THUNDER	B-12	B-2M	B-2M	C	C

APPENDIX B

FALL VERSION OF CutS

```
$TITLE  FIRST DISTRICT SCHEDULING MODEL, 1st Quarter

$OFFUPPER OFFSYMLIST OFFSYMXREF

OPTIONS
    LIMCOL = 0, LIMROW  = 0, SOLPRINT = OFF, RESLIM = 5000,
    OPTCR = 0.05, INTEGER1 = 1, ITERLIM = 100000 ;


$ONTEXT
  Original by:      LT. Robert A. Farmer, USCG  date 05/10/92
                    Dr. Robert F. Dell, Naval Postgraduate
        School, Monterey, California

Description:
     This is an optimization based model to solve the First District's
cutter scheduling problem.  The program needs to be run with GAMS and an
integer solver.  All of the trial runs of this model were run with the
integer solver XA.
     The indices greatly affect the number of variables created, which in
turn affects the ability of the solver to find a reasonable solution.
Care should be exercised when adding new elements to the indices.
     This model will develop the first quarter schedule for the First Coast
Guard District.  The status of the cutters represents the following:

  B-2M   - vessel assigned to the Gulf of Maine OPAREA
  B-2G   - vessel assigned to the Georges Bank OPAREA
  B-2NY  - vessel assigned to the New York Bight OPAREA
  B-2SAR - vessel assigned as the SAR standby cutter
  C      - vessel in maintenance status

**NOTE** B-12 is not included in the index for vessel statuses, but it
will be included in the final output by the print statement at the end of
this file.
     Cutters are assigned by weeks, with week 1 being the first Monday in
the first quarter of a fiscal year.  No days were included in the model
for the transit time of the cutter to the OPAREA.
     If any changes are made to the sets listed below, it is imperative the
same changes be made everywhere the set is used.  For example if a new
cutter the NEVERSAIL is added, NEVERSAIL must be added to SHIPAVAL,
CHARLIE, etc.
$OFFTEXT


 SETS  I  name of the cutter
         / ADAK, WRANGEL, SANIBEL, MONOMOY, JEFF-ISL, GRAND-ISL, BAIN-ISL,
           PT-BONITA, PT-FRANCIS, PT-JACKSON, PT-HANNON,  PT-TURNER,
           PT-WELLS, PENOBSCOT, STURGEON, THUNDER/

       K  status of cutter
         /B-2M, B-2G, B-2NY, B-2SAR, C/
```

```
        T  week the cutter assumes the assigned status
         /51, 52, 1*13 /

$ONTEXT
The numbers in the cost table represent the transit time from
the cutter's homeport to the OPAREA of the patrol statuses.
$OFFTEXT

TABLE  COST(I,k)  cost of scheduling cutter I for patrol k
                  B-2M  B-2G  B-2NY  B-2SAR    C
ADAK               17     9     3      9       2
WRANGEL             3     6    17      6       2
SANIBEL             6     3     6      3       2
MONOMOY             6     3     6      3       2
JEFF-ISL            3     6    17      6       2
GRAND-ISL           3     3    11      3       2
BAIN-ISL           17     9     3      9       2
PT-BONITA          18     7     4      7       2
PT-FRANCIS         14     4     4      4       2
PT-JACKSON         18     5     5      5       2
PT-HANNON           4    11    21     11       2
PT-TURNER          11     4     7      4       2
PT-WELLS           14     5     4      5       2
PENOBSCOT          36    18     6     18       2
STURGEON           36    18     6     18       2
THUNDER             6    18    36     18       2 ;


$ONTEXT
  The matrix SHIPAVAL indicates which weeks a cutter is
  available to be assigned patrols.  This matrix needs to
  be updated to reflect the actual data prior to running the
  model.  A  1  indicates the cutter is available for patrol
  assignment and a  0  indicates it is not.
