A MODEL OF SUBMARINE EMERGENCY DECISIONMAKING AND DECISION AIDING

by

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ABSTRACT

The effect of a decision aid upon the workload and performance of a five member decisionmaking organization is investigated by way of information theoretic modeling and analysis. A generalized submarine ship control party performing the emergency control task is modeled using the Petri Net formalism. The organization is then modified to incorporate a decision aid that provides a situation assessment to the decisionmaker with the greatest workload and decisionmaking responsibility, under the assumption that the information provided by the aid may be: (1) blocked, (2) compared with the user's own situation assessment, or (3) be used directly as the situation assessment. The decisionmakers' workload is computed using an information theoretic model of bounded rationality, and performance is measured as a function of probability of decisionmaking error weighted by error cost. The results are that a decision aid providing emergency situation assessment to the most overloaded and critical of the decisionmakers has mixed effects. Performance of the organization is improved when the aid is used, but the improvement may not be sufficient to offset decision error elsewhere in the organization. On the other hand, the workload of the user varies greatly with the manner in which the aid is used. In the extreme, the workload may be either significantly reduced or increased, while on average, it is not significantly changed by the aid.

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CHAPTER 1

INTRODUCTION

1.1 PROBLEM DEFINITION

The ship control party of a submarine is responsible for the evaluation of complex casualty situations and selection of an appropriate course of action within a matter of seconds, and under great stress. The volume of information to be gathered, processed, and shared within this small time frame can be extremely high. It has therefore been suggested that a decision aid be introduced to alleviate this apparent overloading problem. [1]

However, it is neither clear what information the aid should provide nor, more importantly, whether the presence of the aid, among a crowded panel of instruments already displaying a wealth of information, will benefit or hinder the performance of the ship control party. The intent of this work is to gain a better understanding of submarine emergency control, the role a decision aid might play in this process, and the effects, positive and negative, that such an aid could have on the organization's decisionmaking characteristics. The approach taken toward this end is an analytical one. A model of the organization, with and without a decision aid, is formulated and analyzed. Then a predictive comparison of the key organization properties of workload and performance is made.

1.2 THEORETICAL BACKGROUND AND APPROACH

The background to the problem at hand is both empirical and analytical. On the one hand, experimental work in the field of man-machine systems has addressed the issues of detection, diagnosis, compensation and response to complex system failures, and can provide an empirical basis for this investigation. On the other hand, organization theory and analytical models of decisionmakers are also required for the design, modeling and analysis of organizations.

Problems involving the control of systems and of complex system failures by humans have usually been approached with the goal of describing and reducing the workload and improving the performance of the individual decisionmaker . (For reviews of this work see [2], [3]). These efforts have provided a foundation, but are insufficient for the task of modeling emergency control by an organization rather than a single decisionmaker.

A parallel and growing body of work has emerged which treats problems involving decisionmaking by organizations consisting of humans and machines. The analytical framework this effort shall employ is that of n-dimensional information theory [4], [5], extended for the modeling, design and analysis of the human decisionmaker and organizations of interacting decisionmakers [6], [7], [8], [9] , [10], [11].

This approach recognizes the need to consider the structural characteristics of the organization of which the decision aid will become a part; since decisionmakers interact, their workload and performance characteristics are coupled. The work that the thesis shall build upon, cited immediately above, has been developed primarily for the study of command and control (C^2) organizations. Although the ship control party (SCP) is not a command and control organization in the strict sense, it possesses characteristics similar to those of C^2 organizations. This makes it a promising candidate for the application of the methodology. For example, the task faced by the SCP is too complex for a single decisionmaker to handle alone. The overall task is hence divided among crew members well trained for their specific, well-defined individual tasks. The decision process is subject to a severe time constraint, therefore explicit consideration of the decisionmakers' bounded rationality is important. The analytical approach taken is well-suited to address these problems and will enable an analytic and graphic characterization of the organization's workload and performance.

1.3 GOALS AND CONTRIBUTIONS

The goal of this work is to gain insights about the effects a decision aid may have on the information processing behavior of an organization making time-critical decisions. In addition to this main goal, however, several subgoals must be met which may make a modest contribution. First, a descriptive and, in a sense, prescriptive analytical model is developed to study an organization that had hitherto been studied only empirically. The model is not intended to describe the precise process whereby humans perform fault diagnosis as a team, but how the organization structure may constrain team performance. The second goal is to extend the information theoretic organization modeling and analysis methodology to an example outside of the realm of command and control organizations, and so demonstrate the flexibility and generality, as well as the previously unexposed limitations, of the methodology. Finally, a contribution is offered, in the testing of a new set of tools for the treatment of problems involving the diagnosis and control of complex system failures.

1.4 SUMMARY OF RESULTS

The results, in brief, are that a decision aid providing emergency situation assessment to the most overloaded and critical of the decisionmakers has mixed effects. Performance of the organization is improved when the aid is used, but the improvement may not be sufficient to offset decision error elsewhere in the organization. On the other hand, the workload of the user varies greatly with the manner in which the aid is used. In the extreme, the workload may be either significantly reduced or increased, while on average it is not significantly changed by the aid.

CHAPTER 2

THE SUBMARINE EMERGENCY CONTROL PROBLEM

2.1 AN OVERVIEW OF SUBMARINE EMERGENCY CONTROL

Submarine emergency control has been "broadly defined as those actions taken to counteract the effects of any and all system failures which impede the normal operation of the submarine and the accomplishment of its mission" [1]. Although missions vary, any submarine must, at minimum, be able to submerge to and maintain a commanded depth, maneuver precisely at depth, and rise rapidly to the surface without broaching, in the event of an emergency or in the conduct of its mission. The failures which may befall a submarine range from those of little direct consequence to those threatening catastrophe. They may arise from a variety of sources including design flaws, human error, and battle damage. The gravity of casualties is magnified by the high speed of modern submarines, especially those of the attack classes. The range of operating depths, meanwhile, is on the order of only five times the length of the vehicle. A distressed vessel may therefore, within tens of seconds, plunge to dangerous depths where the hull may crush, or ascend to and broach the surface, giving away its position and potentially exacerbating the casualty or even colliding with another vessel. There is clearly a demand for rapid response to emergencies.

All control decisions, both normal and emergency, are the responsibility of the five member ship control party (SCP), which will be discussed in detail in Chapter 5. The SCP relies upon several effectors for exercising this control: main and variable ballast tanks for aiding in depth and trim control, external control surfaces (rudder, stern planes, fairwater planes) for controlling trajectory, and, naturally, a propeller. (see Figure 2.1)

Although automatic failure detection and recognition is present aboard submarines to a limited extent today, SCP members bear primary responsibility for these jobs and are trained to do them through drill and supervised experience. A thorough familiarity with normal ship indications and response characteristics, combined with constant cross checking of readings, many of which are redundant, maximizes the chances for early detection of even subtle casualties.

Despite this rigorous training and the presence of automatic systems, the recovery from a casualty depends upon close coordination of the ship control party and the processing of upwards of fifteen varied sources of information (see Figure 2.2) according to complicated decision rules, within a matter of seconds, and quite possibly as a matter of life or death. To reduce the chances that such an emergency control decision task will exceed the information processing capabilities of the SCP members and result in a late or inappropriate response, scientists concerned with submarine control processes have suggested, in general terms, the introduction of a decision aid [1]. Whether of not this measure will necessarily improve matters remains to be seen. In order to impart a better understanding of the nature of the decision process and set the stage for the development of the model, various relevant aspects of emergency control shall be briefly discussed. Then, in the chapters to come, a model will emerge that could bare clues about the decision aid question.

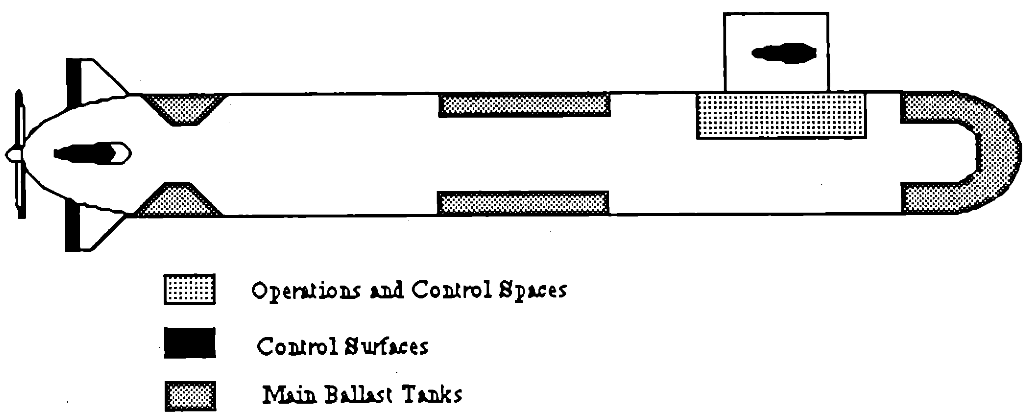


Figure 2.1. Submarine Control Configuration

2.2 INFORMATION SOURCES

To detect and diagnose an emergency, the members of the ship control party have available a number of sources of information. The volume of information is in fact so great that the difficulty is often one of sorting out the relevant information from the irrelevant [18]. The indicators relied upon in responding to an emergency include those used for normal ship control as well as alarms and indicator lights which are activated only when specific anomalies have been detected.

Figure 2.2 depicts the SCP positions before the ship and ballast control panels. On the ship control panel are indicators of ship state (speed, depth, heading, trim and roll conditions) and control surface positions displayed with pointer and dial meters and auxiliary plane indication provided by lights located along the dial perimeters. Also on the ship control panel are the control mode buzzer and lights. When electrical power or normal hydraulic power to a set of planes is lost, the control mode shifts automatically from normal mode (electrical-servo control) to emergency mode (direct hydraulic valve control of auxiliary hydraulic system) accompanied by the sounding of the buzzer and the activation of a light corresponding to the affected plane.

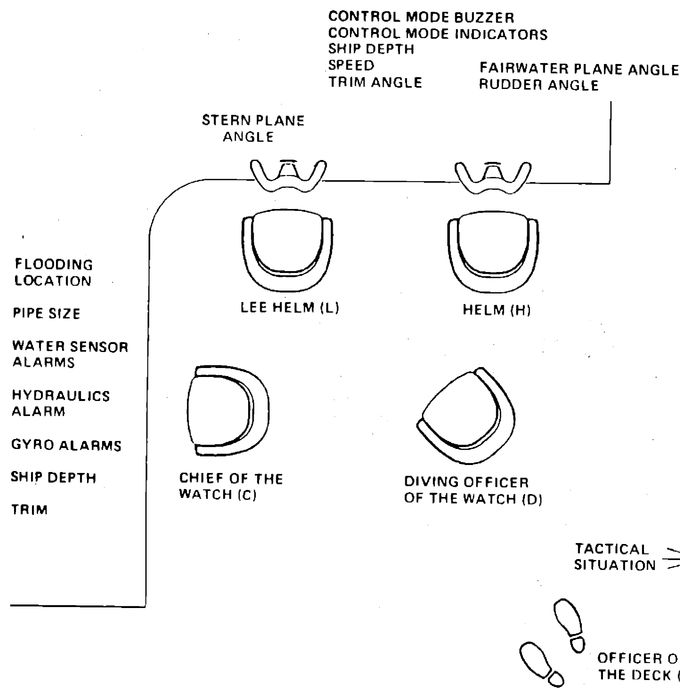


Figure 2.2 The Layout of the Ship Control Party and the Ship Control Panel

The ballast control panel provides information about ship's depth and trim conditions, the status of its ballast tanks and pressurized air banks, as well as information and alarms corresponding to all other vital non-weapon ship systems, e.g. water sensor alarms, gyroscope alarms, and life support system status. The ballast control panel is also equipped with a telephone for communicating with all other ship compartments. This telephone bears reports of flooding casualties.

A final source of information is a loudspeaker providing information about surfaced and submerged sonar contacts and tactical situations which may affect the response to an emergency.

2.3 IMMEDIATE ACTIONS AND SUPPLEMENTARY ACTIONS

Emergency control is treated by the U.S. Navy as a two phase process consisting of immediate actions and supplementary actions [19]. Immediate actions are those which must be performed in seconds, if potentially catastrophic consequences are to be averted. The severe constraint on time means that casualty diagnosis, response selection, and execution must be done without reference to written procedures. Supplementary actions are follow-up measures for minimizing the effects of a casualty. They need not be performed within a strict time frame and usually proceed in a checklist fashion. The distinction between these two tasks will be a pivotal one in formulating the model as well as in selecting a decision aid.

2.4 CLASSES OF CASUALTIES

Emergency situations vary. Among the most dangerous classes of casualties is "loss of control"--specifically over certain control surfaces. This can result from a failure of the actual plane or its mechanical linkage, or it may result from a loss of hydraulic pressure used to drive the planes.

A second class of emergency, also potentially catastrophic, is flooding. Failures of pipes or sealed hull penetrations, or damage inflicted by an external agent, may be responsible for the leakage of seawater into hull compartments. This added weight diminishes the ship's ability to ascend. These classes of emergency are, in addition to being the most dangerous, the most difficult ones for the SCP to handle, since the assessment of and response to such casualties are complicated functions of ship speed, depth, plane configuration, and other information.

Other classes include fire, loss of power, electrical failure, and indicator failure. The occurence of more than one casualty at a given time is known as a compound casualty.

2.5 A NOTE ON SHIP CONTROL OPERATIONS

A submarine, depending upon its class, may operate in one of several modes. An attack submarine, for example, operates in "transit mode" when en route from one location or port to another, or in "patrol mode" when performing its mission. The nature of the vehicle's maneuvers, and hence of the information available to the SCP in the event of an emergency, closely depends upon the mode of operation. This will become important when the task inputs are modeled as random variables.

The ship control party, regardless of the class of submarine or its operating mode, must maneuver within the constraints dictated by the ship's "submerged operating envelope" (SOE). The SOE is a set of curves relating those combinations of speed and depth that define the threshhold of safety in maneuvering. These curves have been derived for specific classes of submarines to account approximately for delays in human and ship response to serious casualties. An ultimate effect of a well-designed decision aid would be to expand the SOE. The characterization of the SOE, which depends upon knowledge of the mode of operation, will be important for modeling the task inputs.

It is axiomatic that submarines, in the conduct of their mission, remain as quiet and as hidden as possible. Therfore, great attention is paid in ship control to minimizing radiated noise due, for example, to cavitation, and to remaining safely submerged when the tactical situation is such that approaching the surface would be adverse. This holds true in the context of emergency control. Since the response to a casualty may be noisy or bring the submarine to the surface, the SCP in emergency control may be faced with conflicting objectives. It must maximize ship safety while minimizing the degree to which the security of the submarine's mission is compromised. This aspect of the decision problem will be reflected in the models developed for the crew's internal decision process, and shall also be invoked when a decision error cost functional is defined.

This chapter has attempted to distill from the exceedingly complex problem of submarine operation and control some of the premises needed to formulate a model. The next chapter shall present the modeling tools to be applied in formulating that model.

CHAPTER 3

THE ANALYTICAL TOOLS

3.1 INFORMATION THEORY

The analytical framework used for modeling the emergency control task, the organization and its decision process, and the presence of the decision aid, is that of n-dimensional information theory. Originally developed [12] as an application in communication theory, information theory has been developed for modeling decisionmakers [2], [6]. This framework will ultimately allow for the prediction of the relative information processing workload of the decisionmakers of the ship control party.

Information theory defines, and builds upon, two key quantities: entropy and transmission. Entropy, the fundamental measure of information and uncertainty, is defined for the variable x, an element of the alphabet X, occurring with probability p(x) as:

$$H(x) \equiv - \sum_{x} p(x) \log p(x) \tag{3.1}$$

When the base of the logarithm is two, entropy is measured in bits.

From the notion of entropy may be derived the second key quantity: transmission, T(x:y), also known as mutual information. The transmission between variables x and y, respectively elements of X and Y and characterized by p(x), p(y), and p(x|y), is given by:

$$T(x:y) \equiv H(x) - H_y(x) = H(y) - H_x(y) \tag{3.2}$$

$H_y(x)$, the conditional entropy of x given y, which may be interpreted as the uncertainty in x that remains when y is fully known, is defined to be:

$$H_y(x) \equiv - \sum_{y} p(y) \sum_{x} p(x|y) \log p(x|y) \tag{3.3}$$

By introducing joint entropy or uncertainty, between variables x and y for example, given as:

$$H(x,y) \equiv -\sum_{x}\sum_{y} p(x,y) \log p(x,y) = H(x) + H_x(y) \tag{3.4}$$

the transmission expression Eq. (3.2) may be rewritten as :

$$T(x:y) = H(x) + H(y) - H(x,y) \tag{3.5}$$

This theory was extended [4] to account for n - dimensions:

$$T(x_1: x_2: \dots : x_N) = \sum_{i} H(x_i) - H(x_1, x_2, \dots , x_n) \tag{3.6}$$

which allows for the modeling of information structures of unlimited complexity. Such modeling is facilitated by a decomposition property characterizing the transmission [5]:

$$T(x_1: x_2 : \dots : x_n) = T(x_1 : x_2) + T(x_3 : x_4) + \dots + T(x_{N-1} : x_N) + T(x_1, x_2 : x_3, x_4: \dots : x_{N-1}, x_N) \tag{3.7}$$

Another property useful in the derivation of activity expressions comes from Eq. (3.4):

$$H(x_1, x_2, \dots , x_{N-1}, x_N) = H(x_1) + H_{x1}(x_2) + \dots + H_{x1,\, x2,\, \dots ,\, xN-1}(x_N) \tag{3.8}$$

The final property of information theory relevant to the thesis is the Partition Law of Information (PLI) [5]. This powerful identity enables straightforward numerical computation of activity as well as an interpretation of how the components of that activity correspond to actual information processing phenomena. For a system with input variable x, N-1 internal variables w_i, i = 1, ... , N-1, and output variable y, also defined as w_N, the PLI states:

$$\sum_{i}^{N} H(w_i) = T(x:y) + T_y(x: w_1, w_2, \dots , w_{N-1}) + T(w_1: w_2: \dots :w_{N-1}: y) + H_x(w_1,w_2, \dots , w_{N-1}, y) \tag{3.9}$$

The terms in Eq. (3.9) may be interpreted in the following way. The expression on the left-hand side yields the total information processing activity of the system, denoted by G. Proceeding to the right, the first term, T(x:y), is simply the information transmission or "throughput" by the system and is designated by G_t. The second term, $T_y(x: w_1, w_2, \ldots, w_{N-1})$, is the amount of information entering the system but not present in the output. This is termed "blockage" and denoted by G_b. The third term, $T(w_1: w_2: \ldots : w_{N-1}: y)$, denoted by G_c, represents the constraining relatedness or "coordination" present among the system's internal variables. Finally, $H_x(w_1,w_2,\ldots, w_{N-1}, y)$, accounts for the information present in the system output but not the input. Although this information, designated by G_n, is called "noise" since it originates within the system, it is not necessarily adverse, as that word usually connotes. For example, the decisionmaking process introduces new information when a choice among alternatives is made.

