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A logistics model of Coast Guard buoy tending operations

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ABSTRACT

A discrete event simulation model has been constructed in SIMSCRIPT II.5 for use in establishing buoy tender system requirements. Since each tender may have characteristics which limit its ability to travel in some waters, the model must plan the tender's travel itinerary. In addition, the model uses a set of tools that automatically generate meta-models for verification.

1. INTRODUCTION

A major responsibility of the Coast Guard is to maintain a system of navigational aids to mariners within the territorial waters of the United States. These aids, buoys and lighthouses, mark navigable waters and warn of submerged dangers such as rocks, sandbars, and sunken vessels. The aids are maintained by a fleet of buoy tenders ranging in size from 65 to 180 feet. The maintenance goal is to keep the aids operating at all times, since a disaster could result if an aid were not positioned or operating properly.

There are predominantly four types of aids to navigation (ATON). They are lights, daybeacons, lighted buoys, and unlighted buoys. In addition, there are four basic services performed; inspection, recharge, mooring inspection, and relief. An inspection is performed every time an aid is visited. Typical functions required during an inspection are painting, cleaning, material replacement, position checks, voltage checks, and lamp replacement. A recharge is the replacement of a lighted aid's batteries. A mooring inspection is a check of the underwater buoy mooring and a relief is the in-kind replacement of a buoy body.

The servicing policy consists of inspections once a year, mooring inspections every two years, and buoy reliefs on a six-year cycle. Recharge times for lighted aids are scheduled according to the rate at which the primary batteries are depleted and range from one to three years. Inspections for lights and buoys are performed each year. Inspections for daybeacons are scheduled once every two years and intervals between mooring inspections are at least every two years.

One measure of the effectiveness of the tending system regarding benefits to the mariner, is the time-average of the number of defective buoys waiting for service. Factors or variables that contribute to this measure are: characteristics of the tender, weather conditions, locations of the buoys, and random failures such as accidental damage to the buoy by shipping. Decision variables, or variables that the decisionmaker has some control over, are scheduling policy and tender operating profiles.

Weather, sea state, temperature, wind, and current all play an important role in determining maximum servicing intervals. Aids in the northern districts are subjected to severe weather and ice, and so buoys are much more likely to be damaged or dragged off station. More seriously, aids in the southeast can encounter hurricanes. The environment also plays an important role in planning aid visits. In extreme weather, the ship and crew cannot work aids safely. The weather often dictates when the aids can be visited. For example, in the New England area, buoys are removed in the fall and replaced each spring due to ice. As a result, these and other seasonal aids require two visits per year by a Coast Guard buoy tender.

An essential feature of overall buoy tending operations is that the buoys are maintained in a variety of environments which can affect the way in which the tender performs service. An example of this would be the differences between the tenders that service the Alaskan coastal area versus those that service the Long Island Sound region between New York and Cape Cod. The tenders servicing the Alaskan area must travel great distances to reach a particular buoy, whereas tenders in the Long Island Sound area travel much shorter distances. In addition, the aids they service are placed closer together and tend to be in groups. Moreover, in comparison with the Alaskan region, many of the aids are smaller in the Long Island Sound region.

A discrepancy is defined as the "failure of an aid to display its characteristics or to be on its charted position." The Coast Guard defines five levels of discrepancy response. They are Immediate, High Priority, Priority, Routine, and Decision/Deferred. Corresponding to each category are the time thresholds of immediately, 18 hours, 36 hours, 72 hours, and when the servicing unit's plans allow, respectively. The hour limits represent the maximum acceptable time from the receipt of the discrepancy report to the moment the servicing unit responds.

Servicing aids to navigation and correcting discrepancies is a complicated activity. Otherwise well-planned servicing trips are often altered to accommodate reported discrepancies in the area or because the weather creates unsafe working conditions. At times, several aids become discrepant simultaneously due to weather, collisions, or vandalism. This demands rapid and extraordinary response from servicing units.