$OFFTEXT


TABLE  SHIPAVAL(I,T) weeks cutter i is available for patrols

            51  52  1  2  3  4  5  6  7  8  9  10  11  12  13
ADAK         1   1  1  1  0  1  1  1  1  1  1   1   1   1   1
WRANGEL      0   0  0  0  0  1  1  1  1  1  1   1   1   1   1
SANIBEL      0   0  0  0  0  1  1  1  1  1  1   1   1   1   1
MONOMOY      1   1  0  0  0  0  0  0  0  0  1   1   1   1   1
JEFF-ISL     1   1  1  1  1  1  1  1  1  1  1   1   1   1   1
GRAND-ISL    1   1  1  1  1  1  1  1  1  1  1   1   1   1   1
BAIN-ISL     1   1  1  1  1  1  1  1  1  1  1   1   1   1   1
PT-BONITA    1   1  1  1  1  1  1  1  1  1  1   1   1   1   1
PT-FRANCIS   1   1  1  1  1  1  1  1  1  1  1   1   1   1   1
PT-JACKSON   1   1  1  1  1  1  1  1  1  1  1   1   1   1   1
PT-HANNON    1   1  1  1  1  1  1  1  1  1  1   1   1   1   1
PT-TURNER    1   1  1  1  1  1  1  1  1  1  1   1   1   1   1
PT-WELLS     0   0  0  0  0  0  1  1  1  1  1   1   1   1   1
PENOBSCOT    0   0  0  0  0  0  0  0  0  0  0   0   0   0   0
STURGEON     1   1  0  0  0  0  0  0  0  0  0   0   0   0   0
THUNDER      1   1  0  0  0  0  0  0  0  0  0   0   0   0   0  ;


PARAMETER
```

```
REQ(K) required number of patrol boats for each OPAREA
       / B-2M     1
         B-2G     2
         B-2NY    1
         B-2SAR   1
         C        0 /

STAT(K) patrol status for variables to clean up program
       / B-2M    1
         B-2G    1
         B-2NY   1
         B-2SAR  1
         C       0 /

$ONTEXT
Penalties greatly affect the model.  These penalties were
developed from the specific cost matrix above.  They were
established to be reasonably larger than any of the costs
of the patrols.  The penalty for missing a B-2G status was
slightly less than the other penalties because two cutters
are assigned to this OPAREA.
$OFFTEXT

PENALTY(K) penalty for not meeting minimum requirements
       / B-2M     40
         B-2G     30
         B-2NY    40
         B-2SAR   40
         C        40 /

$ONTEXT
The array below represents the number of weeks of charlie
status a cutter is to be assigned during the quarter.  Do
not include any charlie statuses from previous quarters, nor
any charlie statuses accounted for in the SHIPAVAL matrix.
**NOTE** ALL NUMBERS IN THE ARRAY BELOW SHOULD BE EVEN.
If more charlie periods are entered for the quarter than there
are weeks available for patrol assignments as listed in
SHIPAVAL, the model will not solve and report the problem
is infeasible.
$OFFTEXT


CHARLIE(I) weeks of Charlie for the quarter for each cutter
       / ADAK            6
         WRANGEL         2
         SANIBEL         4
         MONOMOY         2
         JEFF-ISL        6
         GRAND-ISL       6
         BAIN-ISL        6
         PT-BONITA       8
         PT-FRANCIS      6
         PT-JACKSON      8
         PT-HANNON       6
         PT-TURNER       6
         PT-WELLS        4
         PENOBSCOT       0
         STURGEON        0
         THUNDER         0 /
```

```
WTGB(I) if a cutter is a WTGB
       / ADAK             0
         WRANGEL          0
         SANIBEL          0
         MONOMOY          0
         JEFF-ISL         0
         GRAND-ISL        0
         BAIN-ISL         0
         PT-BONITA        0
         PT-FRANCIS       0
         PT-JACKSON       0
         PT-HANNON        0
         PT-TURNER        0
         PT-WELLS         0
         PENOBSCOT        1
         STURGEON         1
         THUNDER          1 /

WPB(I) if a cutter is a 82 foot patrol boat
       / ADAK             0
         WRANGEL          0
         SANIBEL          0
         MONOMOY          0
         JEFF-ISL         0
         GRAND-ISL        0
         BAIN-ISL         0
         PT-BONITA        1
         PT-FRANCIS       1
         PT-JACKSON       1
         PT-HANNON        1
         PT-TURNER        1
         PT-WELLS         1
         PENOBSCOT        0
         STURGEON         0
         THUNDER          0 / ;

$ONTEXT
These penalties are for the elastic variables used in
the model.  Once again penalties greatly affect the
performance of the model.  PEN2 was chosen to be comparable
with the penalties for not filling all patrol statuses.