Substituting the single letter designations for activity components yields an abbreviated statement of the PLI:

$$G = G_t + G_b + G_c + G_n \tag{3.10}$$

3.2 Introduction to Petri Nets

The formalism of Petri Nets, used extensively in the study of computing systems, has been adapted for the representation [13] and analysis [14], [15] of decisionmaking organizations. Because it permits a precise description of the interactions between elements of discrete event dynamical systems performing concurrent processes, this method shall be used for visualizing the model of the ship control party. The simplicity of Petri Net elements permits here a brief discussion.

Petri Nets are bipartite directed multigraphs consisting, for the modeling of decisionmaking organizations, of four elements: places, transistions, decision switches and directed arcs. Places and transitions respectively may be thought of as conditions and events. A transition is said to be enabled if every place capable of providing it with input has a token. Tokens are symbolic carriers of information. Firing sends a token from an enabled transition to each of its output places. A decision switch is a transition with more than one output place; the choice of which single place receives a token is specified by a decision rule. Tokens proceed between elements along paths represented by directed arcs. Figure 3.1 depicts a simple Petri Net used to represent a model of the decisionmaker, next to be discussed.

The use of Petri Nets does not impinge upon, but facilitates, the use of the information theoretic framework and its decomposition property. In the following description of the information theoretic model of the decisionmaker, subsystem inputs and outputs are represented by places, while each subsystem process or algorithm is denoted by a transition or, if a choice between algorithms is made, by a switch.

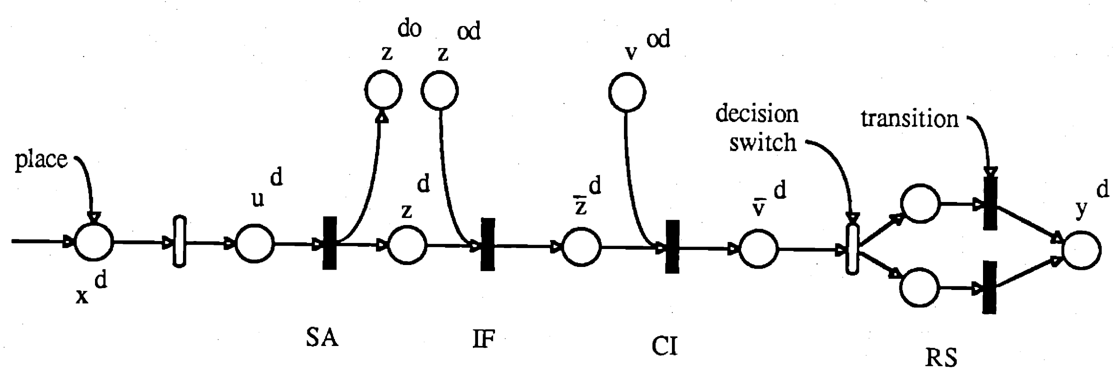


Figure 3.1 Petri Net Representation of Decisionmaker D of Organization O

3.3 THE DECISIONMAKING AND PREPROCESSING MODELS

3.3.1 The Basic Decisionmaker

The information theoretic decisionmaking model [6], [7], [8], [9], [10] is shown in Petri Net form in Figure 3.1. The input signal x arrives from the environment with average interarrival time t. In the generic case, x faces a four stage process. The first and last of these stages, situation assessment (SA) and response selection (RS), model the actual decisionmaking process, while information fusion (IF) and command interpretation (CI) allow for interaction of the decisionmaker with others in the organization.

The SA stage consists of a switch and U algorithms, to which the switch may be set by the decision variable u according to the internal decision strategy p(u) (or p(u|x), if a preprocessor is present). The selected algorithm, f, operates upon x to produce an assessed situation z. This information may, in turn, be combined with information from other decisionmakers, z', to yield $\bar{z}$.

The assessed situation, $\bar{z}$, is to be processed by one of V RS algorithms. The CI stage of the model allows for $\bar{z}$ and external information v' to affect the choice of this algorithm; v' may be considered to be a command capable of restricting response options. The RS algorithm, h, is chosen according to a second strategy, $p(\bar{v} \mid \bar{z}, v')$.

The fundamental assumptions, under which the model to be used in this work was developed, are:

(1) the model is memoryless (memory has been investigated by Hall [16] and Bejjani [17])

(2) the algorithms are deterministic (the stochastic decisionmaker has been modeled by Chyen [11])

(3) the algorithms have no rejection

(4) the sets of algorithm variables are mutually disjoint, i.e., only one algorithm is active in each stage at any particular time.

3.3.2 The Preprocessor

Preprocessors operate between an information source and a decisionmaker. As modeled by Chyen [11], they may describe an external decision aid or an internal subsystem of the decisionmaker, as depicted in Figure 2. The purpose served by the preprocessor is, by gaining knowledge about x, to influence the internal decision strategy which is now p(u|x). Chyen's preprocessor model assigned to each arrival a desired decision strategy -

the best for processing the input. She also modeled the process of filtering, that is, the blocking of extraneous arrivals.

Although the inclusion of a preprocessing function in an organization is intended to reduce workload and improve performance, it is quite possible that such benefits may not be realized. A poorly designed aid may in fact have adverse effects [11]. An internal preprocessing stage affects the DM's workload in two ways. Its mere presence and operation are bound to increase the total activity of the system which may be analyzed by applying the PLI. However, the preprocessor's output has a cascading influence upon the activity of the subsequent stages which may or may not offset the actual preprocessing activity. The concept of preprocessing is important for this work since the model presented in Section 4 includes an internal preprocessor and the decision aid to be proposed in Chapter 5 can be considered an external preprocessor of sorts. The thrust of this work is to analyze the effects of the latter.

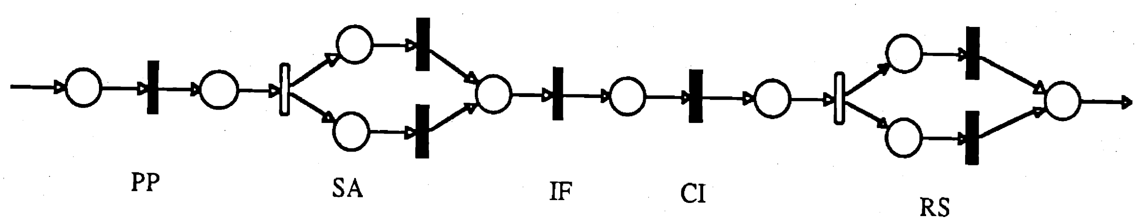


Figure 3.2 Petri Net Representation of the Decisionmaker with a Preprocessor

This chapter presented the analytical framework to be used for developing a model of submarine emergency control decisionmaking. Petri nets shall represent the topology and protocols of the organization. Information theory, particularly an information theoretic model of the interacting decisionmaker, will permit the translation of the structure into an analytic expression of information processing workload, an indicator of reaction time. The next two chapters shall apply this framework to the problem of emergency control.

CHAPTER 4

BASIC ASSUMPTIONS AND THE TASK MODEL

4.1 BASIC ASSUMPTIONS THAT BOUND THE PROBLEM

The opening chapters introduced the submarine emergency control decision problem and a set of analytical tools with which to model it. As with any model, it is necessary to make certain assumptions that permit the application of the tools. In the present case, the same set of assumptions conveniently serves to bound the problem. Although this work seeks to characterize both the performance and workload of the ship control party, it is the latter, the information processing workload, which represents the bulk of the modeling problem. It is not surprising, therefore, that most of the assumptions to be made are necessary for the application of the information theoretic methodology presented in Chapter 3. These assumptions will be presented first, since they provide a precise definition of the problem to be solved. As shall be seen, by properly scoping the problem, the assumptions become quite reasonable. Those assumptions necessary for modeling the task input depend upon these opening assumptions and shall be presented thereafter.

Information theory is a statistical theory that has been extended for measuring the entropy, or information, of a signal processed by a system. The signal is assumed to take values from a finite set, called the input alphabet. Inputs are generated by a source at a given average rate. In emergency control, the decision process begins with a rapid observation of such an information source. By periodically inspecting or sampling that subset of the information made available to him by the ship and ballast control panels, each DM may be thought of as receiving a subset of the elements of a discrete input vector. Therefore,

- an emergency shall be modeled as a discrete event occurring at an instant in time.

This implies that the model will not consider evolving situations. Consideration of evolving situations is also precluded by the assumption that the decisionmakers are memoryless.

The information theoretic model of the human decisionmaker allows the computation of workload associated with the processing of repeatedly arriving tasks. In the case of emergency control, it is clear that the task interarrival time is large, on the order of months or more. (see Figure 4.1). In this case, a measure of average activity rate, F, is given by

$$F = G/\tau \tag{4.1}$$

$$F \rightarrow 0 \quad \text{as} \quad \tau \rightarrow \infty \tag{4.2}$$

where G is the total activity and τ, the mean signal interarrival time. As the time between emergencies approaches infinity, the average activity rate approaches zero.

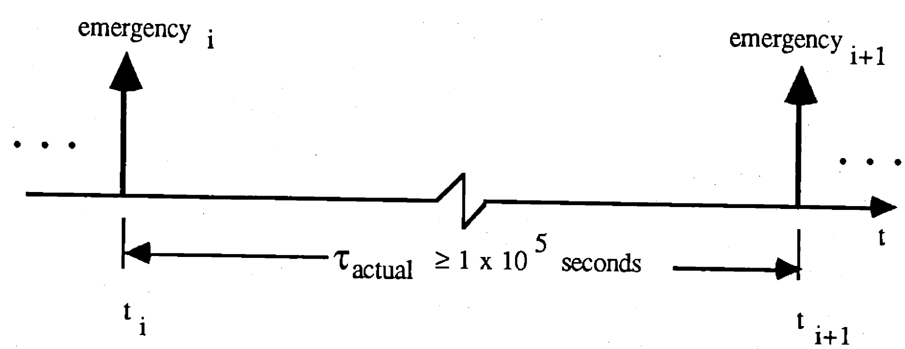


Figure 4.1. Interarrival Rate of Actual Emergencies

Another difficulty arising out of the large emergency interarrival time is the specification of probability distributions, which also approach zero as τ approaches infinity. Again, note that the SCP members are trained to inspect their instruments every several seconds [18], and to initiate the immediate actions (defined in Section 3.5) within approximately 5-7 seconds. Because one casualty may often trigger or be followed by other damage, the decisionmakers respond virtually as if another casualty were about to occur. Therefore it is reasonable to assume that:

- emergencies are considered not as rare events but repeated, independent ones (as in Fig. 4.2)

This single assumption allows information theory to be applied in this rare event context and at the same time facilitates the derivation of the task input.

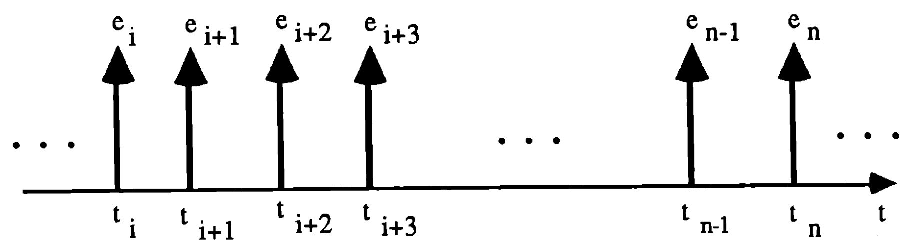


Figure 4.2. Assumed Interarrival Rate of Emergencies

$$5 \text{ secs} \leq \frac{\sum_{i=1}^{n} t_i}{n} \leq 7 \text{ secs} \tag{4.3}$$

Limiting consideration to the immediate actions permitted the assumption that task events arrived repeatedly. Fortunately, the same assumption can make this problem amenable to information theoretic modeling in yet another way. The immediate actions serve the purpose of rapidly identifying the precise nature of the situation and selection of a response to treat the "symptoms" - that is the potential dangers - of a casualty. The supplementary actions are more in the nature of a set of executable prescribed steps, taken after the resolution of the immediate danger, to identify and treat the causes and less urgent effects of a casualty. Therefore the following assumption, which is basic to the decisionmaking model, is rendered quite reasonable:

- model only the decision process consisting of situation assessment and response selection.

It is serendipitous that the immediate actions phase of the emergency control process, the phase placing the heaviest workload and the most extreme stress upon the decisionmakers, facilitates the use of an information theoretic approach. As such, it provides the most interesting problem to examine in terms of modeling workload and bounded rationality. This also means that a decision aid intended for workload reduction is most appropriate in the context of the immediate actions. Therefore it is assumed formally that:

- only the immediate actions shall be considered.

Finally, in this work

- detection of the emergency situation and execution of the selected response are not treated.

This implies that the specification of the task model will be such that the probability of the arriving input is conditioned upon knowledge that a casualty has been detected but not identified.

The information theoretic framework also requires assumptions to be made about the decisionmaking organization. The most notable of these assumptions is that the organization structure must be modeled as being acyclical and fixed in time. The actual organization is indeed well-structured. It is composed of decisionmakers whose tasks are well defined, and it operates according to certain protocols for the communication of information. Yet , perhaps the constraints placed by the information theoretic approach seem strong. Emergencies in complex systems may arise in an infinite variety of ways. So, it is impossible and unnatural for the organization designer to prescribe a single, fixed information structure that is best for all situations, at all times. Further, one easily imagines that the resolution of a complex emergency situation might cause cyclical interaction of decisionmakers.

However, by delimiting the model to consider only the extremely time-constrained immediate actions minimizes the likelihood that the organization structure will evolve during the emergency. Similarly, the tendency for time-consuming cyclical information exchanges should also be minimized.

4.2 TASK MODELING

An information theoretic discrete event task model is simply a specification of the letters of the organization's input alphabet, and the assignment to each of a probability. If the input is a vector, as it is in the case of emergency control, this means defining all possible, permissible combinations of element values which can occur, and the probability of each occurring. This combinatoric aspect of the modeling demands economy on the part of the modeler. The temptation to include information sources to enhance the model's fidelity and completeness exists, but their inclusion can quickly render the analysis computationally infeasible.

Submarine emergency control is a complex process. A simplified representation of the problem is therefore required which does not trivialize the decision process. The first step toward simplification is to discard all but the most difficult and dangerous casualties, the ones for which a decision aid could be most helpful. The casualties to be modeled are :

• plane casualty	loss of control casualties
• loss of hydraulic pressure	

• flooding

• indicator failure (false alarm)

The last of these accounts for the possibility that aspects of a casualty are manifest when the situation is not dangerous. This models the case that a response is erroneously and unnecessarily undertaken in response to a false alarm, which would exact a cost in terms of unnecessary noise and possibly damage to the ship.

This list does exclude the possibility of fire, loss of power, and other casualties. Since these emergencies only concern the ship control party indirectly, this exclusion seems sound.

Another simplification is to assume that

- only one casualty occurs at at time.

In this way, casualties will be considered mutually exclusive for the purpose of deriving probability distributions. This assumption is consistent with and reflects Navy training practice: the SCP is not taught to respond to compound casualties, only to one casualty at a time [18]. This means that decision rules have been formulated for the classes of emergencies under consideration here, and will be expressed as decision algorithms in the model.

It is further assumed that the task is that of

- fast attack submarine operating in patrol mode.

This is arguably the most interesting case. Patrol mode operation involves complex maneuvering and changes in depth at high speeds, as well as a high likelihood of encountering a complicating tactical situation.

As a formality, it is assumed that the submarine does not exceed the vehicle's maximum operating depth, also known as test depth. A final modeling assumption is that

- the sensed and indicated signals shall, in general, not be corrupted by noise.

Given the assumptions made thus far, it is possible to begin the formulation of a task model. Note that the probability distributions assigned are subjective probabilities derived from the experience of a U.S. Navy submariner [18]. In this sense they are modeling assumptions that can easily be adjusted to reflect differing sets of subjective probabilities pertaining to differing individual assessments, different submarine operating modes, or different submarines.

First, since the classes of casualties to be modeled have been assumed to be mutually exclusive and collectively exhaustive, a probability may be assigned to each such that:

$$\text{pr}(\text{plane casualty}) + \text{pr}(\text{hydraulic failure}) + \text{pr}(\text{flooding casualty}) = 1 \qquad (4.4)$$

Recall from Section 4.1 that these probabilities are assumed to be conditioned upon knowledge that a single, unidentified casualty has occurred.

It is now possible to consider individual information sources and the probabilities associated with them. The modeler soon discovers, though, that this step is closely coupled with the modeling of decision algorithms (to be discussed in Section 5.2). In the present case, this aspect of the modeling process was iterative; the original model incoporated a large number of information sources and developed algorithms of commensurate complexity to process this volume of information. This led to extreme complexity of representation and to computational infeasibility. Subsequent formulations of the model were of necessity less ambitious. In order to reduce the size of the input alphabet, the number of sources, as well as the number of states each discrete source was permitted to take, were reduced. The challenge here was to simplify the input, and the algorithms for processing this input, while retaining sufficient complexity for the model to capture the essence of the decision process.

The modeled inputs were thus reduced from the entire set below to include only those listed in boldface. These sources have been described in Section 3.3

control mode buzzer
control mode lights
stern plane angle
stick position cue

ship (forward) speed
ship depth
depth rate of change
trim angle
trim angle rate of change

hydraulics indicator
loss of power alarm
gyro alarms
water sensor alarms

flooding location
size of flooding pipe
(or hull penetration)

tactical situation

In this model discrete variables are represented as such. Continuous measurements, on the other hand, are discretized such that the "grain" of the sample space is as rough as non-trivial decision algorithms could process.