The present fleet of buoy coastal and oceangoing tenders used to service these aids is on the average 35 years old with some vessels dating back to 1942. They require ever-increasing amounts of maintenance and are no longer cost efficient. Over the next decade the Coast Guard plans to replace these tenders with a new fleet, possibly of a new design (class). This means that many of the designs to be considered have never been constructed and thus have no historical track record by which the Coast Guard can evaluate their operational performance.

In order to investigate logistics reliability and maintainability in each tender's design process, and to ensure the tender's ability to operate and be maintained under defined operational and support concepts, it was necessary to develop a logistics, operational simulation model. The model will assist the logistician in establishing concepts and requirements for each tender system during the life cycle of the equipment. This includes defining the actions and support necessary to ensure that the tender system or equipment attains the specified operational capability, with minimum life cycle cost. The model will be used to assist the logistics support manager in determining the workloads, and time phasing for accomplishing depot maintenance requirements; providing a decision support tool to Project Officers for integrated logistics support issues; and assisting the project officers in defining the requirements for supply support, packaging, handling, transportation, and logistics support management information.

2. OVERVIEW

The ATON General Event-Step Logistics (ANGEL) model essentially provides the "driver" for moving the tender around, servicing the field of buoys. Figure 1 below displays a flow chart of the major modules of the model. Among the tender's activities considered are the working of a buoy, docking to resupply the tender, R&R for the crew, anchoring due to bad weather, waiting for the desired time in which to work a buoy, and the transiting of the tender between a set of buoys. The ANGEL model must take into account intricate routing patterns, draft restrictions, sea state, time of day, emergency discrepancy

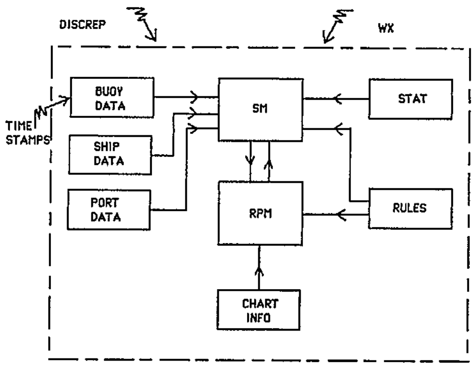

Figure 1: Overview of ANGEL

response, routine buoy maintenance schedules, and diverting to prosecute Law Enforcement or Rescue missions.

Geographical limitations (navigable waters) (see Figure 2) are dependent on land obstacles and water depth for a given area. Each tender may have characteristics which limit its ability to travel in some waters. The difference between land, navigable and non-navigable waters is represented by a boundary polygon. A route consists of a sequence of line segments lying entirely within this polygon. The polygons are derived from a nautical geographical data base for the region to be modeled. Importantly, the polygons serve to delimit the area for travel and define the navigable region for the ship. Therefore, an individual tender has its area of navigable waters specified by boundaries defined by polygons which can be used to route the tender properly.

ANGEL addresses a select group of environmental factors that have an influence on the performance of the tender. For each of these environmental considerations the tender has attributes that designate the operational limits of the tender with respect to each of these factors. The height of waves, and the speed and direction of prevailing winds, have a significant effect on the cruising speeds of the tenders. Moreover, visibility is a factor when positioning a buoy, e.g., if reference sites are not visible because of haze or fog, then maintenance and repositioning of the buoys cannot be performed.

In working an aid, stability of the tender is critical. Therefore, wave height affects the overall operation of the tender. When a certain wave height state is reached, the tender cannot work buoys and returns to the nearest port. Moreover, proper positioning is critical to mariners. Surface visibility affects the tender's ability to position buoys after servicing. In positioning a buoy, the tender's crew must take measurements that require visible reference points. If visibility falls below the minimum level at which accurate buoy placement can be made, the tender cannot