PEN3 is the penalty for the elastic variable of the fairness constraints.
It was chosen to allow a cutter to receive an extra patrol only if the
OPAREA is reasonably close to the cutter's homeport.
$OFFTEXT


SCALARS PEN2 penalty for temporary charlie variables /40/
        PEN3 penalty for fairness constraints /25/ ;


$ONTEXT
The following four parameters calculate the number of
patrols each cutter should receive in order for there
to be an equal workload.  If for some reason a cutter
should receive a different amount it can be easily done.
For example, say the cutter WRANGEL was assigned more
patrols last quarter than any other cutter, and it should be given rest
this quarter.  Right under
  FAIRHI(I) = FAIR + 2.0 ;
put
```

```
  FAIRHI("WRANGEL") = maximum number of patrols desired ;
**NOTE** If you assign a FAIRHI value which is less
then the FAIRLO value, the model will not solve and
report the problem is infeasible.  To insure this
does not happen, first run the model and find the value
for FAIRLO from the LST file.  Make the desired changes
and run tne model again.
$OFFTEXT

PARAMETER REQTOT total of the requirements ;
     REQTOT = SUM(K, REQ(K)) ;

PARAMETER FAIR equal number of patrols for each cutter;

     FAIR = ROUND(REQTOT*(CARD(T)-2.0)/CARD(I)) ;

PARAMETER FAIRLO(I) lower limit on number of patrols;

     FAIRLO(I) = SUM(T$(ORD(T) GT 2), SHIPAVAL(I,T)) -
     CHARLIE(I) ;
     FAIRLO(I)$(FAIRLO(I) LT 0) = 0 ;
     FAIRLO(I)$(FAIRLO(I) GT FAIR) = FAIR ;

PARAMETER FAIRHI(I) upper limit on number of patrols cutters can be
assigned ;

     FAIRHI(I) = FAIR + 2.0 ;

VARIABLES

X(I,K,T)  1 if cutter i assigned status k for week 1                 0
otherwise
TC(I,T)   elastic variable to allow for no more than 3 "C" in
a row
E(K,T)    elastic variables for unfilled status
TC2(I,T)  elastic variable for consecutive charlie periods
LIM(I)    elastic variable for fairness constraints
TOTCOST   objective variable (total cost) ;

BINARY VARIABLE X ;
POSITIVE VARIABLE TC ;
POSITIVE VARIABLE E ;
POSITIVE VARIABLE TC2 ;
POSITIVE VARIABLE LIM ;

$ONTEXT
The .UP variables place an upper limit on the number of times
the constraints in which the variable is used may be violated.
$OFFTEXT

TC.UP(I,T) = 1.0 ;
LIM.UP(I) = 1.0 ;

X.FX(I,K,"51") = 0.0 ;
X.FX(I,K,"52") = 0.0 ;

$ONTEXT
Below is the mechanism used to inform the model of the patrol
assignments for the last two weeks of the previous quarter.
Be sure the matrix SHIPAVAL also accurately reflects the last
two weeks of the previous quarter.  Only input the statuses
```

```
listed under index k above.  In particular "UNAVAL" and
"B-12" should not be entered.  A patrol can be fixed for any
week of the quarter simply by using the same format as below
with the cutter's name, the patrol, and the week the cutter is
to have the patrol.  It is important to remember fixing variables can
adversely affect the solution time of the model.
**NOTE**  The patrol assignments for the last two weeks of the previous
quarter must be properly filled in along with SHIPAVAL in order for the
model to return a reasonable schedule.