The development of the task model is divided into two parts. Casualty-independent and casualty-dependent sources are modeled separately, the latter derived on a case by case basis. Casualty-independent information, for this problem, consists of measurements of ship speed and depth, which are jointly distributed. Although stern plane angle position is not strictly independent of casualty state - since failure at a particular angle of this control surface is itself a most serious class of casualty - its distribution is strongly coupled with speed and depth. Therefore its distribution will be conditioned on these two variables.

The derivation of a joint distribution on speed and depth is facilitated by a set of curves known as the submerged operating envelope (SOE), discussed in Section 3.2, and depicted below in Figure 4.3. The reader should attach no special significance to the ranges given for speed and depth, nor to the absence of actual values. The SOE curves for specific vessels are not published; however, the numbers themselves do not enter into the analysis. They may be substituted and adjusted to suit any user of the model. Of greater importance are the number of states each variable is permitted to assume, and the probability associated with each state. The latter may also be conveniently adjusted. That the probabilities have been defined to two significant figures is not intended to imply precision in assignment, but to reflect subjective probability and simultaneously enable the probabilities to sum to one.

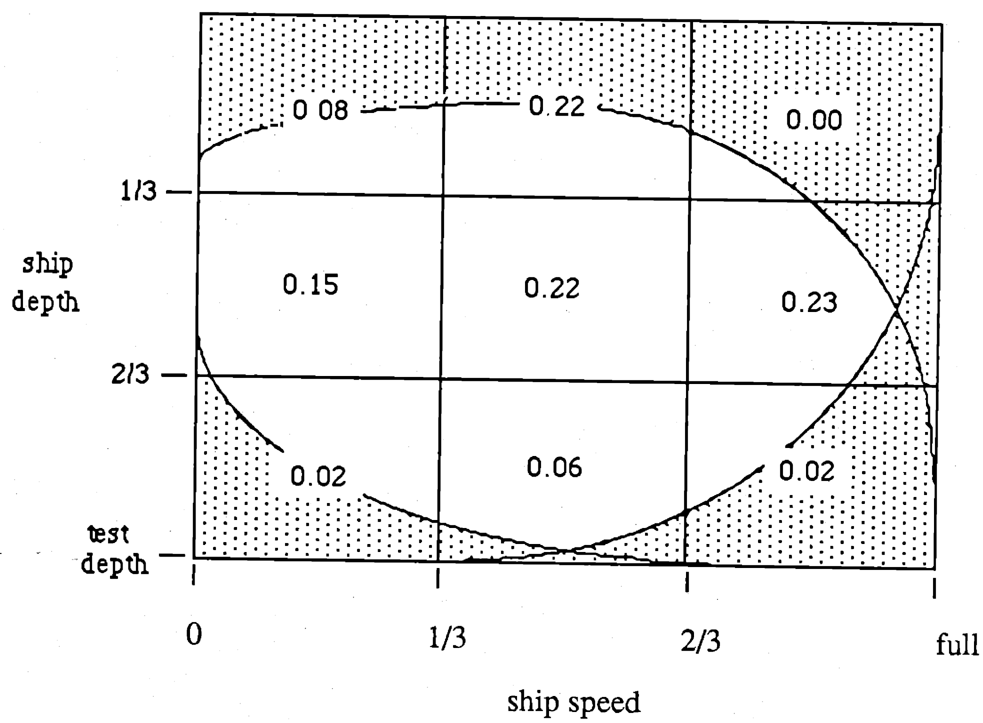


Figure 4.3 Assumed Joint Probability Distribution of Submarine Speed and Depth
(Superimposed on the Submerged Operating Envelope)

What this figure says, in brief, is that for safe operation, a submarine will seldom operate at the extremes of its speed and depth ranges.

Next, stern plane angle is considered as a function of speed and depth. The first assumption here is that the stern plane angle has its position measured at the time of failure. This distribution will likely be independent of the ship's depth. It should, however, depend upon its speed: at slow speeds, planes are controlled in "normal mode" or "follow-up control" which is subject to electrical failure, while at higher speeds "rate control" is used, subject primarily to human error (assumed to be minimal). This equates to greater concentration of the stern plane angle probability distribution about zero. The assumed distribution, then, for low and medium speeds, is given in Table 4.1.

TABLE 4.1 PROBABILITY DISTRIBUTION OF STERN PLANE ANGLE FOR LOW AND MEDIUM SPEEDS

pr (large negative angle)	= 0.10
pr (medium negative angle)	= 0.15
pr (small negative angle)	= 0.25
pr (small positive angle)	= 0.25
pr (medium positive angle)	= 0.15
pr (large positive angle)	= 0.10
Σ	= 1.00

For high speed operation, the assumed distribution is that shown in Table 4.2:

TABLE 4.2 PROBABILITY DISTRIBUTION OF STERN PLANE ANGLE FOR HIGH SPEEDS

pr (large negative angle)	= 0.00
pr (medium negative angle)	= 0.10
pr (small negative angle)	= 0.40
pr (small positive angle)	= 0.40
pr (medium positive angle)	= 0.10
pr (large positive angle)	= 0.00
Σ	= 1.00

The joint distribution for speed, depth and plane angle appears in Appendix A.

Next, the casualty-dependent information sources are characterized, beginning with the control mode buzzer. It is assumed that this source is activated for all plane casualties. Since the probability that a particular casualty is a plane casualty has been assumed to be 0.40, then the distribution for the control mode buzzer becomes:

pr (control mode buzzer is active)	= 0.40
pr (control mode buzzer is inactive)	= 0.60
Σ	= 1.00

For the actual system, the probability that the buzzer is always activated when a plane failure occurs is not strictly equal to one, but the probability of the buzzer system failing in this manner is assumed to be negligible.

Recall that the control mode light indicates the set of planes which the control mode buzzer warns may have failed. The distribution on the four states this variable may take, derived as being conditioned upon knowledge of the control mode buzzer state, assumes essentially equal probability of failure for each set of planes, as in Table 4.3.

TABLE 4.3 PROBABILITY DISTRIBUTION OF CONTROL MODE LIGHT
(CONDITIONED UPON KNOWLEDGE OF CONTROL MODE BUZZER STATE)

pr (control mode light : inactive l control mode buzzer : inactive)	= 0.00
pr (control mode light : sternplane l control mode buzzer : active)	= 0.34
pr (control mode light : rudder l control mode buzzer : active)	= 0.33
pr (control mode light : fairwater planes l control mode buzzer : active)	= 0.33
Σ	= 1.00

With respect to the physical system, there exists, as in the case of the control mode buzzer, a non-zero probability of failure of the control mode light system itself, but it is assumed here to be negligible.

Characterization of the hydraulic alarm is analogous to the control mode buzzer:

$$\begin{aligned} pr\,(\text{ hydraulic alarm is active}) &= 0.20 \\ \underline{pr\,(\text{ hydraulic alarm is inactive })} &= \underline{0.80} \\ \Sigma &= 1.00 \end{aligned}$$

The probability distribution for the stick position cue embodies the information gained by observing whether the indicated stern plane angle follows the position commanded by the Lee Helm's stick. It is given in Table 4.4 as a distribution conditioned upon knowledge of the states of the control mode buzzer, control mode light, and the hydraulic indicator. The probability of the buzzer being activated spuriously, or for trivial plane casualties, is incorporated in this distribution. For convenience, the variable states are represented by integer codes: 1 and 0, respectively, indicate activity and inactivity of any binary source, while 1, 2, and 3 correspond to stern planes, rudder, and fairwater planes states of control mode lights.

TABLE 4.4 PROBABILITY DISTRIBUTION OF STERN PLANE ANGLE AND STICK POSITION CUE

(CONDITIONED UPON KNOWLEDGE OF CONTROL MODE BUZZER, CONTROL MODE LIGHT, HYDRAULIC ALARM)

$$\begin{aligned} pr\,(0 \mid 0, 0, 0) &= 1.00 \\ \underline{pr\,(1 \mid 0, 0, 0)} &= \underline{0.00} \\ \Sigma &= 1.00 \end{aligned} \qquad \begin{aligned} pr\,(0 \mid 1, 1, 0) &= 0.10 \\ \underline{pr\,(1 \mid 1, 1, 0)} &= \underline{0.90} \\ \Sigma &= 1.00 \end{aligned}$$

$$\begin{aligned} pr\,(0 \mid 1, 2, 0) &= 1.00 \\ \underline{pr\,(1 \mid 1, 2, 0)} &= \underline{0.00} \\ \Sigma &= 1.00 \end{aligned} \qquad \begin{aligned} pr\,(0 \mid 1, 3, 0) &= 1.00 \\ \underline{pr\,(1 \mid 1, 3, 0)} &= \underline{0.00} \\ \Sigma &= 1.00 \end{aligned}$$

$$\begin{aligned} pr\,(0 \mid 0, 0, 1) &= 0.50 \\ \underline{pr\,(1 \mid 0, 0, 1)} &= \underline{0.50} \\ \Sigma &= 1.00 \end{aligned}$$

The probability of all other joint states of the conditioning variables, as derivable from the marginal distributions presented, is zero.

The final distributions to be characterized are those that define flooding casualties. This information is typically provided in the form of verbal reports of flooding in which the location and magnitude of the leak are given. The flooding location has been discretized by limiting flooding to three spaces: (1) engine room, (2) torpedo room, and (3) diesel room. In addition to an inactive state representing the arrival of "no flooding" report, a fifth state is included to model the possibility of a garbled and unidentifiable flooding location report.

pr (flooding location : inactive)	= 0.60
pr (flooding location : active)	= 0.40
	Σ = 1.00

If no garbling were modeled, the assumed distribution for active flooding cases would be:

pr (flooding location : engine room)	= 0.28
pr (flooding location : torpedo room)	= 0.08
pr (flooding location : diesel room)	= 0.04
pr (flooding location : active)	= 0.40

However, for an assumed garbling rate of 10%, i.e. garbling of every tenth report on average, the distribution becomes:

pr (flooding location : engine room)	= 0.25
pr (flooding location : torpedo room)	= 0.07
pr (flooding location : diesel room)	= 0.04
pr (flooding location : garbled)	= 0.04
pr (flooding location : active)	= 0.40

The severity of flooding is indicated by a report of the size of pipe or hull penetration admitting seawater. Three size ranges are permitted in the model: (1) 1/2" - 2" (small), (2) 2" - 6" (medium), or (3) > 6" (large).

Because ship spaces differ in terms of piping configuration, these two variables are statistically dependent. The distribution for pipe size reports is derived as conditional upon knowledge of the flooding location. For example, the large hull penetrations in the torpedo room appear as a high probability of the flooding pipe size being large, > 6". (Note that in the event of garbled flooding location reports, the conditional distribution of pipe size is equivalent to pipe size's marginal distribution, since the knowledge that [flooding : garbled] contributes only the information that a flooding condition exists). Using the integer codes for convenience, the conditional distribution is given in Table 4.5.

TABLE 4.5 PROBABILITY DISTRIBUTION OF FLOODING PIPE SIZE
(CONDITIONED UPON KNOWLEDGE OF FLOODING LOCATION)

inactive	small: 1/2" - 2"	medium: 2" - 6"	large: > 6"	Σ pr
pr (0 I 0) = 1.00	pr (1 I 0) = 0.00	pr (2 I 0) = 0.00	pr (3 I 0) = 0.00	1.00
pr (0 I 1) = 0.00	pr (1 I 1) = 0.10	pr (2 I 1) = 0.50	pr (3 I 1) = 0.40	1.00
pr (0 I 2) = 0.00	pr (1 I 2) = 0.05	pr (2 I 2) = 0.10	pr (3 I 2) = 0.85	1.00
pr (0 I 3) = 0.00	pr (1 I 3) = 0.80	pr (2 I 3) = 0.20	pr (3 I 3) = 0.00	1.00
pr (0 I 4) = 0.00	pr (1 I 4) = 0.30	pr (2 I 4) = 0.20	pr (3 I 4) = 0.50	1.00
Σ = 1.00	Σ = 1.25	Σ = 1.00	Σ = 1.75	5.00

Since the pipe size distributions for five flooding report condtions are presented, the sum of all the probabilities must sum to 5.00. Dividing the sums at the bottom of each active pipe size column by 4.00, which is the sum of the four distributions conditioned upon an active flooding state, yields:

pr (pipe size: small)	= 0.31
pr (pipe size: medium)	= 0.25
pr (pipe size: large)	= 0.44
Σ	= 1.00

which are the assumed probabilities of flooding by compartment, when a flooding condition is known to exist.

This chapter made explicit the assumptions necessary to model the emergency control decision problem using an information theoretic approach, and showed how those assumptions were used to bound the problem and how bounding the problem made reasonable many of the assumptions. It then applied some of these assumptions in the formulation of a task model, characterizing the sources of information necessary to make an emergency control decision. It should be kept in mind that the numbers cited herein reflect the underlying assumptions and the subjective experiences of a submariner [18], and can readily be adjusted. Furthermore, as will be seen in Chapter 6, fluctuations in the input do not significantly disturb the computed workload.

Some basic assumptions introduced in the first section of this chapter, but not yet addessed, are germane to the descriptive organizational model, developed in the following chapter. That chapter describes the SCP in detail, models the organization, and proposes a decision aid on the basis of this description. It concludes with a discussion of the theory behind the analysis of the organization, which is implemented in Chapter 6.

CHAPTER 5

THE ORGANIZATION MODEL

The previous chapter introduced assumptions basic to the formulation of the model and derived from these, and from the physical problem, a model of the task faced by the Ship Control Party. This chapter describes the ship control party in its response to such an emergency task in order to develop an organization model.

Recall the organization-relevant assumptions made in section 4.1. In brief they are that the immediate actions (described in section 2.3) be modeled, and be considered to include, neither casualty detection nor response implementation, but focus on situation assessment and response selection. The organization is assumed to be acyclical, that is, it contains no feedback loops, and processes each discrete task on a single pass. This model should therefore embody a structure that is both likely and well-configured for handling the emergency task in such a manner. The development shall begin by describing the organization in overview - which decisionmakers receive what information and how the processed information is shared - and shall culminate in a Petri Net representation of the modeled structure. Then, a description of the process at a lower level will enable the formulation of models of the individual decisionmakers at the structural and algorithmic levels.

Once the model has been laid out in detail, a decision aiding scheme is introduced, with an explanation provided as to how the aid fits into the existing model conceptually and analytically. Next, the analytic expressions for information processing activity are given, followed by a discussion of the organization's decision strategies in the unaided and aided cases. The chapter concludes with a discussion of organization performance.

5.1 ORGANIZATION MODELING

The ship control party consists of five decisionmakers: the Officer of the Deck (OOD or O), the Diving Officer of the Watch (DOOW or D), the Chief of the Watch (COW or C), the Lee Helm (L), and the Helm (H). The organization has hierarchical and parallel aspects (see Figure 5.1).

At the top of the structure is the OOD, who has the responsibility for integrating the ship control process with the other aspects of the ship's mission. For emergency control, his job is

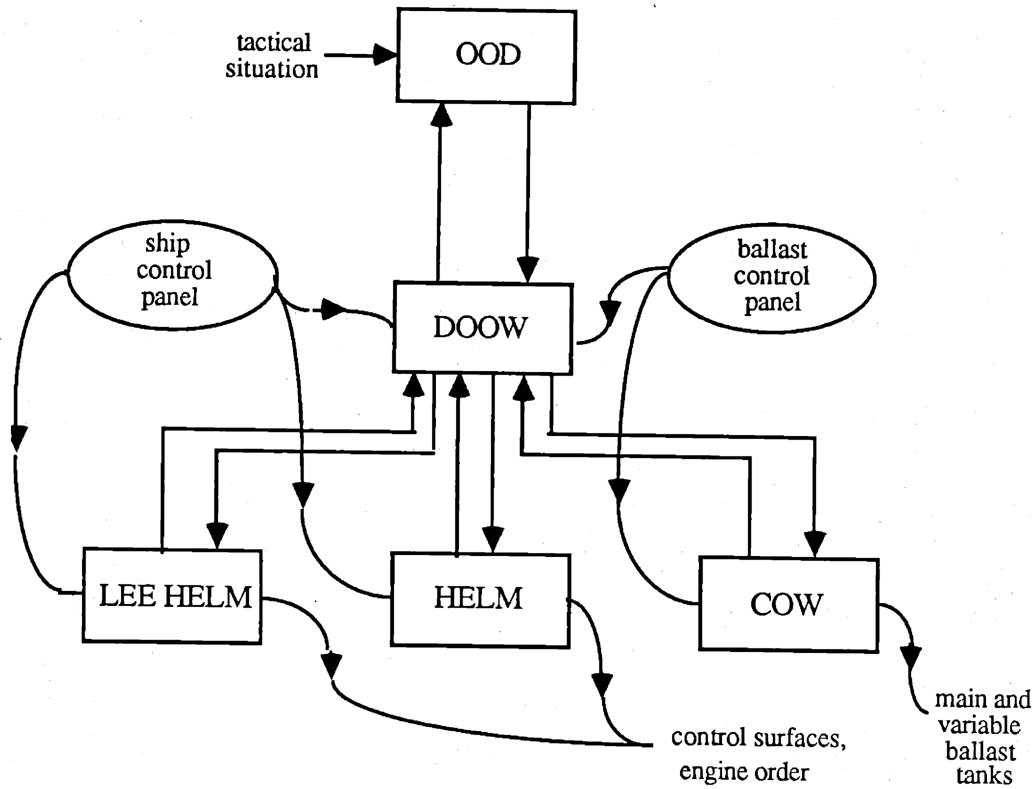


Figure 5.1 The Ship Control Party

essentially to decide whether certain aspects of the emergency response should be restricted because of the existence of a sensitive tactical situation. Second in command is the DOOW whose task in the emergency context is to direct and monitor the actions of his subordinates responding to the casualty, subject to any restrictions placed by the OOD. The COW and the helmsmen comprise the bottom tier of the organization, immediately under the DOOW. The COW receives all information on flooding casualties and hydraulic failure, which he shares with the DOOW. He is also in charge of controlling the ship ballast system for aiding in the control of depth. The Lee Helm, L, drives the ship's stern planes, the control surface that modulates the vehicle's trim angle and thus its depth. In performing this task, L receives information about the plane angle and the control mode (discussed in 3.3) as well as ship state information (speed, depth, trim, etc.). Finally, the Helm, H, controls the ship's rudder and fairwater planes (the small control surfaces located on either side of the sail, as in Figure 3.1) based on plane angle information, and the same control mode and ship state information available to L.