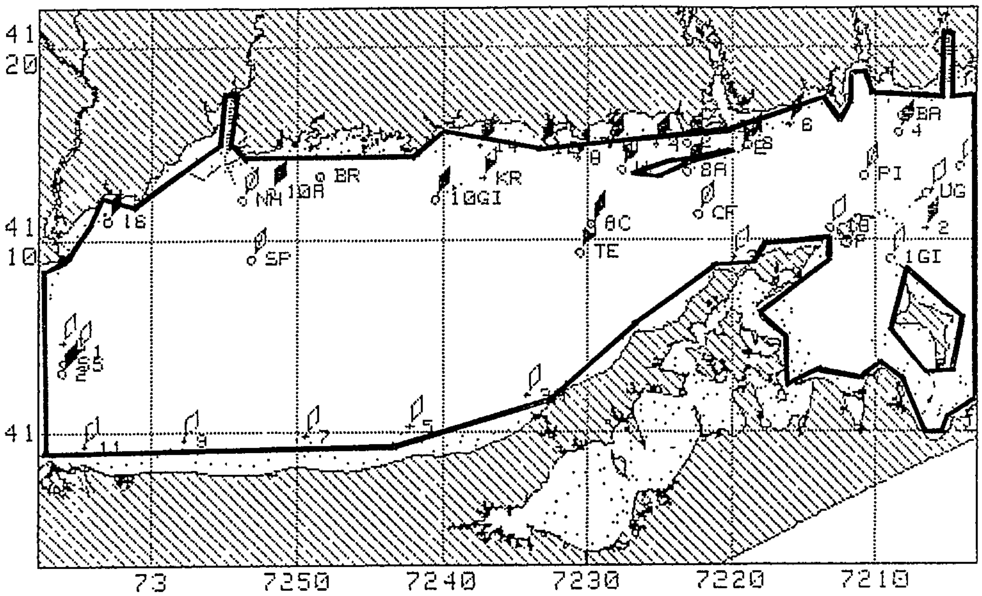

Figure 2: Navigable Waters

complete its work until the visibility returns to acceptable levels. This increases the downtime of the buoy and tender under-utilization, thereby degrading performance.

Sea State is generated by defining 12 Markov Transition Matrices, one for each month. The transition probabilities are developed using wave data from weather buoys local to the area being simulated. This data was obtained from the National Oceanic and Atmospheric Administration's Data Buoy Center and the U.S. Army Wind and Wave Summaries. The Sea State procedure takes into account total time at a given wave height as well as the average time at that interval.

Visibility is generated by defining 96 Markov Matrices, one for each three-hour interval of a day for each month. The transition probabilities are developed using readings taken from local airports. These matrices were calculated directly by following the actual state changes in the data. Figures 3 and 4 show simulated data produced by the weather models.

Tender design characteristics, in addition to environmental factors, play a role in the vessel's overall performance as well. Buoys must be lifted out of the water for cleaning or replacement. If the weight of the buoy exceeds the crane's lifting capacity, the buoy cannot be serviced on location by the tender. Deck space is required for both buoy storage and a place to set the buoy when working a buoy on site. Another important characteristic, tender endurance, is the amount of time the tender can remain at sea without a port call. Furthermore, tender endurance encompasses crew fatigue and the tender's ability to store supplies. Finally, fuel capacity can affect the tender's range and the number of port calls it makes.

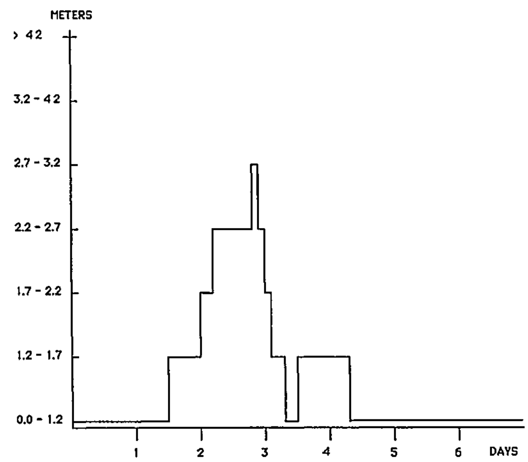

Figure 3: Wave Simulation Results

In summary, ANGEL is a SIMSCRIPT II.5 simulation model which can be used to simulate buoy tenders with different attributes such as speed, lifting capacity, draft, length, weight limitations, deck space, etc. This allows the analyst to measure the effectiveness of a new buoy tender design with respect to logistics support. The measures of effectiveness will be related to output data which reflects quality of service to the mariner, e.g., how long a buoy is out of service.