$OFFTEXT

X.FX("ADAK","B-2G","51") = 1.0 ;
X.FX("MONOMOY","C","51") = 1.0 ;
X.FX("JEFF-ISL","C","51") = 1.0 ;
X.FX("GRAND-ISL","C","51") = 1.0 ;
X.FX("BAIN-ISL","B-2G","51") = 1.0 ;
X.FX("PT-BONITA","B-2NY","51") = 1.0 ;
X.FX("PT-JACKSON","C","51") = 1.0 ;
X.FX("PT-HANNON","B-2M","51") = 1.0 ;
X.FX("PT-TURNER","B-2SAR","51") = 1.0 ;
X.FX("ADAK","B-2G","52") = 1.0 ;
X.FX("MONOMOY","B-2SAR","52") = 1.0 ;
X.FX("JEFF-ISL","C","52") = 1.0 ;
X.FX("GRAND-ISL","C","52") = 1.0 ;
X.FX("BAIN-ISL","C","52") = 1.0 ;
X.FX("PT-BONITA","C","52") = 1.0 ;
X.FX("PT-FRANCIS","B-2NY","52") = 1.0 ;
X.FX("PT-JACKSON","C","52") = 1.0 ;
X.FX("PT-HANNON","B-2M","52") = 1.0 ;
X.UP(I,"B-2SAR",T)$WTGB(I) = 0.0 ;
X.UP(I,"B-2SAR",T)$(WPB(I)$(ORD(T) GT 2)) = 0.0 ;

EQUATIONS

COVREQ(K,T)       constraint to meet minimum coverage for status k
MINCHARL(I)       constraint to meet minimum amount of charlie time
WEEKLY(I,T)       cannot assign a vessel more than 1 status
CONCHAR1(I,T)     charlie periods need to be in consecutive periods
CHAR2(I,T)        consecutive charlie periods should not exceed 2
LOWLIM(I)         sum of patrol status cannot be less than lower limit
UPPERLIM(I)       sum of patrol status cannot be more than upper limit
NOREPEAT(I,T)     cannot have more than two consecutive patrols
NOSAR(I,T)        cannot have consecutive SAR patrols
TOTCOSTE ;

TOTCOSTE..

     TOTCOST =E= SUM((I,K,T)$((ORD(T) GT 2)$SHIPAVAL(I,T)),
     X(I,K,T)*COST(I,K)) + SUM((K,T)$(ORD(T) GT 2),
     PENALTY(K)*E(K,T)) + SUM(I, LIM(I)*PEN3) +
     SUM((I,T)$((ORD(T) GT 2)$SHIPAVAL(I,T)), PEN2*TC(I,T)) +
     SUM((I,T)$((ORD(T) GT 2)$SHIPAVAL(I,T)), TC2(I,T)*PEN2) ;
     COVREQ(K,T)$((ORD(T) GT 2)$STAT(K))..
     SUM(I$SHIPAVAL(I,T), X(I,K,T))  =E=  REQ(K) - E(K,T) ;

WEEKLY(I,T)$((ORD(T) GT 2)$SHIPAVAL(I,T))..
      SUM(K, X(I,K,T)) =L= 1.0 ;

MINCHARL(I)..
      SUM(T$((ORD(T) GT 2)$SHIPAVAL(I,T)), X(I,"C",T))
      =G= CHARLIE(I) ;
```

```
CONCHAR1(I,T)$((ORD(T) GT 2)$(CHARLIE(I) GT 1) $SHIPAVAL(I,T))..
     X(I,"C",T)$SHIPAVAL(I,T) - X(I,"C",T-1)$SHIPAVAL(I,T-1) -
     X(I,"C",T+1)$SHIPAVAL(I,T+1) - TC2(I,T)$SHIPAVAL(I,T)
     =L= 0 ;

CHAR2(I,T)$((ORD(T) GT 2)$(CHARLIE(I) GT 1)$SHIPAVAL(I,T))..
     X(I,"C",T)$SHIPAVAL(I,T) + X(I,"C",T-1)$SHIPAVAL(I,T-1) +
    X(I,"C",T-2)$SHIPAVAL(I,T-2) =L= 2 + TC(I,T)$SHIPAVAL(I,T);

LOWLIM(I)..
     SUM((K,T)$((ORD(T) GT 2)$STAT(K)$SHIPAVAL(I,T)), X(I,K,T)) =G=
    FAIRLO(I) - LIM(I) ;

UPPERLIM(I)..
     SUM((K,T)$((ORD(T) GT 2)$STAT(K)$SHIPAVAL(I,T)), X(I,K,T)) =L=
    FAIRHI(I) + LIM(I) ;

NOREPEAT(I,T)$((ORD(T) GT 2)$SHIPAVAL(I,T))..