The topology of the modeled ship control party is represented as a Petri Net, as shown in Figure 5.2. Petri Net theory not only permits a precise representation of the organization structure but may be used as a tool for analyzing such properties of the organizations as delays [14], [15]. Provided below is an explanation of the model in general terms. Note that all shared information and commands in the model represent verbal communications.

As seen in Figure 5.2, the OOD is modeled as a single algorithm, denoted as IF^o, which considers the information fused by the DOOW, $\bar{z}^{do}$, and the tactical situation to produce the command v^o which may restrict the response options available to the DOOW.

The DOOW appears in the model as the most complex member, which reflects the complexity of the decision task he faces. The DOOW model illustrates as complicated a decisionmaker as can be modeled with the present methodology, complete with rich examples of the four stages of the Boettcher model [6] - SA, IF, CI, and RS - as well as an internal preprocessing stage (PP) introduced by Chyen [11]. Inputs to the DOOW's preprocessing stage are the partition $\underline{x}^d$ of the input vector X, as well as shared information from the COW, z^{cd}. While shared situation information normally is fused in the IF stage, the methodology is flexible enough to permit situation information from one DM to be considered in the situation assessment stage of another, as this particular application required. The preprocessing stage filters extraneous information and selects, using u^d, the appropriate SA algorithm from the available three. One SA algorithm handles apparent plane casualties, another hydraulic failures, and the third, flooding casualties. This assessment is fused with the assessments of the two helmsmen, L and H, to produce $\bar{z}^{do}$ (shared with the OOD) and z^d. The situation $\bar{z}^d$ and the command v^o serve as the basis for the choice of the RS algorithm to process $\bar{z}^d$. Four such algorithms are modeled, two for flooding casualties and two for loss of control casualties; one of each is better suited than its counterpart for situations of tactical concern. The selected RS algorithm yields a vector of three commands directed at the COW, L and H.

The COW receives $\underline{x}^c$ from the ballast control panel and telephone and produces an assessed situation, z^{cd}, transmitted to the DOOW. The signal $\underline{z}^c$ (which includes the information in z^{cd} as well as ship state information relevant to response selection) is fused with v^{oc} (an audible command to the DOOW) and z^{lc}, yielding $\bar{\underline{z}}^c$. The signals $\bar{\underline{z}}^c$ and y^{dc} in turn influence the choice of RS algorithm.

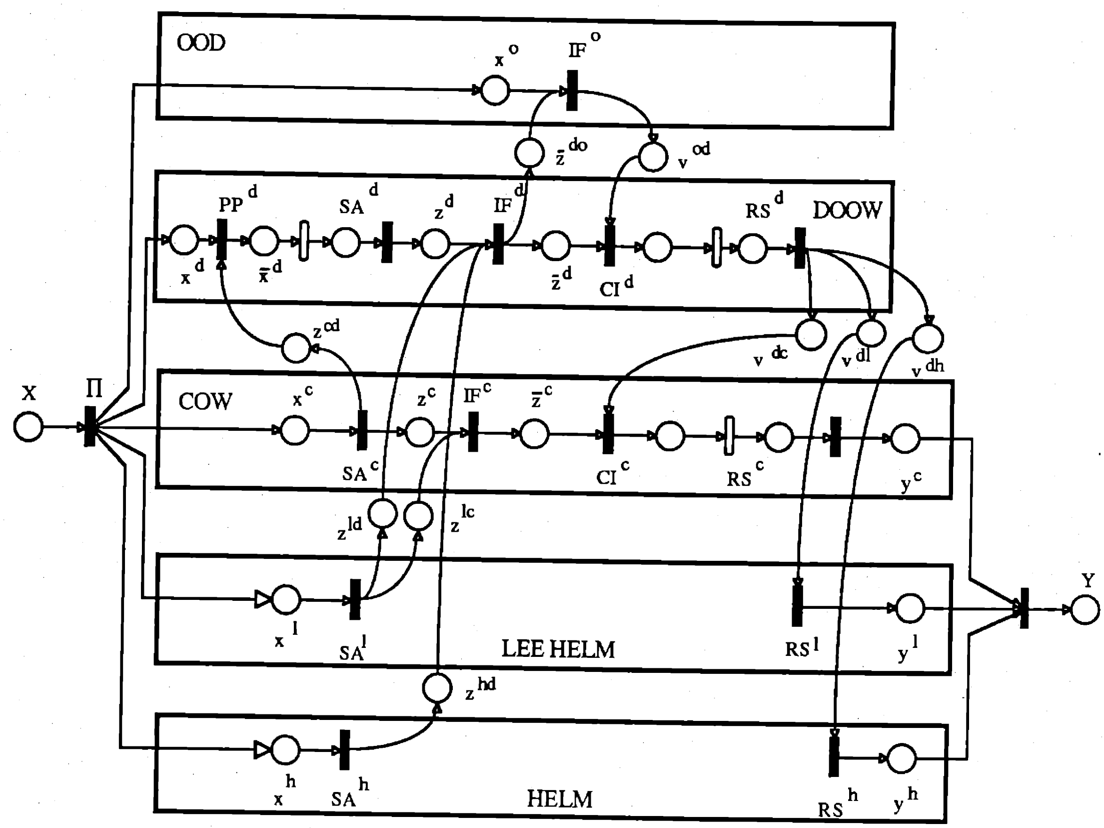


Figure 5.2 Petri Net Representation of the Ship Control Party

The helmsmen, L and H, both gather information, $\underline{x}^l$ and $\underline{x}^h$ respectively, from the ship control panel. Both share their assessed situation with the DOOW. The Lee Helm shares situation information as well with the COW. Neither carry information through to the RS stage. IF and CI are omitted and the response is identically that commanded by the DOOW.

5.2 THE DECISION PROCESS

The previous section described the decisionmakers and their internal algorithms only inasmuch as they pertain to the overall structure of the organization. Fleshing out this skeletal model means representing a complex cognitive process as a well-defined one for which all variables and variable interconnections are specified such that probability distributions on these variables may be derived. Recall from Section 2.3.1 the key assumptions: (1) DMs are memoryless, (2) the internal algorithms are deterministic, (3) no rejection of information by algorithms occurs, and (4) only one algorithm in any particular stage is active at a given time. With these and with the task model, organization structure, and an understanding of the actual decision problem, the individual DMs may be modeled in detail.

5.2.1 The OOD Model

At the top of the hierarchy is the Officer of the Deck (OOD), with responsibility for all ship control matters pertaining to the conduct of the submarine's mission. Control of the motion of the ship is an integral part of target identification, tracking, and pursuit and must be closely coordinated with other aspects of the ship's mission, such as fire control. Most of emergency control thus consists of decisions on a lower level than that attended to by the OOD, whose supervisory role consists in restricting the severity of response to an emergency when the ship's tactical situation is such that an unrestricted response would jeopardize the submarine's mission. Such harm could result from the creation of undue noise or potentially from collision with a submerged or surfaced sonar contact. Restriction of response options, also discussed in the explication of DOOW's algorithms, essentially imposes a more stringent set of conditions for the emergency blowing of the main ballast tanks, which normally aid in controlling rate of ascent. An emergency main ballast tank (EMBT) blow drastically reduces the weight of the ship, but radiates much noise. The limited nature of the OOD's involvement in actual emergency control, especially in terms of information processing, led to the modeling decision that a single algorithm would suffice to represent it. The apparent simplicity of the OOD in this model, and the low information processing workload one would expect from it, reflect only the fraction of the total OOD load that he may dedicate to the emergency control task. The modeled algorithm combines properties of three stages of the basic DM model (presented in 2.3.1): (1) processing task information X^o, as in the generalized SA stage, (2) fusing shared information, $\bar{z}^{do}$, from the DOOW, and (3) producing a command response. For labeling purposes this algorithm will be referred to as information fusion (IF^o). The OOD is modeled as receiving tactical situation information that is either critical or non-critical. A series of binary comparisons produces a restrictive response, if the tactical situation is critical and if the fused situation assessment is serious enough that a tactical restriction could apply. If the tactical situation is non-critical, or if it is critical but the assessed situation is not, no option-restricting command is issued by the OOD.

5.2.2 The DOOW Model

The Diving Officer of the Watch (DOOW) is responsible for the bulk of the emergency control decision process. The job requires a thorough understanding of all ship systems and how their failure during any state (depth, speed, orientation, weight) should be diagnosed and handled. The latter knowledge, in the form of a complex set of decision rules, has been modeled as a set of binary decision trees, given in Appendix A.

The DOOW receives the partition of raw task input from the ship's control panel nearly identical to that processed by the helmsmen. This DM also has a vantage of the ballast control panel but, since any significant information from this source is reported by the COW and since this may include flooding reports over a telephone heard solely by the COW, all ballast control panel information received by the DOOW is modeled as a signal transduced by the COW. Both sources of information, $\underline{x}^d$ and z^{cd}, first enter the DOOW's preprocessing stage (PP^d). A preprocessing function was chosen here because the DOOW consistently activates a single, best situation assessment algorithm to process each instance of the particular class of casualty suspected to have occurred. The role of the preprocessor is to check key elements of the vector $\underline{x}^d$ and scalar z^{cd}, for activity of the control mode buzzer, the hydraulic alarm, or flooding reports, set the decision variable, u^d, to point to the single appropriate algorithm of the three available, and transmit to it $\bar{\underline{x}}^d \in \underline{x}^d$, that subset of raw information relevant to the assessment of the active class of casualty.

The first SA algorithm, f^{d1}, (note that the numbering of multiple algorithms in a particular stage is arbitrary) assesses suspected stern plane casualties. An indicator failure is presumed to exist if indicated stern plane angle tracks stick position. Should these fail to correspond, however, the plane angle is checked to determine whether a rise or dive condition exists, and how severe that condition is. Since rate of depth change is a positive function of plane angle magnitude and ship speed, and since depth extremes represent the danger to be avoided, speed and depth are taken into account in assessing the seriousness of the casualty. Severe dive or rise conditions are known as "jams", while less serious ones are referred to as "stuck" conditions.

The second SA algorithm, f^{d2}, assesses potential hydraulic failures. A failure of the hydraulic system often leads to the loss of control of planes. By checking stick/plane angle correspondence, stern plane angle, speed and depth, as illustrated in Appendix A, an apparent hydraulic failure may be assessed either as non-serious or as a virtual stern plane casualty.

The third and final SA algorithm of the DOOW assesses flooding casualties. It determines whether the failure is severe (pipe size > 6") and whether or not it has occurred in the engine room, in which case the implications and appropriate response differ from those for other flooded spaces. For all three algorithms, $\underline{z}^d$ is a three element vector consisting of assessed situation, speed, and depth, respectively.

THe DOOW's information fusion algorithm, IF^d, sets the fused situation assessment, $\underline{\bar{z}}^d$, equal simply to $\underline{z}^d$ unless $\underline{z}^d$ indicates a non-serious situation and either z^{ld} or z^{hd} indicate a rudder or fairwater plane failure, in which case $\underline{\bar{z}}^d$ is assigned the indicated failure. At this point the DOOW sends to the OOD $\bar{z}^{do}$, which is exactly equal to $\bar{z}_1{}^d \in \underline{\bar{z}}^d$.

The command interpretation algorithm receives as input $\underline{z}^d$ and v^{od} and deterministically produces $\bar{v}^d$. The decision variable v^d points to one of four RS algorithms, consisting of a set of two algorithms appropriate for loss of control casualty response (h^{d1}, h^{d3}) and another set of two for flooding casualties (h^{d2}, h^{d4}). Each set contains one algorithm for tactically restricted cases and one for unrestricted cases.

The loss of control RS algorithms (h^{d1}, h^{d3}) primarily determine for stern plane casualties whether the situation, in terms of speed and depth, is serious enough that an EMBT blow is in order. If so, the action is ordered. If not, the less severe response of pumping water overboard is selected. The location of the flooding affects the commanded engine order. The DOOW selects a stock response when control over rudder or fairwater planes is lost. The algorithms h^{d2}, h^{d4} operate analogously for flooding casualties and select different responses on the basis of flooding location. The difference between restrictive and unrestrictive algorithms for both classes is that restrictive algorithms utilize a more extreme set of rules for selecting EMBT blow as a response.

The RS stage of the DOOW produces one of twelve response states represented by the three element vector $\underline{y}^d$, whose elements y^{dc}, y^{dl}, and y^{dh} may take on four, eight, and nine values respectively (see Table A.1).

5.2.3 The COW Model

This decisionmaker is responsible for the monitoring and operation of a number of ship systems, the most notable, in the context of emergency control, being the main and variable ballast tanks. These are critical in attaining and maintaining ordered depth and trim. As described in previous sections, EMBT blow also serves as an extreme (and extremely noisy) response to situation in which the ship would otherwise descend to a depth from which no recovery would be possible.

The first emergency control process of the modeled COW is to transduce hydraulic failure or flooding casualty information to the DOOW. This is normally straightforward, except in the event that flooding reports arriving over the phone are garbled. In this case, the COW interprets the report before relaying it to the DOOW. Information fusion, IF^c, consists simply of incorporating any reports by the Lee Helm of potential jam dive, which may be processed in the RS stage. The command interpretation stage, CI^c, points to one of five RS algorithms on the basis of v^{dc} and the strategy $p(\bar{v}^c \mid \bar{z}^c, v^{dc})$ (to be discussed in detail in Section 5.4). When the command, v^{dc}, is EMBT blow (due to a dive or flooding situation), or to pump water on board (due to stern plane jam or stuck rise), a deterministic selection of the corresponding algorithm is made. If, however, the DOOW commands that water be pumped overboard or that no emergency response be undertaken, a stochastic choice between algorithms is made according to the RS strategy (see Section 5.4.2).

Of the five RS algorithms, four (h^{c1}, h^{c2}, h^{c3}, h^{c5}) are simply identity algorithms, while the fifth (h^{c4}) is a complex algorithm which models the COW's ability to select an EMBT blow according to his own discretion. The decision rules here are more restrictive than the DOOW's restrictive conditions for EMBT blow, and may be invoked if, for some reason, the DOOW selects a response almost certain to result in the loss of the ship.

5.2.4 The Lee Helm Model

Also known as the outboard planesman, the Lee Helm is responsible for controlling the stern planes. Doing so requires periodic inspection of the ship control panel and cross checking of various redundant sources of information. For this model, L is presumed to receive a subset of the vector of information modeled as issuing form the ship control panel, as discussed in Chaper 4. Upon the sounding of the control mode buzzer, L inspects the control mode light to ascertain if the stern planes are indicated. If so, L checks whether the stick moves the stern plane angle indicator. If not, L determines and reports the severity of the condition, stuck or jammed, and whether the position is rise or dive. The response selection algorithm processes received commands with an identity algorithm, no discretion being involved.

5.2.5 The Helm Model

This DM, sometimes called the inboard planesman, controls the rudder and fairwater planes and is repsonsible for transmitting the engine order. The Helm's decision process is relatively simple, modeled as a transduction of the status of the rudder and fairwater planes, jammed or not. Like the Lee Helm, the Helm is modeled as responding strictly as ordered.

5.3 SELECTION AND MODELING OF THE DECISION AID

The organization's emergency decision problem is to arrive at an appropriate response, subject to a constraint on time. A decision aid should therefore improve the likelihood of appropriateness of the response or the ability of the decisionmaker to meet the time constraint or both. A preprocessing decision aid, as described in [11], does so by improving the DMs' ability to choose an appropriate decision strategy and/or by reducing the information processing workload faced by the DM. Clearly, the first task facing the designer of the aid is to determine where in the organization overload or error is likely to occur.

The model shows, in the Petri Net representation (Figure 5.2) and workload equations, (Section 5.4) how the DOOW forms the bottleneck in the organization, clearly bearing the greatest burden in terms of information processing workload and responsibility for appropriateness of response [18]. This is also seen in the workload results presented in

Chapter 6. The DOOW is therefore the most logical candidate for decision aiding. The question now is precisely what information should this decision aid supply?

Aboard existing submarines, the DOOW is aided in making emergency decisions by a number of aural and visual alarms (some of which were described in Section 3.3). These alarms may be considered crude preprocessors since, in addition to aiding detection of a casualty, they flag the DOOW to an appropriate decision strategy.

Modern and emerging technology for sensing, information processing, and display may lead to aids of increasing sophistication and to individuals who envision "aids" that compute actual decision responses. It is important to note that such a device would not merely aid but, in effect, replace the DM by automating the entire decision process. This thesis draws a distinction between decision aiding and automation; the latter, considered a separate issue, is not treated here. Instead, the philosophy is to keep the human decisionmaker "in the loop", retaining control over and responsibility for the outcome of the decision process. This view is consistent with most military practice. Automation thus proscribed, the question becomes: how might a sophisticated fault tolerant processor and display reduce the workload and improve the performance of the SCP?

A new preprocessor might display situation-relevant information only, filtering out that which is extraneous. Such an aid could reduce workload and indirectly improve performance. What could do this more effectively, and with little additional effort, is a situation assessment aid, i.e. a preprocessor operating upon a vector of input information subsuming that which the DOOW normally receives, which computes an actual situation assessment and transmits to the DM the assessment and only that information necessary to select a response given the assessment [as in 20, p.58]. The reason that this is not much more difficult than the filtering preprocessor is that transmitting situation-relevant information requires knowledge of the situation, which could be transmitted as well. This might reduce workload and, if the aid is reliable, increase performance. Now that an aiding scheme has been arrived at, how will it be modeled?

First it is presumed that the aid will <u>not</u> replace existing instruments but be included among them on the ship control panel. Instrumentation redundancy is an important consideration here; another is that standard training methods based upon traditional instrumentation are not likely to be radically changed by the introduction of a single exotic component which, under ideal conditions, will never be used. Additional assumptions are that the aid is absolutely reliable, generating situation assessments without error, and that the user is not certain about the reliability of the aid. Given these assumptions, what is the real nature of the decision faced by the user should a casualty be detected?

The aided DOOW is in fact faced with a decision about the use of the aid itself. At one extreme, the DOOW could block the information provided by the decision aid and assess the situation with the usual algorithms. Such a decision could result from any number of individual factors ranging from a lack of trust in the aid, perceived devaluation of hard-won skills, or simple resistance to change [21]. At the opposite extreme, the DOOW may rely solely on the aid for the assessed situation without employing the SA algorithms at all. This might be the case if the DOOW were inexperienced or panic stricken. Between these two extremes lies a third possibility: situation assessment by algorithm, followed by comparison of the resulting assessment with the information offered by the aid.