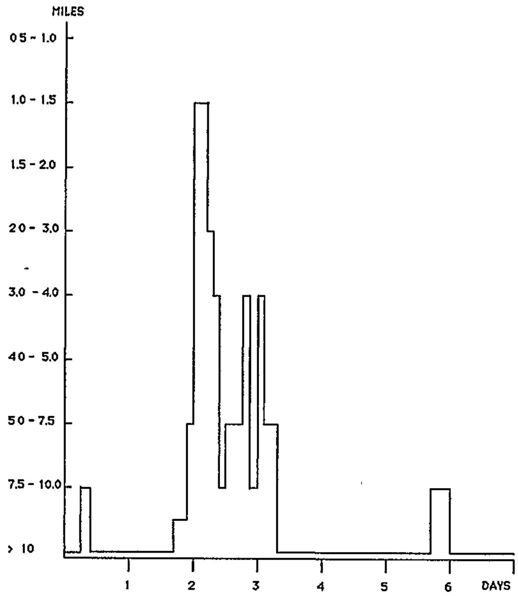

Figure 4: Visibility Simulation Results

3. ROUTE PLANNING MODULE

A significant aspect of modeling is that the needs of a ship within a region depend critically on its particular geography. Possible travel routes vary according to which ships can successfully travel them, due to depth of water or weather exposure. Therefore, the modeling process must take into account geographical constraints such as shoals and islands.

In order to address tender routing and scheduling, an important module, the Route Planning Module (RPM), has been designed and implemented in ANGEL. Basically, the RPM acts like a planning office in that it schedules the buoys that the tender is to service. Interestingly, the RPM bases its plan on actual charts of the given area.

The RPM is called by the simulation model when it is required to plan the tender's travel itinerary. The RPM will select routes based on a multitude of inputs from the simulation model. These include factors such as; geographic limitations, buoy attributes, weather limitations, and resource requirements such as fuel for the ship. Moreover, the RPM is called when the simulation model generates interrupts of the normal buoy servicing for such things as unscheduled buoy maintenance and responding to emergencies. As a consequence, upon interrupt, the ship must be reassigned temporarily and then rescheduled from a new starting point to efficiently service the remaining buoys.

The vessel may either transit to the next buoy, remain overnight, or anchor in a designated area at night. Emergencies such as search and rescue cases or important buoy outages require ships to be reassigned or rescheduled on short notice. Resource limits can be of a variety of different kinds, including distance, fuel, time, daylight, day of the week, storage space, lifting capacity, crew fatigue, depth of water, rough weather survivability, currents, wind, etc.

One of the fundamental tasks is to plan a route using available nautical chart information and knowledge to satisfy the mission requirements. In a real environment, situations change dynamically, therefore, plan execution monitoring and fast replanning capabilities become critical. The route planning model not only needs to find an optimal path, but also requires reasoning ability to identify critical locations along the path for spatial attention.

Concisely, the route-planning problem can be stated as follows: A base has a single ship and N buoys, where N is too large to be visited on a single trip. The navigable space is defined as the interior of a specified polygon. Islands are represented as polygon "holes" within the outer specified boundary polygon. The objective is to find the least expensive and timely set of trips that visits each buoy once for the length of time required to perform the specified maintenance.