     SUM(K$STAT(K), X(I,K,T)$SHIPAVAL(I,T) +
    X(I,K,T-1)$SHIPAVAL(I,T-1) + X(I,K,T-2)$SHIPAVAL(I,T-2)) =L= 2 ;

NOSAR(I,T)$((ORD(T) GT 2)$SHIPAVAL(I,T)$(WTGB(I) LT 1))..
     X(I,"B-2SAR",T)$SHIPAVAL(I,T) +
    X(I,"B-2SAR",T-1)$SHIPAVAL(I,T-1) =L= 1 ;

MODEL ONE /ALL/ ;

SOLVE ONE USING MIP MINIMIZING TOTCOST ;

DISPLAY X.L, E.L, TC.L, TC2.L, LIM.L, REQTOT, FAIRLO, FAIRHI, FAIR;

$ONTEXT
The parameters break down the total costs associated with
the model into the coverage costs and the costs associated
with penalties.
$OFFTEXT

PARAMETER COVCOST coverage cost of the objective function ;
     COVCOST = SUM((I,K,T), X.L(I,K,T)*COST(I,K)) ;

PARAMETER PENCOST penalty cost of the objective function ;
     PENCOST  =  SUM((K,T),  PENALTY(K)*E.L(K,T))  +  SUM(I,
     LIM.L(I)*PEN3) + SUM((I,T), TC.L(I,T)*PEN2) +
     SUM((I,T), TC2.L(I,T)*PEN2) ;

DISPLAY COVCOST, PENCOST ;

$ONTEXT
The following code generates the quarter employment schedule
report into the file SKED1D.put
$OFFTEXT

FILE SKED1D;
PUT SKED1D;
SKED1D.NW = 12;
SKED1D.TW = 12;
PUT '1ST QUARTER'//
     @15, LOOP(T,
        IF (ORD(T) LT 6,
           PUT T.TL);
     );
```

```
LOOP(I, PUT / I.TL;
   LOOP(T,
      IF (ORD(T) LT 6,
         IF (SHIPAVAL(I,T) EQ 0,
            PUT 'UNAVAL';
         ELSE
            IF (SUM(K, X.L(I,K,T)) EQ 0,
               PUT 'B-12';
            );
         );
         LOOP(K,
            IF (X.L(I,K,T) EQ 1,
               PUT K.TL);
         );
      );
   );
);
PUT //
@15, LOOP(T,
   IF (ORD(T) GT 5,
      IF (ORD(T) LT 11,
         PUT T.TL);
   );
);
LOOP(I, PUT / I.TL;
   LOOP(T,
      IF (ORD(T) GT 5,
         IF (ORD(T) LT 11,
            IF (SHIPAVAL(I,T) EQ 0,
               PUT 'UNAVAL';
            ELSE
               IF (SUM(K, X.L(I,K,T)) EQ 0,
                  PUT 'B-12';
               );
            );
            LOOP(K,
               IF (X.L(I,K,T) EQ 1,
                  PUT K.TL);
            );
         );
      );
   );
);
PUT //
@15, LOOP(T,
   IF (ORD(T) GT 10,
      PUT T.TL);
);
LOOP(I, PUT / I.TL;
   LOOP(T,
      IF (ORD(T) GT 10,
         IF (SHIPAVAL(I,T) EQ 0,
            PUT 'UNAVAL';
         ELSE
            IF (SUM(K, X.L(I,K,T)) EQ 0,
               PUT 'B-12';
            );
         );
         LOOP(K,
            IF (X.L(I,K,T) EQ 1,
               PUT K.TL);
```

```
               );
            );
         );
      );

$ONTEXT
       The following code creates the input file for interface with a
spread sheet.  The name of the file is FAL1.PUT.
$OFFTEXT


FILE FAL1 ;
PUT FAL1 ;
FAL1.PC = 5 ;
LOOP(T,
   LOOP(I,
      LOOP(K,
         IF (X.L(I,K,T) EQ 1,
            PUT / I.TL, T.TL, K.TL);
      );
         IF (SHIPAVAL(I,T) EQ 0,
            PUT / I.TL, T.TL, 'UNAVAL';
         ELSE
            IF (SUM (K, X.L(I,K,T)) EQ 0,
               PUT / I.TL, T.TL, 'B-12';
            );
         );
   ); );
```

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