Modeling this range of possibilities required modifying the model of the DOOW. This was done in such a way that the DOOW would possess three SA algorithms, one representing each extreme described above, and a third capturing the option where both approaches would be employed and the results compared.

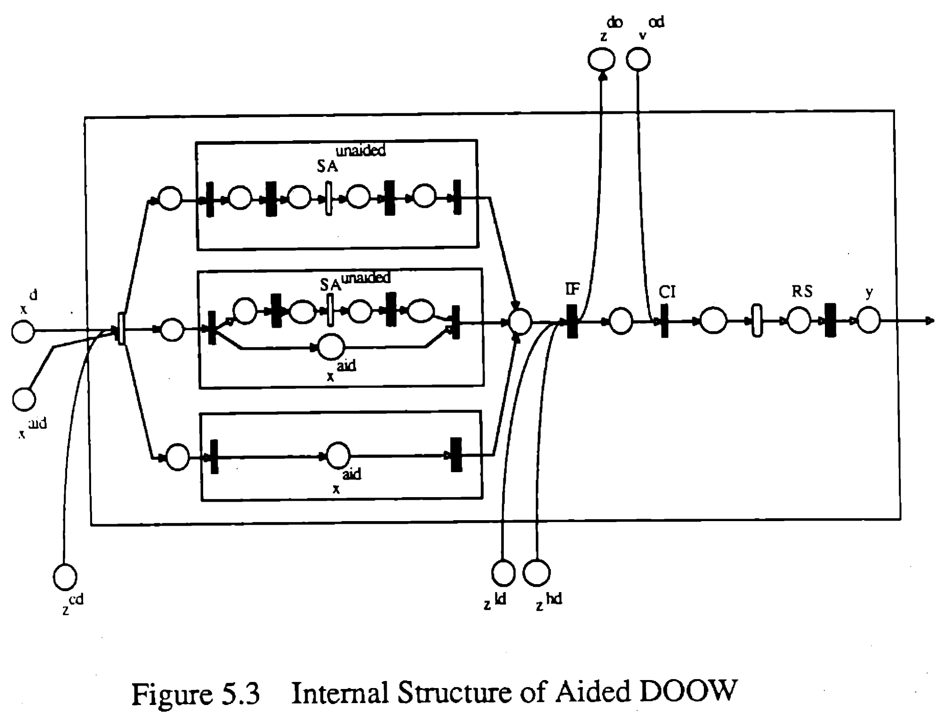


Figure 5.3 Internal Structure of Aided DOOW
(SA transitions expanded to show detail)

Refer to Figure 5.3. The top SA algorithm is composed of the PP and SA stages of the unaided DOOW. The bottom algorithm is simply an identity algorithm mapping the aid's assessment directly into the variable z^d. Finally, the middle algorithm, representing those possiblilites that fall in between, incorporates both the other SA algorithms. It was assumed that the DOOW would compare the two assessments and choose the worst case. Although other schemes are conceivable, this one seems most likely. As will be discussed in Section 5.4.4, it is more costly to respond insufficiently to a casualty than to respond excessively.

The worst case comparison is modeled with a constant 11 x 11 matrix (11 being the dimension of the assessed situation z^d). This is presented in Figure 5.4. To each pair of assessments that could feasibly be made for a particular casualty, the matrix simply yields that which is more serious, or that the assessments are equally serious. (Note: this ranking scheme was specified subjectively by an experienced submariner [18] but can be adjusted to reflect any set of beliefs). In the event that the assessments are of equal seriousness, the model sets z^d equal to the DOOW's own assessment.

z^d \ x'	normal (ind. flr.)	jam dive	stuck dive	stuck rise	jam rise	rudder flr.	fwplane flr.	fldg. >6" eng. rm.	fldg. >6" not e.r.	fldg. <6" eng. rm.	fldg. <6" not e.r.
normal (ind. flr.)	0	1	1	1	1	1	1	1	1	1	1
jam dive	-1	0	-1	-1	-1	-1	-1				
stuck dive	-1	1	0	0	0	-1	-1				
stuck rise	-1	1	0	0	1	-1	-1				
jam rise	-1	1	0	-1	0	-1	-1				
rudder flr.	-1	1	1	1	1	0	1				
fwplane flr.	-1	1	1	1	1	-1	0				
fldg. >6" eng. rm.	-1							0	0	-1	-1
fldg. >6" not e.r.	-1							0	0	-1	-1
fldg. <6" eng. rm.	-1							1	1	0	0
fldg. <6" not e.r.	-1							1	1	0	0

Figure 5.4 The Situation Assessment Worst-Case Comparison Matrix

With the three aid options cast as situation assessment algorithms, evaluation of workload and performance may be performed essentially as in the unaided case, except that the organization now has, because of the three new paths, three times as many pure organizational strategies as in the unaided case (see section 5.4). As will be seen, analysis of the convex combinations between these pure strategies will capture as information processing workload any uncertainty faced by the decisionmaker in choosing a strategy for use of the decision aid.

5.4 WORKLOAD, DECISION STRATEGIES, AND EVALUATION

With the model completely specified, steps toward evaluating the organization may proceed. Chapter 2 introduced the approach as a twofold process, computing both workload of the individual DMs and a measure of organization performance as functions of decision strategy. This section first develops the information theoretic expressions describing the organization's workload, for both the unaided and aided cases, then moves on to discuss the nature of the decision strategies in both cases, especially as they pertain to evaluation.

Derivation of the expressions for information processing workload depends upon specification of the organization structure and, at minimum, the number of SA and RS algorithms and the number of internal variables they possess. Presented in 5.1, 5.2 and Appendix A, these aspects of the model permitted the following expressions to be derived. The derivations are presented in Appendix B.

5.4.1 Analytic Expressions of Workload

5.4.1.1 Officer of the Deck

$$G_t^o = H(v^{od}) \tag{5.1}$$

$$G_b^o = H(x^o, \bar{z}^{do}) - H(v^{od}) \tag{5.2}$$

$$G_n^o = 0 \tag{5.3}$$

$$G_c^o = \sum_{i=2}^{8} H(w_i) \tag{5.4}$$

5.4.1.2 Diving Officer of the Watch (Unaided Case)

$$G_t^d = H(\underline{x}^d, u^d) + H(\underline{z}^d) + H(\underline{\bar{z}}^d) + H(v^d) + H(\underline{y}^d) \tag{5.5}$$

$$G_b^d = H(\underline{x}^d, z^{cd}) - H(\underline{z}^d) + H(\underline{z}^d, z^{ld}, z^{hd}) - H(\underline{\bar{z}}^d)$$

$$+ H(\underline{\bar{z}}^d, v^{od}) - H(\bar{v}^d) + H(\underline{\bar{z}}^d, \bar{v}^d) - H(\underline{y}^d) \tag{5.6}$$

$$G_n^d = 0 \tag{5.7}$$

$$G_c^d = \sum_{i=0}^{3} \sum_{j=1}^{\alpha_i} H(W_j^{di}) + H(u^d) + H(\underline{\bar{x}}^d) + H(\underline{z}^d) - H(\underline{\bar{x}}^d, z^{cd})$$

$$+ \sum_{i=1}^{5} H(w^{d4}) + H(\underline{\bar{z}}^d) + H(\bar{z}^{do}) - H(W^{d4})$$

$$+ \sum_{i=0}^{4} \sum_{j=1}^{\alpha_i} H(w^{d5+i}) + H(v^d) + H(\underline{y}^d) - \sum_{i=6}^{9} H_{W^{d5}}(W^{d9})$$

$$+ H(\underline{z}^d, z^{ld}, z^{hd}) - H_{\underline{x}^d, z^{cd}}(z^{ld}, z^{hd}) + H(\underline{z}^d, \bar{v}^{od})$$

$$- H_{\underline{x}^d, z^{cd}, z^{ld}, z^{hd}}(v^{od}) \tag{5.8}$$

5.4.1.3 Diving Officer of the Watch (Aided Case)

$$G_t^{d\,aid} = H(\underline{z}^d) - H_{\underline{x}^d, z^{cd}, x^{aid}}(\underline{z}^d) + H(\bar{z}^d) + H(\bar{v}^d) + H(\underline{y}^d) \quad (5.9)$$

$$G_b^{d\,aid} = H(\underline{x}^d, z^{cd}, x^{aid}) - H(\underline{z}^d) + H_{\underline{x}^d, z^{cd}, x^{aid}}(\underline{z}^d) + H(\underline{z}^d, z^{ld}, z^{hd})$$

$$- H(\bar{z}^d) + H(\underline{z}^d, \bar{v}^{od}) - H(\bar{v}^d) + H(\underline{z}^d, \bar{v}^d) - H(\underline{y}^d) \quad (5.10)$$

$$G_n^{d\,aid} = H(u^{aid}) \quad (5.11)$$

$$G_c^{d\,aid} = \sum_{i=1}^{3} p(u=1)\, g_c^{di} + \alpha_i \boldsymbol{H}\, [p(u=i)] + H(\underline{z}^d)$$

$$+ \sum_{i=1}^{5} (w_i^{d4}) + H(\underline{z}^d) - H(W^{d4})$$

$$+ \sum_{i=5}^{9} \sum_{j=1}^{\alpha i} H(w_j^{di}) + H(v^d) + H(\underline{y}^d) - \sum \sum H_{W^{d5}}(w_j^{di})$$

$$+ g^{d\,if} + g^{d\,ci\cup rs}$$

$$+ H(\underline{z}^d, z^{ld}, z^{hd}) - H_{\underline{x}^d, z^{cd}, x^{aid}}(z^{ld}, z^{hd})$$

$$+ H(\underline{z}^d, v^{od}) - H_{\underline{x}^d, z^{cd}, x^{aid}, z^{ld}, z^{hd}}(v^{od}) \quad (5.12)$$

where: $g_c^{d1} \equiv g_c^{pp/sa}$ (coordination of pp$\cup$sa in unaided case)

$$g_c^{d2} \equiv g_c^{pp/sa} + H(w_z^{d\ aid}) + H(w_c^{d\ aid}) + H(\underline{z}^d) - H_{\underline{x}^d,\ z^{cd}}(x^{aid})$$

$g_c^{d3} = 0$ (coordination of the identity algorithm mapping x^{aid} into $\underline{z}^d$)

$w_z^{d\ aid} \equiv$ the variable into which the DOOW's own assesment is mapped in algorithm $h^{d2\ aid}$

$w_c^{d\ aid} \equiv$ the worst case situation comparison matrix

$g^{d\ if} \equiv$ IF stage activity from unaided case

g^{d} $ci{\cup}rs \equiv$ joint CI∪RS activity from unaided case

5.4.1.4 The Chief of the Watch

$$G_t^c = H(\underline{z}^c) + H(\underline{z}^c) + H(v^c) + H(y^c) \tag{5.13}$$

$$G_b^c = H(\underline{x}^c) - H(\underline{z}^c) + H(\underline{z}^c, z^{lc}) - H(\underline{z}^c) + H(\underline{z}^c, v^{dc})$$

$$- H(\bar{v}^c) + H(\bar{\underline{z}}^c, \bar{v}^c) - H(y^c) \tag{5.14}$$

$$G_n^c = H_{\bar{\underline{z}}^c,\ v^{dc}}(\bar{v}^c) \tag{5.15}$$

$$G_c^c = \sum_{i=1}^{17} H(w^{c1}) + H(\underline{z}^c) + H(z^{cd}) - H(\underline{x}^c) + H(\underline{z}^c)$$

$$+ \sum_{i=1}^{3} H (w^{c3}) + H (\bar{v}^{c}) - H (w_1^{c3}, w_2^{c3})$$

$$+ p (v^{c}=4) \{ \sum_{i=1}^{10} H (w^{c7}) + H (y^{c}) - H (W^{c5}) \} \; p (\bar{\underline{z}}^{c} \mid \bar{v}^{c} = 4)$$

$$+ \alpha_j \boldsymbol{H} (p_j) + H (y^{c})$$

$$+ H (\underline{z}^{c}, z^{lc}) - H_{\underline{x}^{c}} (z^{lc}) + H (\bar{\underline{z}}^{c}, v^{dc}) - H_{\underline{x}^{c},\, z^{lc}} (v^{dc}) + H (\bar{\underline{z}}^{c}, \bar{v}^{c})$$

$$- H_{\underline{x}^{c},\, z^{lc},\, v^{dc}} (\bar{v}^{c}) \tag{5.16}$$

5.4.1.5 The Lee Helm

$$G_t^{l} = H (z^{ld}) + H (v^{dl}) \tag{5.17}$$

$$G_b^{l} = H (\underline{x}^{l}) - H (z^{ld}) \tag{5.18}$$

$$G_n^{l} = 0 \tag{5.19}$$

$$G_c^{l} = \sum_{i=1}^{10} H (w_i^{l1}) + H (z^{ld}) - H (\underline{x}^{l}) + H (y^{d}) - H_{\underline{x}^{l}} (y^{d}) \tag{5.20}$$

5.4.1.6 The Helm

$$G_t^{h} = H (z^{hd}) + H (y^{dh}) \tag{5.21}$$

$$G_b^h = H(\underline{x}^h) - H(z^{hd}) \tag{5.22}$$

$$G_n^h = 0 \tag{5.23}$$

$$G_c^h = \sum_{i=1}^{5} H(w_i^{h1}) + H(z^{hd}) - H(\underline{x}^h) + H(y^{dh}) - H_{\underline{x}^h}(y^{dh}) \tag{5.24}$$

5.4.2 The Decision Strategies

The mathematical theory of organizations ([7], [8], [9], [10]) applied in the formulation of the SCP model defines the k^{th} pure internal decision strategy, D^r, of DM r as :

$$D_k^r = \{p(u = i), p(\bar{v} = j \mid \bar{z} = \bar{z}_m, v' = v')\} \tag{5.26}$$

where the distributions are respectively on SA and RS strategies, $z_m \in z$, and $v_m \in V'$ represents a command input. The strategy is known as a pure strategy if both probabilities equal one, otherwise it is a mixed strategy. For this model of decisionmaking, an upper bound on the number of pure internal decision strategies is given by the expression:

$$n_r = U \cdot V^M \tag{5.27}$$

where U, V, and M are respectively the number of algorithms in the SA and RS stages of the DM, and the dimension of the set z. The number n_r can be shown, using this equation for the DMs in the SCP, to be quite large, numbering far into the millions. Further, the interaction among decisionmakers means that performance and workload are functions of the strategy of the organization taken as a whole, i.e. its organizational strategy, given by the r-tuple

$$\Delta_{i,j,\ldots,k} = \{ D^1_i , D^2_j , \ldots , D^r_k \} \tag{5.28}$$

where r is the number of DMs in the organization and i,j,...,k are pure internal strategies defined in Eq. (5.26). In other words, the number of possible ways to choose information paths for an organization like the SCP can be shown to be astronomical. The problem under consideration, however, is essentially descriptive and constraints on the strategy space have been applied *a priori*. Although a very large number of organizational pure strategies, Δ^{scp}, could be shown mathematically to exist, many if not most of these would not be meaningful in terms of the physical system. By defining:

$$\Delta^{scp}_f \in \Delta^{scp} \tag{5.29}$$

as the subset of organzational pure strategies that are feasible from the standpoint of the system being modeled, and considering only these, the descriptive organization modeling problem can be made quite manageable.

Let us apply this definition to the emergency control problem. Inspection of the SA and RS stages of the DMs shows that only two of these, D and C, are equipped with a switching mechanism. This constraint limits the number of organizational pure strategies to

$$\dim (\Delta^{scp}) = \{ (U^d)^{[x^d ,\, z^{cd}]} , (V^d)^{[\bar{z}^d ,\, v^{cd}]} , (V^c)^{[\bar{z}^c ,\, v^{dc}]} \} \tag{5.30}$$

where the square-bracketed superscripts denote the size of the joint space of the variables in the brackets. Even if the pure strategies depending upon shared information were ignored, the number would equate to:

$$\dim(\Delta^{scp}) = \{ (3^{432} \bullet 4^{88}) \bullet (5^{88}) \} \tag{5.31}$$

which is large beyond comprehension.

The solution to this problem comes from recognizing the nature of the decision process used by the SCP. Unlike the general case, where the DMs have several SA algorithms for processing any given arrival and several RS algorithms for any assessed situation, which algorithms are selected according to a probabilistic strategy, the DOOW is modeled so that a single best algorithm, f^d, is chosen deterministically by his internal preprocessor to process the tasks belonging to each class of casualty, $X_i \in X$, (i = plane casualty, hydraulic failure, flooding). This means that the DOOW utilizes a single pure situation assessment strategy, $p(u^d \mid \underline{x}^d, z^{cd})$.

In the RS stage of the modeled DOOW, an analogous situation exists. The assessed situation, $\underline{z}^d$, can be considered to consist of two subsets, one corresponding to control casualties and the other to flooding casualties. To each subset correspond two RS algorithms, one restrictive, the other non-restrictive. The deterministic selection of the appropriate RS algorithm, given $\bar{z}^d$, v^{od}, described in 5.2.2, is equivalent to a single pure RS strategy. Thus the modeled DOOW, in the unaided case, operates according to a single pure strategy.