3.1 Subjective Elements of Route Planning

One important set of variables that influence the routes are those derived from human judgement. A ship's captain can rescind orders given on land if he "feels" that at the present time the circumstances are no longer applicable. For example, Headquarters may direct the ship to patrol a particular area for a certain period of time. The captain can terminate this patrol if in his judgement the evolving conditions do not warrant continuation. Moreover, the process of tending buoys is very dangerous. The buoys are quite heavy and must be hauled on board for repairs. This is only attempted when the seas are relatively calm. Moreover, since a servicing schedule is generally made well in advance and weather is unpredictable, the captain must often reschedule according to the actual weather conditions. Therefore, in the short term, the captain is not forced to follow any particular schedule for tending buoys, i.e., the schedule is used only as a guide. In addition, ship captains differ in their preferences and their decisions can depend on many variables.

Smith (1987) pointed out the difficulty of obtaining a satisfactory solution to this problem using mathematical programming techniques. Therefore, simplifying assumptions must be made to deal with the problem of human judgement. To include judgement or preference in the model requires a framework which will reflect the preferences or utility of a particular ship captain. Two significant factors were found to be most important in constructing a route based on judgemental factors: timeliness and minimizing the time to complete a route of buoys.

Basically the captain is asked to construct two utility functions which give a measure of timeliness and time to complete service. Judgemental Independence is assumed and the two utility functions are combined additively as follows:

$$U(DELTA,TAVG) = 1 - W_D M_D \, DELTA - W_T M_T \, TAVG$$

Subject to $W_D + W_T = 1$

where

W_D, W_T: Scaling constants obtained at the "Best" values of both utility functions, i.e., DELTA = TAVG = 0

M_D, M_T: Slopes of the single attribute utility functions.

DELTA: The difference between the scheduled time and the actual time to complete service.

TAVG: The average time to transit and service the buoys.

The utility curves (see Figure 5 below) are assumed to be linear functions with negative slopes. The point of intersection is at the threshold of the least acceptable values on each criteria.

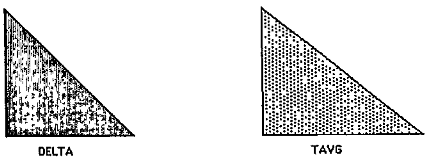

Figure 5: Hypothetical Utility Functions

By obtaining the most preferred attribute, i.e., DELTA or TAVG, and the scaling weights for the functions, allow one to combine the attributes into a 2-dimensional utility function. Once a set of alternative routes are constructed, the most preferred route, can be selected using the utility function.

This leaves the problem of searching the nodes for feasible sets of routes. This is performed using two linear evaluation functions which look quite similar to the utility functions described above, except that the slope of x is positive (see Figure 6 below), i.e., attempt to service the latest buoy first. The search is performed depth first and is controlled by using scaling weights on the evaluation functions.

The evaluation function is defined as:

$$f(t,x) = W_x M_x x + W_t (1 - M_t)$$

subject to: $W_x + W_t = 1$

where

W_x W_t: scaling constants which control the search for a feasible route

x: difference between the scheduled time and the actual time to complete service.

t: the total time to complete service including transit time.

M_x, M_t: slopes of the individual evaluation functions.

Figure 6: Hypothetical Evaluation Functions

Every buoy is considered as a possible starting point for the tender. Consequently, a search tree is created for each buoy within a predefined cluster of buoys. The next buoy visit selection is made based on applying the evaluation function. First, each buoy's completion time is calculated by testing for any constraints that will have to be satisfied before working that buoy. The completion time accounts for transit times, anchorage time, and the estimated time it will take to work the buoy. Then, the difference between the completion time and the scheduled time, x, is calculated. The evaluation function is calculated using x and the completion time, t. The buoy with the highest value resulting from the application of the evaluation function is selected as long as its x value is greater than zero. If all the x's are zero, selection is based on the earliest completion time unless more than one buoy is scheduled to be worked on the same day. If this is the case, the buoy with the shortest transit time is selected. Once the buoy selection is made, the buoy and any port calls are selected for the route. This process is continued until all the feasible routes have been generated. Finally, the utility function is calculated for each feasible route, resulting in the route's combined utility. The route selection is based on maximizing utility of the routes.