In the case of the modeled COW, the scheme for selection of RS algorithms permits the occurrence of multiple pure strategies. Referring to the description in 5.2.3 and Appendix A {diagram of CI^c} two of the terminal nodes point deterministically to a specific RS algorithm, while the remaining two choose an RS algorithm on the basis of the internal RS strategy. This decision process is equivalently represented by the expressions given below:

$$p(\bar{v}^c = 1 \mid \bar{z}^c, v^{dc} = 1) = 1, \; p(\bar{v}^c \neq 1 \mid \bar{z}^c, v^{dc} = 1) = 0 \; ; \forall \bar{z}^c \tag{5.32}$$

$$p(\bar{v}^c = 2 \mid \bar{z}^c, v^{dc} = 2) = \delta_1{}^c, \; p(\bar{v}^c \neq 4 \mid \bar{z}^c, v^{dc} = 2) = 1 - \delta_1{}^c \; ; \forall \bar{z}^c \tag{5.33}$$

$$p(\bar{v}^c = 3 \mid \bar{z}^c, v^{dc} = 3) = 1, \; p(\bar{v}^c \neq 1 \mid \bar{z}^c, v^{dc} = 1) = 0 \; ; \forall \bar{z}^c \tag{5.34}$$

$$p(\bar{v}^c = 4 \mid \bar{z}^c, v^{dc} = 2) = \delta_2{}^c \; ; \; p(\bar{v}^c \neq 4 \mid \bar{z}^c, v^{dc} = 2) = 1 - \delta_2{}^c \; ; \forall \bar{z}^c, z \neq 0 \tag{5.35}$$

$$p(\bar{v}^c \mid \bar{z}^c, v^{dc} = 0) = 0 \; ; \quad \forall \bar{v}^c \neq 4,5 \tag{5.36}$$

$$p(\bar{v}^c = 5 \mid \bar{z}^c = 0, v^{dc} = 0) = 1, \; p(\bar{v}^c = 5 \mid \bar{z}^c, v^{dc} \neq 0) = 0 \; ; \forall \bar{z}^c \tag{5.37}$$

$\delta_r{}^c \in [0,1] \quad r=1,2$

The meaning of the deterministic expressions above is manifest in the terminal nodes of the decision tree in Appendix A {diagram of CI^c}. In essence, commands to blow the EMBT or to pump water onboard ($v^{dc}=1$ and $v^{dc}=3$ respectively) offer no alternatives; they are always followed exactly. The responses that are functions of δ_1^c, δ_2^c may be interpreted as follows.

The RS strategy determined by δ_1^c and δ_2^c is intended to capture the discretion the COW has over the emergency response in certain situations. When a stern plane jam dive or serious flooding situation threaten to sink the submarine, the COW may decide, according to decision rules that might be thought of as rules of last resort, to perform an EMBT blow. Because the COW's decision rules require more severe conditions to warrant an EMBT blow, such a discretionary decision would only occur when the DOOW has erred.

The decision parameter δ_1^c, as it ranges between 0 and 1, directly varies the propensity of the COW to resort to the discretionary algorithm (h^{c4}) rather that the ordered one (h^{c2}). Similarly, the parameter δ_2^c varies the likelihood that the COW will utilize the discretionary algorithm or choose the no response algorithm in the event that the COW believes an emergency situation exists but the DOOW orders no response.

The two binary parameters, δ_1^c and δ_2^c, then define four pure organization strategies, Δ_{ij}, i,j = 1,2 when $\delta_1^c, \delta_2^c = 0,1$. The set of all organizational strategies (called mixed strategies), for the unaided case, can be expressed as the convex combination of the four pure strategies [7], which compose the subset defined as feasible strategies Eq. (5.29):

$$\Delta_f^{scp} = [\,(1-\delta_1^c),\ \delta_1^c\,] \begin{bmatrix} \Delta_{f_{11}}^{scp} & \Delta_{f_{21}}^{scp} \\ \Delta_{f_{12}}^{scp} & \Delta_{f_{22}}^{scp} \end{bmatrix} \begin{bmatrix} (1-\delta_2^c) \\ \delta_2^c \end{bmatrix} \qquad (5.38)$$

5.4.3 The Aided Case

The decision aid, as modeled in Section 5.3, introduces three internal pure strategies, all defined to be feasible, into the DOOW:

$$D_i^d = \{ p(u=i) = 1 \} \tag{5.39}$$

for any particular i, i=1,2,3. The definition of the organizational pure strategy (5.28) indicates that for the aided case, twelve feasible pure organizational strategies exist. When the decision parameters corresponding to the DOOW's pure internal strategies are δ_i^d, i=1,2,3, the aided feasible organizational strategies are given by:

$$\Delta_{f_{ijk}}^{scp\text{-}aid} = \{ D_i^d , D_{jk}^c \} \qquad i = 1, 2, 3 \qquad j, k = 1, 2 \tag{5.40}$$

When the decision parameters corresponding to the DOOW's pure internal strategies are δ_i^d, i=1,2,3 , the mixed feasible strategies of the aided organization are given by:

$$\Delta_f^{scp\text{-}aid} = \sum_{i=1}^{3} \delta_i^d \, \Delta_{f_i}^{scp\text{-}aid} \tag{5.41}$$

$$\sum_{i=1}^{3} \delta_i^d = 1 \tag{5.42}$$

where

$$\Delta_f^{scp\text{-}aid} = [\,(1-\delta_1^c),\ \delta_1^c\,] \begin{bmatrix} \Delta_{f_{i11}}^{scp\text{-}aid} & \Delta_{f_{i21}}^{scp\text{-}aid} \\ \Delta_{f_{i12}}^{scp\text{-}aid} & \Delta_{f_{i22}}^{scp\text{-}aid} \end{bmatrix} \begin{bmatrix} (1-\delta_2^c) \\ \delta_2^c \end{bmatrix} \tag{5.43}$$

5.4.4 Performance Evaluation

The mathematical organization modeling and design methodology poses the design problem as a constrained optimization or satisficing problem [6], [7], [8], [9], [10]. In the present case, the aim is first to develop a descriptive model, then to draw from analysis of the model results that are both descriptive and normative. Here, the decision problem may be posed as an optimization problem of the following form: subject to a constraint on reaction time, minimize the cost of response. The cost, an index of performance, is denoted by J and is computed as a single value for the organization as a whole. To compute J first requires the definition of a function d(Y,Y') capable of assigning a value to each pair of actual and optimal responses, Y and Y' respectively. For the emergency control problem where, in addition to minimizing cost of error, it is appropriate to minimize probability of error, the performance index J may be defined as:

$$J = \sum_i p_i \ (d(Y_i, Y_i')) \tag{5.44}$$

The cost function serves as a function for weighting, on the basis of error gravity, the probability that an error is made.

In submarine emergency control, errors can be considered to be of two types: (1) the SCP may decide upon a response insufficient or inappropriate to handle the emergency without resulting in damage to the ship and/or its crew, or (2) the SCP may choose a response too severe for a casualty and incur a cost in terms of unnecessarily radiated noise that could compromise the submarine and its mission by disclosing its presence or location to the enemy. The best way to represent a cost function capable of assigning a value to all of the many possible errors is to specify a matrix associating a predefined value to any

(Y,Y') pair. Figure 5.5 shows the cost matrix assumed to apply to submarine emergency control response errors.

Y \ Y'	no action	jam dive	jam dive (restr.)	stuck dive	stuck rise	jam rise	rudder flr.	fwplane flr.	major pipe fldg. eng.rm.	major pipe fldg. not e.r.	minor pipe fldg. eng.rm.	minor pipe fldg. not e.r.
no action	0	1	1	0.2	0.1	0.2	0.1	0.2	1	1	0.6	0.5
jam dive	0.3	0	0.2	0.2	0.2	0.2	0.2	0.2				
jam dive (restr.)	0.1	0.8	0	0.1	0.2	0.3	0.1	0.1				
stuck dive	0.1	0.9	0.8	0	0.1	0.2	0.1	0.1				
stuck rise	0.1	0.9	0.8	0.1	0	0.2	0.1	0.1				
jam rise	0.1	1	1	0.5	0.1	0	0.1	0.1				
rudder flr.	0.1	1	1	0.3	0.2	0.3	0	0.1				
fwplane flr.	0.1	1	1	0.3	0.2	0.3	0.1	0.30				
major pipe fldg. eng.rm.	0.3								0	0.2	0.3	0.3
major pipe fldg. not e.r.	0.3								0.2	0	0.3	0.3
minor pipe fldg. eng.rm.	0.1								0.9	0.9	0	0.2
minor pipe fldg. not e.r.	0.1								0.9	0.9	0.2	0

Figure 5.5 The Error Cost Matrix

The error cost varies between 0, indicating no cost, and 1, representing total loss of the ship and its crew. The left and top margins correspond to Y and Y', respectively. In these margins are labels for responses, which may be categorized by the specific situation to which they correspond. In emergency control, code words like "jam dive" are ordered to elicit specific response actuations by the COW and helmsmen. An explanation of these labels, in terms of actual physical actions is given in Appendix A.

The model is thus formulated in its entirety. What remains is to implement this model computationally and evaluate the results.

CHAPTER 6

RESULTS AND EVALUATION

The previous chapters introduced the problem of the ship control party of a submarine performing emergency control, and a set of analytical tools, with the ultimate aim of investigating the effects of a decision aid upon the performance and workload characteristics of this organization. Bringing the tools to bear toward this goal required a thorough description of the system and a delineation of the assumptions necessary to bring the system within the purview of the tools. Finally, a model of ship emergency control decisionmaking and decision aiding emerged, in the form of probability distributions, a Petri Net, decision algorithms, and a set of information theoretic equations.

This chapter first describes briefly the approach taken to implement the conceptual model developed in the foregoing chapters. It then proceeds to present the results obtained from running the model. These will be interpreted quantitatively, and qualitatively in terms of the emergency control problem, and will be qualified according to the assumptions upon which the results rest.

6.1 COMPUTATIONAL IMPLEMENTATION

A formal mathematical statement of the information processing workload and its components, for each of the decisionmakers, was derived from the model and is presented in Appendix B. Theoretically, it is possible, by substituting the required probability distributions into these expressions, to compute the information processing workload. However, as the expressions in Appendix B show, a number of joint and conditional distributions on several variables is required, followed by a tedious and unwieldy substitution process. Fortunately, the Partition Law of Information (2.9) may be invoked to yield an alternative procedure for computing individual workloads [6]. By simulating the organization on a computer, accounting for all system variables, and running the simulation for each letter of the input alphabet, X, distributions on these variables may be derived. Then the entropies of these variables may be computed as a function of organization behavioral strategy. This approach facilitates the computation of organization performance, which can also be figured as a function of decision strategy.

A flow chart of the computational implementation and analysis of the model is depicted in Figure 6.1. First, the input alphabet, consisting of 1496 combinations of the 10 input vector elements, is generated by a task model embodying the assumptions made in Sections 4.1 and 4.2, and operating upon the assumed distributions presented at the end of that chapter. This simulation produces each letter X_i, an associated probability, p_i, the optimal response Y_i', as well as the optimal situation assessment used as the aid output x_i^{aid}.

The next stage consists of a set of algorithms implementing those represented as decision trees in Appendix A. Connected in the same order of precedence as they are in the Petri Net model, Figure 5.2, these algorithms process X_i, $\forall i$, for each pure strategy. Corresponding to each X_i, the organization generates a response Y_i, compares it with Y_i' according to the cost functional, L (Y,Y'), given in Figure 5.5 and weights the result by p_i. For each pure strategy, the activity is computed according to the left-hand side of the PLI (3.9), and the performance J_i is summed. Finally, with an organization cost and individual workload associated with each pure strategy, the convex combinations, yielding all the mixed strategies, are computed using Eq. (5.38) and Eq. (5.41), producing the points from which the J-G loci are drawn.

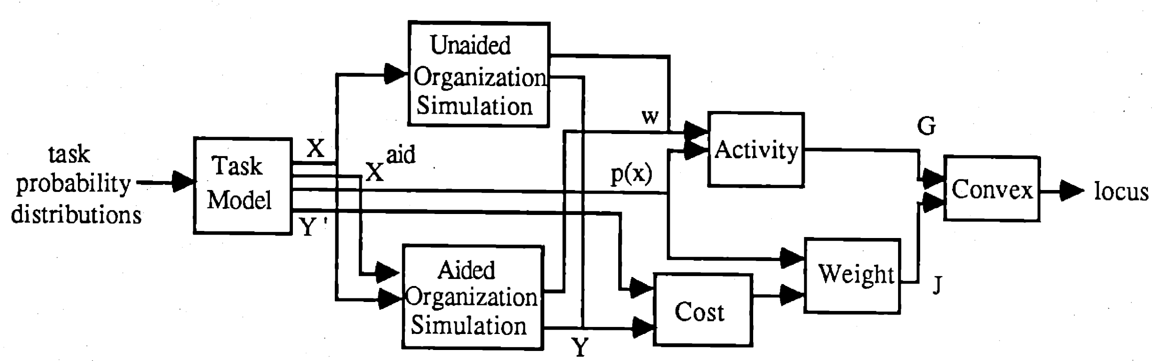


Figure 6.1 Computation Implementation Schematic

6.2 INITIAL RESULTS

6.2.1 The Noiseless Case

The computer model described in section 6.1 was initially run for the unaided organization simulation model, shown in Figure 6.1. In this simulation, the DOOW utilizes the PP and SA algorithms given in Appendix A. The simulation operates on the input vector defined in Chapter 4 and shown in Table 6.1.

TABLE 6.1
NOISELESS INPUT VECTOR

Input Element: x	Element Domain: $\{x_i\}$
control mode buzzer	{ 0, 1 }
control mode light	{ 0, 1, 2, 3 }
hydraulic indicator	{ 0, 1 }
flooding location	{ 0, 1, 2, 3, 4 }
flooding pipe size	{ 0, 1, 2, 3 }
stern plane angle	{ 1, 2, 3, 4, 5, 6 }
speed	{ 1, 2, 3 }
depth	{ 1, 2, 3 }

Recall that this vector is a noiseless model of the emergency task, with the exception of the flooding location report which may assume a garbled state. Table 6.2 provides a summary of the results, with the range, average, and standard deviation of the performance and individual workloads over the decision strategies δ_1^c, δ_2^c.

TABLE 6.2

UNAIDED ORGANIZATION RESULTS

(NOISELESS CASE)

	RANGE	AVERAGE	STD. DEV.
J	0.007 - 0.033	0.020	0.094
G^o (bits)	constant	5.135	0
G^d "	constant	54.048	0
G^c "	27.277 - 30.396	29.31	0.9261
G^l "	constant	11.271	0
G^h "	constant	7.509	0

Note that the workloads of the decisionmakers appear to reflect well, in relative terms, what one would expect the actual workloads of each to be in performing emergency control. Recall that, in the case of the OOD, this figure represents only the emergency control workload of the OOD, who has other decisionmaking responsibilities not modeled here.

Note also that, even in the absence of the decision aid, the performance of the organization, as assumed by the model, (which varies inversely with the cost J) appears quite good. The cost J is in the range $0.007 \leq J \leq 0.033$, with the variation being a function of the decision parameters $\delta_1{}^c$, $\delta_2{}^c$. The reason for the quality of performance is that the algorithms, modeled as deterministic and processing noiseless input, are very unlikely to err. Another reason is that costly casualties occur at depth extremes at which the submarine is modeled as operating only infrequently. This assumption of input noiselessness, appears to be a strong one in this analysis, which could lead to misleading conclusions about the effect of the aid. Therefore, this assumption was relaxed; results will be discussed in Section 6.2.3. Relaxation of the noiselessness assumption will permit the evaluation of the robustness of the model output with respect to variation in the assumptions about the input.

6.2.2 Relaxation of the Assumption of Noiseless Input

This section relaxes the assumption of noiseless input by developing a model of input noise that reflects the likelihood of failure of sensors and indicators, or of humans reporting flooding conditions. Again, the model is formulated on the basis of subjective probabilities [18], but can be varied to reflect empirical findings, should they differ significantly from the assumptions.

TABLE 6.3
INPUT NOISE MODEL

Input Element x	Element Domain $\{x_{i-}\}$	Assumed Noise Corruption $\{x_{i-}\} \rightarrow \{x_i'\}$	Assumed Rate of Noise Corruption %
control mode buzzer	{ 0, 1 }	$\{1\} \rightarrow \{0\}$	≤ 1%
control mode light	{ 0, 1, 2, 3 }	$\{1, 2, 3\} \rightarrow \{0\}$	≅ 10 %
hydraulic indicator	{ 0, 1 }	$\{1\} \rightarrow \{0\}$	≤1%
		$\{0\} \rightarrow \{1\}$	≤1%
flooding location	{ 0, 1, 2, 3, 4 }	$\{1, 2, 3\} \rightarrow \{1, 2, 3\}$	≅ 20 %
flooding pipe size	{ 0, 1, 2, 3 }	$\{1, 2, 3\} \rightarrow \{1, 2, 3\}$	≅ 30%
stern plane angle	{ 1, 2, 3, 4, 5, 6 }	$\{s.p.\angle_i\} \rightarrow \{1, s.p.\angle_i, 6\}, \forall_i$	≤1%
speed	{ 1, 2, 3 }	$\{speed_i\} \rightarrow \{1, speed_i, 3\}, \forall_i$	≤1%
depth	{ 1, 2, 3 }	$\{depth_i\} \rightarrow \{1, depth_i, 3\}, \forall_i$	≤2%
tactical situation	{ 0, 1 }	$\{0\} \rightarrow \{1\}$	≅ 10%
		$\{1\} \rightarrow \{0\}$	≅ 1%

The columns in Table 6.3, from left to right, indicate: (1) the particular information source subject to error, (2) the possible discrete values the source may take, also described in Chapter 4, (3) the random mappings from x_i to x_i' that the model permits, and (4) the rate at which such mappings occur. For example, the control mode buzzer and control mode light tend to fail in an "off" or inactive state, denoted by $\{0\}$. Stern plane angle, speed, and depth indicators, on the other hand, tend to stick at a particular reading or to move erroneously to either extreme. Note that the failure rate of mechanical devices is assumed to be low, less than or equal to approximately 1%. Human assessments of flooding, or of the tactical situation, are modeled as more prone to failure, with a rate of error as high as 30% error for flooding pipe size determination.

The effect of the assumed input noise corruption on organization performance and decisionmaker workload was determined by a sample of ten runs of the model. For all cases, the noise in each indication and report was the maximum defined in the rightmost column of Table 6.3. The following results were obtained (Table 6.4). Again, as in the noiseless case, the unaided results in the presence of noise are given in terms of range, average, and standard deviation over the decision strategies δ_1^c, δ_2^c.

TABLE 6.4

UNAIDED ORGANIZATION RESULTS

(NOISE - CORRUPTED CASE)

	AVERAGE	RANGE	STD. DEV.
J	0.101 - 0.040	0.026	0.001
G^o (bits)	constant	5.140	0
G^d "	constant	54.05	0
G^c "	27.21 - 30.55	29.30	0.920
G^l "	constant	11.272	0
G^h "	constant	7.525	0

These numbers correspond to the locus in Figure 6.2, which depicts G^d, G^c, and J in the unaided, noisy case. The decisionmaker workloads proved robust with respect to the assumed input noise, the maximum variation in workload for any sample being 0.006 bits, and the maximum standard deviation among the samples being 0.058 bits. The reason for this robustness is that the input distribution p(X), defined on a very large number of input states, is quite spread out, approaching a uniform distribution which is characterized by a high entropy. The noise corruption, while affecting this distribution, can only do so marginally. Its effect on the the probability distributions on system variables is similar. This models the physical system well; the decisionmakers can rarely be certain whether a signal is erroneous and on average treat signals as if they were equally uncertain. Another interesting result is that the probability of error that resulted from the assumption of this noise rate fell in the range $0.067 \leq pr(error) \leq 0.13$, which corresponds well to the subjectively assessed rate of decisionmaker error [18].

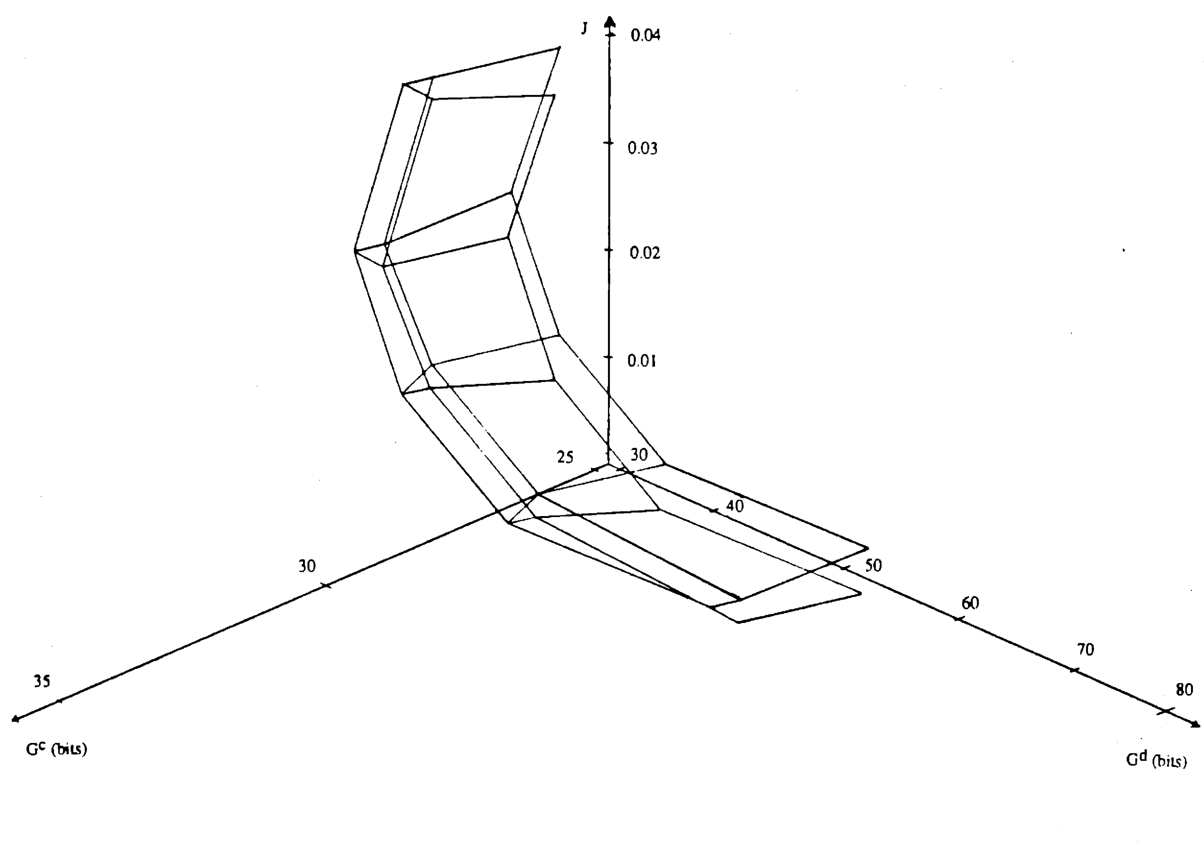


Figure 6.2 The Unaided Locus (J, G^c, G^d)

6.3 EFFECTS OF THE DECISION AID

The unaided organization model was run with the noiseless input assumption relaxed, and it yielded results that were robust and that seemed to correspond reasonably well to common sense notions about the decision problem and to subjective assessments by a submariner with DOOW experience. Therefore, the model of the aided organization was run under the same noise-corrupted conditions. The results of those runs, ten of which were made as in the unaided case, are presented in this section. Each run of the aided model consists essentially of three runs of the unaided case, with the decision parameter δ^d varied between its three possible states to produce each of the three runs. The variable δ^d signifies the DOOW's choice between three options (or pure strategies) for use of the aid information, as described in section 5.3. To reiterate, the options for use of the decision aid are: 1) block decision aid information and assess situation with own PP and SA algorithms, 2) assess situation and compare it with decision aid situation assessment, choosing the worst case, 3) rely fully upon the decision aid for situation assessment. The convex combinations of the pure strategies, known as mixed strategies, were computed, and from these pure and mixed strategies were drawn the results summarized in Table 6.5 and plotted in Figures 6.3 through 6.6.

TABLE 6.5
AIDED ORGANIZATION RESULTS
(NOISE - CORRUPTED CASE)

	RANGE	AVERAGE	STD. DEV.
J	0.004-0.040	0.023	0.01
G^o (bits)	5.140-5.141	5.140	0.0004
G^d "	41.143-62.474	54.430	6.020
G^c "	27.258-30.7065	29.354	0.923
G^l "	11.233-11.2715	11.258	0.012
G^h "	7.476-7.525	7.507	0.015

The point of this work is to investigate the effect of the decision aid proposed in Chapter 5 on the performance of the organization and on the workload of the DOOW. A qualitative determination of this effect is possible by examining the organization loci. Specifically, the questions to consider are how J and G^d vary with respect to the decision aid strategy, δ^d, as well as how they vary between the unaided and aided cases.

6.3.1 Some Qualitative Results

The aided J, G^c, G^d, locus, presented in Figure 6.3, depicts three sub-loci corresponding in shape to that of the unaided locus (Figure 6.2).

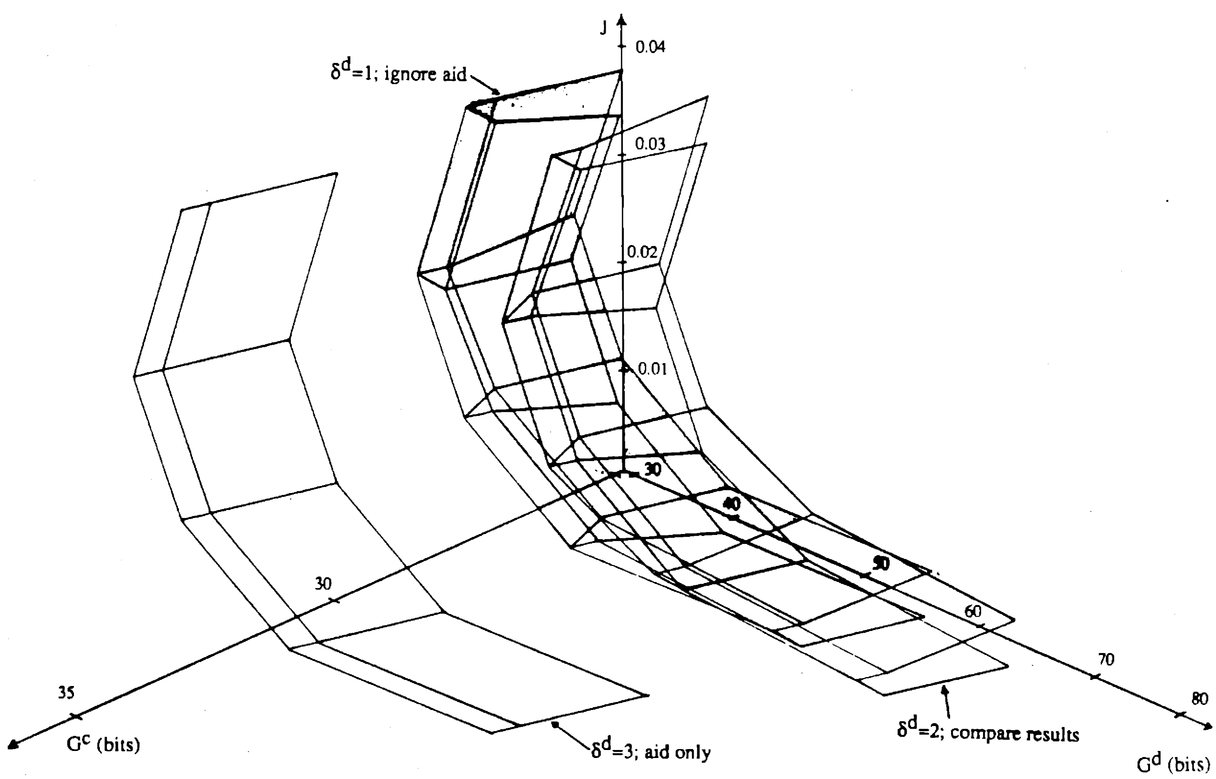


Figure 6.3 The Aided Locus for Pure Decision Aiding Strategies (J, G^c,G^d)

Each of these sub-loci corresponds to a pure strategy for use of the decision aid. Proceeding from the left, the first sub-locus illustrates J, G^d, G^c corresponding to the strategy in which the DM relies fully upon the decision aid for the situation assessment (given as the δ^d=3 in previous explanations). The expected error cost, J, and workload, G^d, are seen to be lower in Figure 6.3 than for the other aiding strategies. Referring to Figure 6.4, which depicts the unaided locus in contrast to the envelope of the aided locus, the fully aided strategy, which defines the left edge of the envelope is somewhat lower in J than the unaided locus.

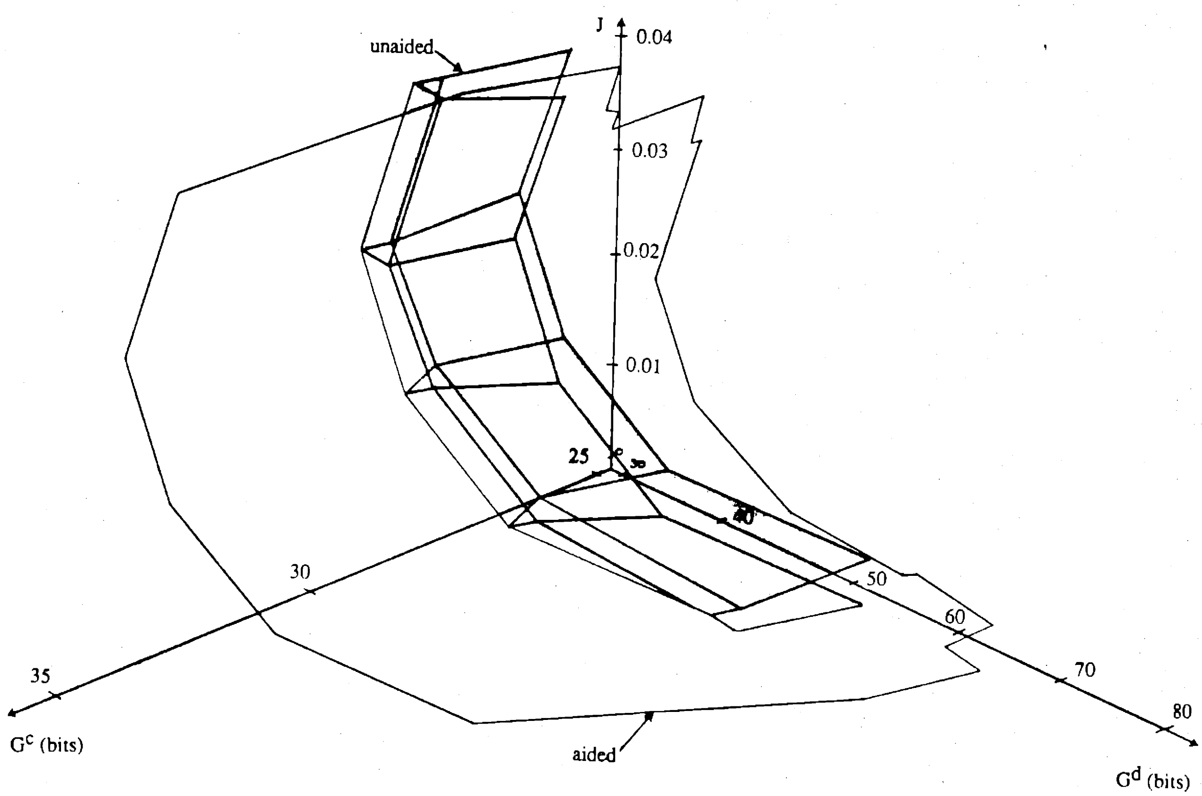


Figure 6.4 Comparative View of the Unaided and Aided Loci (J, G^c, G^d)

The middle sub-locus in Figure 6.3 characterizes the option where the DOOW blocks the decision aid situation assessment (δ^d=1). This is identical to the unaided locus, except that G^d, for evey point, is approximately 3 bits greater than in the unaided case. (This phenomenon will be discussed with the quantitative results.) Finally, the rightmost locus represents the decision option in which the DOOW compares his situation assessment with that of the aid and chooses the worst case (δ^d=2). The cost, J, is reduced, but to a lesser extent than in the fully aided case. This improvement is, however, accompanied by an increase in DOOW workload.

It is important to note the way in which the aid modifies the unaided performance-workload locus. Recall from Section 5.4.2 that the existence of the three decision aiding options triples the number of decision strategies. Thus, to each point in the unaided locus there corresponds a surface in the aided locus with three vertices each falling on a pure decision aiding strategy. Four examples of these, corresponding to the four pure strategies given by (δ_c^1, δ_c^2) are shown in Figure 6.5, connecting the three decision aid sub-loci introduced in Figure 6.3.

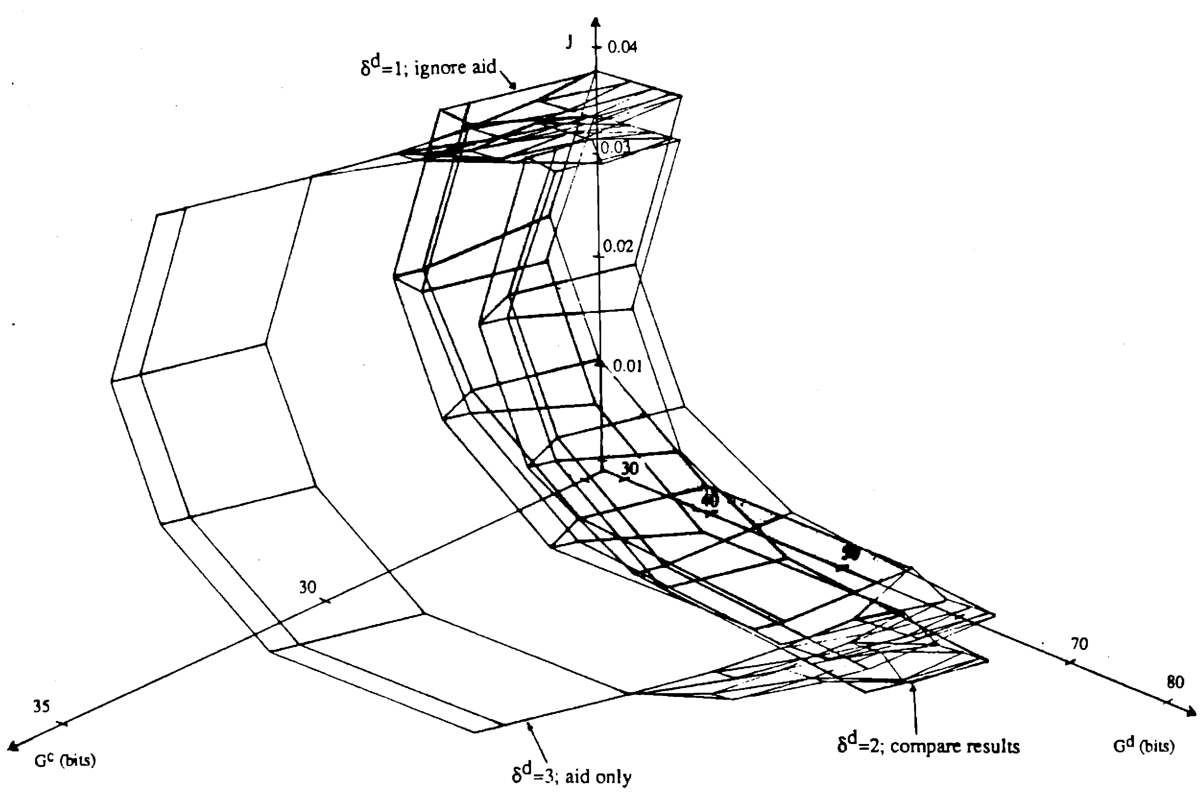


Figure 6.5 The Pure Decision Aiding Locus
$(\delta_1^c, \delta_2^c$ held constant at pure strategies)

To isolate and illustrate the effects of the aid for any strategy ($\delta_c 1$, $\delta_c{}^2$), one may examine such a surface, projected onto the plane of interest, the J-G^d plane.

Figure 6.6 shows these two variables , J and G^d, as a function of δ^d, for the unaided pure strategy seen as that of the two vertices in the lower right of the locus in Figure 6.2 with the higher value of J. Recall that G^d is independent of these strategies. The numbers 1,2, and 3 denote respectively the three strategies for decision aiding. The point labeled U depicts the corresponding unaided (J, G^d) pair (J at this point is identical to point 1 in the aided locus). Note that decision aiding strategies 1 and 2, and the mixed strategies in which they figure strongly, are characterized by a greater workload, G^d, than in the unaided case. On the other hand, the reduction in G^d brought about by the fully aided strategy is quite visible at point 3. Finally, note how, with the decision aid, J is always improved (when $\delta^d \neq 1$), and how the degree of improvement varies with δ^d.