4. MODEL VERIFICATION AND VALIDATION

The techniques of verifying the adequacy, accuracy and precision of Simulation Models has been traditionally based on two techniques. First, one can perform regression analyses on the masses of output data. Second, one can carry out various "structured walkthroughs." It would be of a significant additional value if one could generate, possibly automatically, a higher level meta-model of a Simulation Model that would not only serve as the tool for verification and validation but could also accelerate the computer runs that yield the results of the Simulation Model.

No matter how carefully a Simulation Model is constructed, various types of errors are likely to occur in large, complex systems. These errors can be of the following types:

o The model does not reproduce all situations that may appear in real life;

o The model reproduces situations that are not allowed in real life (illegal combinations of situational variables);

o The responses of the model (actions, events) to given situations are not consistent (the stochastic components of the responses are outside acceptable levels and assume extreme values, so-called statistical "outliers").

o The responses of the model are identical or much too similar over a large domain of the situation space, which fact contradicts world knowledge and expectations.

A simulation model can be conceived as receiving both deterministic and pseudo-random input from which a situation is created. The model then "responds" to it in computing some action or event. A component of this can be fed to the model to generate the next situation. Situation, actions and events can be recorded in a "history file," a selected part of which, possibly after some statistical processing, is outputted for the user.

4.1 Meta-Model Generation

The first task is to generate a meta-model of the Simulation which has such characteristics that are conducive to the processes of verification and validation. The program generating the meta-model first interrogates the user about certain fundamental properties of the model and the real-life environment it depicts. It then interacts with the model through an interface to collect the information needed for the meta-model. A structural and statistical analysis of the meta-model reveals problems extant with the model.

A new, unique set of integrated tools has been developed over the past six years by Findler (1983), which can automatically generate a computer model (descriptive theory) of a simulation. (See Figure 7 below.) The ANGEL model is the first application of this largely domain-independent system called the Quasi-Optimizer (QO). The QO observes and measures a sequence of environments and the simulation's response to it in one of two modes. In the passive mode of observation, it does not interfere with the environment but makes a record of the situations and actions. Moreover, a useful by-product of this mode of observation is the probability distribution of situations. The second is the active mode of observation, sometimes referred to as "laboratory conditions." The Quasi-Optimizer system generates a series of situations according to a statistical design of experiments. Accordingly, the simulation is asked to prescribe an action in each of the situations.

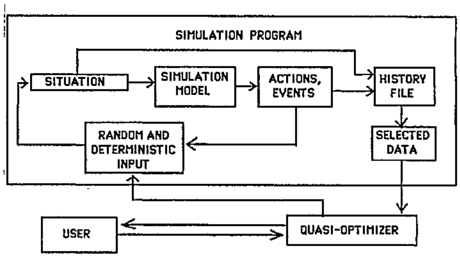

Figure 7: Quasi-Optimizer System

The basic information structure the Quasi-Optimizer builds is a decision tree. The system has facilities to discover which situational variables, from the superset specified by the user, are relevant for the model's actions. These are termed decision variables, each of which is associated with one distinct level of the decision tree. Whenever an illegal combination of decision variables values is produced by the model, the Quasi-Optimizer immediately discovers it, flags the situation and reports it to the user.

The decision variables can be of three types:

o Numerically oriented

o Ordered categorical variables which can be mapped onto a number scale, such as rank numbers of quality, days of the week, ranks of military personnel, etc.

o Unordered categorical variables which have no meaningfully ordered mapping onto a number scale, such as the states of the Union along the coast line or colors of people's hair.

In the course of repeated experiments, the Quasi-Optimizer identifies responses that are either outside acceptable levels, improper sequences, or have a large stochastic component rendering them statistical "outliers." The validation of the model depends on this and similar types of information feedback.

The Simulation Model and the Quasi-Optimizer run as separate processes on a MicroVAX AI Work Station in a manner similar to that of co-routines, i.e., when one of the two is running, the other is waiting to be restarted. When the running system has finished its current processing, it restarts the waiting process from where it left off and goes into a waiting state. This cycle continues until all processing is done.

In summary, the Quasi-Optimizer verifies the correctness of a model on the basis of a decision tree generated. The Quasi-Optimizer may utilize the Passive Observation Mode, which simply observes the model or one of two Active Experimentation Modes, which create situations for the model to respond to, using a form of statistical experimental design. As model situations and responses are passed via a shared file to the Quasi-Optimizer, they are checked for correctness.

The portion of the Quasi-Optimizer that is used to verify the ANGEL model is the passive operation mode. It receives decision variables and results from the ANGEL model and verifies that the correct results were obtained. One verifiable result could be the state that the tender is in after finishing its previous activity. The decision variables are those that cause a change of state. An example response would be a state change from traveling to a buoy, state A, to fixing the buoy, state B. The categorical decision variables are; arriving at the buoy and the buoy needing repair.

The decision tree, i.e., meta-model, can be transformed into a form usable by a decision support system (DSS). This is used to generate approximate results much more quickly. Even without the DSS, the decision tree can be used to observe tendencies and trends that the model generates for different values for the decision variables. Moreover, decision trees can be used to show the effects of certain aspects of ANGEL. One such example is the effect of weather on the performances of the buoy tender.

Lastly, the Quasi-Optimizer will be used to generate a meta-model for certain aspects of a tender. This will demonstrate the relative effect of a larger deck surface, draft, endurance, speed, etc., on the performance of the tender. A response tree of this type will give a general idea of a good tender design. The meta-model is also used in a DSS to generate the results of different tenders. One enters the characteristics of the tender and a quick approximation of the effectiveness of the tender is generated.

5. DISCUSSION

ANGEL over its lifetime will be simulating within a variety of geographical environments as diverse as the differences between Alaska and the Gulf of Mexico. In the course of simulating within these environments, both in the development of routes and driving the tender, decisions must be made as to how to handle various situations. Examples of some situations are: the occurrence of a buoy discrepancy; a weather change; completion of a process; or the working of a buoy.

These decisions are based on facts and rules that are given by Coast Guard policy and influenced in their application by the particular captain in charge of the tender. Coast Guard policy reflects what is normally to be considered in making a decision. The influence of the captain will be the exception, i.e., the captain can rescind policy if he "feels" that at the present time the circumstances are no longer valid. The application of these rules and facts, which are converted into production rules, are broken down into groups that specifically address the various situations.

Currently, ANGEL uses a special structure to handle the grouping of production rules by having a SIMSCRIPT procedure for each situation to be addressed, i.e., the applicable production rules are hard coded within the routines. Accordingly, a unique procedure is written for each situation in which there is an exception to the normal application of the facts and rules. Such a structure allows the user to update routines with respect to policy changes that may occur over ANGEL's lifetime. It also allows the user to personalize a simulation run to reflect the captain's way of handling the tender operations for a particular area. In other words, isolating these routines in such a way makes ANGEL code easier to read and thus easier to modify for updates. Unfortunately, the user must recompile each procedure that is required due to policy change.

Although this structure makes ANGEL flexible, it requires that a user be intimately familiar with ANGEL's design. An experienced SIMSCRIPT II.5 programmer will be required to modify the procedure reflecting changes in the production rules. Moreover, the recompile and linking of the program is time-consuming and subject to errors.

Another way to approach this problem would be to use a knowledge-based system. In this type of approach the production rules could be stored in a database. The model could then make the adjustments without requiring human intervention to select the correct procedures or update the rule base. Unfortunately, implementation of such a knowledge-based system is outside the realm of SIMSCRIPT II.5's capabilities at this time. In order to accomplish such an implementation, the simulation would have to be written in an AI language such as LISP. However, writing a simulation model in LISP would require routines for handling the timing mechanism and statistical output offered by SIMSCRIPT II.5. A possible solution would be to construct a parser within SIMSCRIPT II.5 that allows the same abilities that LISP provides for rule-based systems.

6. ACKNOWLEDGEMENTS

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