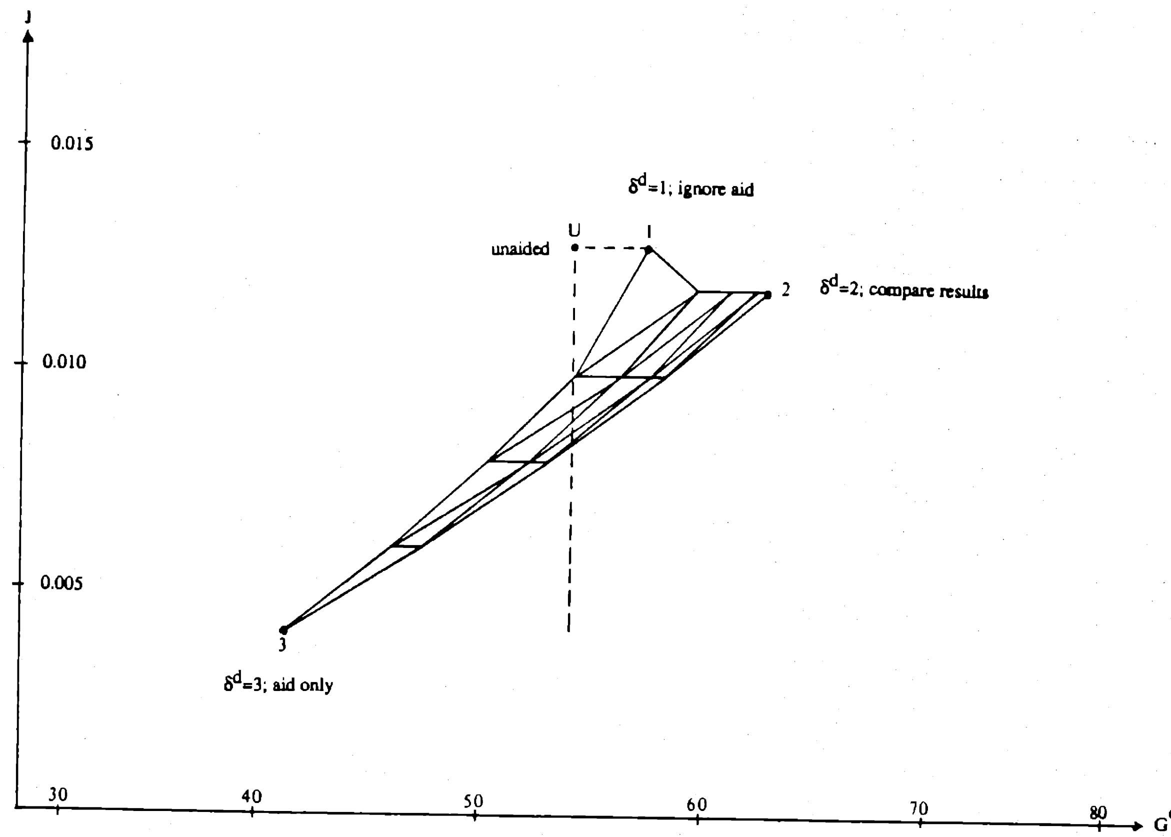


Figure 6.6 J vs. G^d ($\delta_1{}^c$, $\delta_2{}^c$ held constant)

Equipped with the performance-workload locus and the qualitative results that it affords, it is possible to develop quantitative conclusions about the effect of the aid.

6.3.2 Quantitative Effects of the Decision Aid

Obtaining quantitative information about the effect of the aid requires analyzing the data used to plot the performance workload locus.

The first thing one might consider is the probability that a decision aid will bring about an improvement in performance and workload. In the case of performance, when the constraint of bounded rationality is not exceeded, it can be seen from examining the data in Tables 6.4 and 6.5, or Figures 6.4 and 6.6, that J in the aided case never exceeds that in the unaided case but in general is lower. Therefore, it can be concluded that

- the aid will never harm, but will in general improve, organization performance, if the information processing workload of the decisionmakers does not exceed the bounded rationality constraint

It turns out, as was pointed out in the previous section, that the aid does not necessarily bring about an improvement, that is a reduction, in DOOW workload. In order to see this quantitatively consider the following. The unaided locus is a surface in 6-space parametric in δ_1^c, δ_2^c. The aided locus is a volume in 6-space, corresponding to the unaided surface. Since, $G^{d\ \mathrm{unaided}}$ is fixed for all pairs (δ_1^c, δ_2^c), this value forms a plane in performance-workload space. By computing the fraction of the locus volume that falls on either side of this plane, one can obtain the probability that the aid improves or harms these characteristics. In this work, the volume was estimated by counting the data points of the locus, each of which marks an equal unit of probability, falling on either side of the planes. The result of this estimation is that

- the aid will decrease the workload of the DOOW with a probability of 0.47

Such a result is seen graphically, for a single pure strategy (δ_1^c, δ_2^c), in Figure 6.6. Note how the aided locus straddles, in terms of workload, the value of this variable in the unaided case (shown as a dotted line extending down from the unaided point). The number given above is an average of all such strategies, pure and mixed.

The result for G^d obtained above presumes that all strategies for use of the aid are equally likely. Naturally, any given individual, or perhaps group of individuals, is apt to be characterized by a strategy confined to some sector of the locus. The locus can thus be used to characterize such individuals or groups.

This property is apparent in Figure 6.6. Strategies in the vicinity of the pure strategy in the lower left hand corner, the fully aided strategy, can bring a sharp reduction in the workload and an improvement in performance. In the extreme, the average benefit over strategies $\delta_1{}^c$, $\delta_2{}^c$ are:

$$\text{maximum improvement J: } \sum_{i,j} \frac{(J_{i,j}{}^{unaided} - J_{i,j}{}^{aided})}{J_{i,j}{}^{unaided}} = 42.5\ \% \qquad i,j = [1,2]$$

$$\text{maximum reduction in } G^d: \frac{(G^{d\ unaided} - G^{d\ aided})}{G^{d\ unaided}} = \frac{(54.047 - 41.143)}{54.047} = 24\ \%$$

for the case that the DOOW always to relies upon the aid during situation assessment.

If all strategies are given equal likelihood, aided performance is improved to a lesser degree, and the average workload of the aided DOOW is actually slightly higher, based upon the model, than in the unaided case. Using the same measure as above:

$$\text{average improvement J: } \frac{(J^{unaided} - J^{aided})}{J^{unaided}} = \frac{(0.026 - 0.023)}{0.026} = 11\ \%$$

$$\text{average reduction in } G^d: \frac{(G^{d\ unaided} - G^{d\ aided})}{G^{d\ unaided}} = \frac{(54.047 - 54.430)}{54.047} \cong -1\ \%$$

This result shows that the difference in average workload does not seem significant. In terms of dispersion of the workload, the unaided case has none, as it does not depend upon the unaided organizational strategies, modeled as strategies of the COW. In the aided case, the standard deviation is large

standard deviation of $G^{doow\ aided}$ = 6.02 bits

which illustrates the wide range in workload possible under the assumed decision aiding scheme.

Again, consideration of the average case is valuable but leaves much information unrevealed. One valuable feature of the model, offering information beyond simple averages, is its ability to expose properties of the locus at, and in the vicinity of, pure strategies. This can yield descriptive performance-workload information about individual behaviors identified as falling in regions of the locus near the pure strategies.

Pure Decision Aiding Strategies:

1) perform own assessment/block aid assessment:

The DOOW workload is 57.20 bits as compared with 54.05 bits in the unaided case. The additional workload could arise from the blockage of the information provided by the aid and from the fact that coordination increased slightly by the added complexity of the entire SA stage. Performance, not surprisingly, is identical to the unaided case.

2) perform own assessment, compare with aid assessment, and choose worst case:

The workload is 62.47 bits in this case, an increase over the unaided case of 16 %. This increase may have two sources: (1) greater coordination associated with processing the aid assessment and making the comparison, (2) greater blockage, since more information is being used to produce a signal of entropy of the same order as that in the unaided case. Performance for this pure strategy is improved, but only by 4 %, on average.

3) rely solely upon aid assessment

The workload is greatly reduced by employing this pure strategy, from 54.05 bits in the unaided case, to 41.14 bits, a 24% improvement. This workload reduction is accompanied by an average improvement in performance of 43%. This is the maximum improvement in performance that the decision aid could yield and occurs only when this pure strategy is always chosen. A plausible explanation for why the aid did not bring about a greater improvement in performance is that error can be generated at any stage in the decision process. Any error occurring "downstream" of the decision aid could reduce or nullify the benefit of even a perfect decision aid. Recall that an error-less decision aid has been assumed; the results obtained so far are thus a best-case results.

Consideration of Bounded Rationality

One rationale for the use of the information theoretic model of the human decisionmaker was its ability to model bounded rationality explicity. A natural question at this point is how the decision aid affects the workload of the DM with respect to its bound. Although there have been attempts by psychologists to discover experimentally actual numbers for such rational bounds (see [2] for a review of this work), the fact that individuals vary and that the individuals in the SCP are under the stress of a life-or-death situation, imposing numbers on the loci produced by this model would not be meaningful.

One way to pose the bounded rationality constraint, for the purpose of investigating the aid, could be as follows: consider the workload in the unaided case as an upper bound on the the value of the constraint. An interpretation for this is that the DOOW may indeed be overloaded (when the actual rational bound is less than this upper bound). However, when the DOOW is not overloaded, he is certain to be processing information at his maximum possible rate, since many lives, including his own, depend upon the appropriateness and speed of his decision. Couched in this way, the results presented above could be considered to apply to the expected effectiveness of the aid in lowering average workload below the bounded rationality constraint.

An interesting normative use of the locus is to identify how high need be the probability of the DOOW, using the fully aided option, for workload to be reduced and performance improved. From the organization locus data, fractional views of which were plotted in Figures 6.3, 6.5 and 6.6, it was determined that, although performance will always be improved when the probability of utilizing the aid is non-zero (as discussed at the beginning of this section), the aid will bring about an improvement in the average DOOW workload only if the DOOW employs a strategy for which the probability of choosing the fully aided situation assessment option is approximately at least 50 %, lower if the likelihood of employing the worst-case comparison strategy is low.

However, it is important to realize that any tendency on the part of the DOOW to perform his own situation assessment can cause both a drop in performance and a significant increase in workload, hence delay. The results indicate that the most severe increase in DOOW average workload possible is:

$$\text{maximum increase in } G^d: \quad \frac{(G^{d\ \text{unaided}} - G^{d\ \text{aided}})}{G^{d\ \text{unaided}}} = \frac{(54.047 - 62.474)}{54.047} = 16\ \%$$

illustrated in Figure 6.5, point 2.

Therefore it is clear that the decision aid, even if it is perfectly reliable, does not guarantee a benefit in terms of performance and workload. In fact, averaging over all strategies for use of the aid, performance is improved only marginally, and workload actually increases slightly as shown in Table 6.4.

6.3.3 Relaxation of the Assumption of a Perfectly Reliable Decision Aid

It is important to note that the decision aid strategy , δ^d, is likely to be affected by the reliability of the aid. Any suspicion by the DOOW of decision aid fallibility is bound to reduce his willingness to utilize it. This subject, although it merits investigation by psychologists, is beyond the scope of this thesis. However, with the model developed in this work, it is possible to see how the possibility of decision aid error can affect performance and workload, even in the absence of psychological effects. In particular, the question may be addressed: with how high an error rate may the aid operate and still bring about an improvement in performance? The aided organization simulation was run for the input X subject to noise as defined in Section 6.2.2, and with the aid situation assessment perturbed by random noise at rates between 0 and 10 %. This modeled the rate at which the aid could produce an erroneous situation assessment whether or not its own input were noisy. The expected error cost, generated by the model under the conditions of these runs, appeared to exceed that of the unaided case when the incidence of aid noise was in the region of 6-7%. Therefore,

- to result in an improvement in performance, the decision aid should have an error rate less than 6 - 7 % even when subject to imperfect information.

If this figure seems high, it could be because, in certain strategies, the COW can "catch" errors on the part of the DOOW - the organization possess some robustness with respect to aid error. As before, it has been assumed that a uniform distribution on decision strategies exists, although the effect of individual differences, discussed in 6.2.3 applies here as well. The figure is approximate, and as such, is intended only as a guideline. Certainly, any decision aid to be used in the emergency control context should operate virtually perfectly since, although average figures of error and cost are helpful, it is the single error that could result in catastrophe.

CHAPTER 7

CONCLUSIONS

This thesis formulated an analytical model of the ship control party of a submarine performing emergency control, proposed and modeled a decision aid, and analyzed the organization model in the aided and unaided cases. By limiting the scope of the model to the situation assessment and response selection aspects of the initial stage of emergency control, known as immediate actions, most assumptions necessary for the application of the analytical modeling tools were rendered more reasonable. The immediate actions comprise the time-critical phase of emergency control, in which time pressure is most extreme, the probability of error most high, and the consequences of error the gravest.

The analysis was originally performed under the assumption that the organization's input information was noiseless, but this assumption was relaxed by developing a model of noise corruption reflecting an assessment of sensor and indicator failure. The resulting organization error rate, hence organization performance, corresponded to a subjective assessment of such error. Individual decisionmaker workload generated by the model was robust with respect to the noise disturbance of the input, the maximum variation between the two cases being well under one bit. All results of the decision aid analysis were produced for the noise-corrupted case.

The results, in brief, are that a decision aid will bring a percent improvement in performance between 6% and 42%, with an average of 11%. However, the absolute improvement in performance for any organization strategy is roughly constant and may be small compared to the variation in performance as a function of organization strategy. In terms of workload of the DOOW, the decision aid, on average, will not bring about an improvement. The effects of the aid upon workload depend on the characteristics of the decisionmaker in choosing among strategies for use of the aid. In the extreme case that the DOOW relies solely upon the aid for the situation assessment, a 24% workload reduction could be expected. However, if the DOOW compares his own situation assessment with the decision aid's, the expected workload is 16 % greater than in the unaided case. These results are predicated upon the assumption that the decision aid is perfectly reliable; in this sense they constitute a "best case" scenario. A 5-7 % chance of random error by the decision aid could result in the decision aid producing no performance improvement.

It is important to stress that the results obtained in this thesis apply to the situation assessment and response selection aspects of submarine emergency control immediate actions, and that emergency detection and response implementation have not been considered. The benefits of a decision aid in terms of detection could be significant. Therefore, decisions about developing an emergency control decision aid capability of the sort envisioned in this thesis require futher research to illuminate the implications for the detection problem that such a decision aid could have.

APPENDIX A

THE DECISION ALGORITHMS

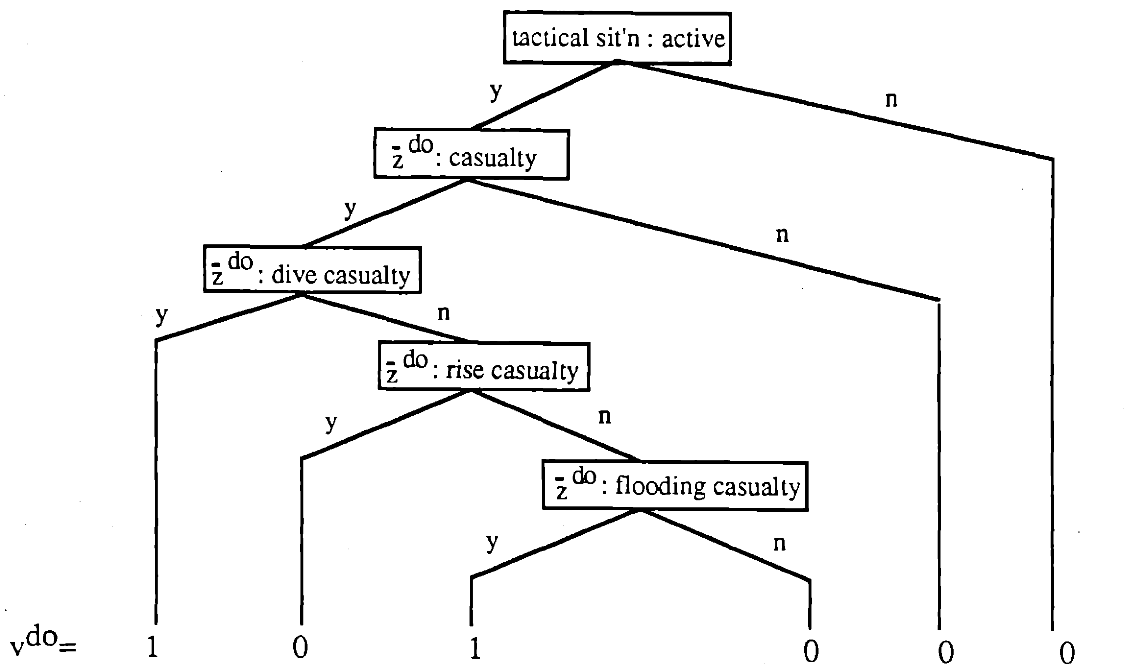
A.1 THE OFFICER OF THE DECK

Information Fusion

Inputs: x^o: tactical situation {1}
no tactical situation {0}

z^{do}: normal / indicator failure {0}
jam dive {1}
stuck dive {2}
stuck rise {3}
jam rise {4}
rudder failure {5}
fairwater plane failure {6}
> 6" pipe flooding, engine room {7}
> 6" pipe flooding, not engine room {8}
< 6" pipe flooding, engine room {9}
< 6" pipe flooding, not engine room {10}

Outputs: v^{do}: tactical restriction {1}
no tactical restriction {0}



A.2 THE DIVING OFFICER OF THE WATCH

Internal Preprocessor

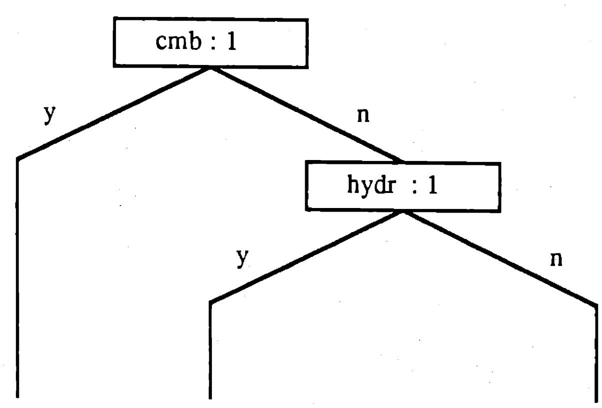
Inputs: $\underline{x}^d$: (defined in Chapter 4)

x_1^d: control mode buzzer (cmb)
x_2^d: stick position cue (spc)
x_3^d: stern plane angle (s.p. angle)
x_4^d: speed
x_5^d: depth

z^{cd} : COW casualty report

Outputs: u^d: {1,2,3}
$\underline{x}^d$:
x_1^d: normal {0}
hydraulic failure {1}
>6" flooding, engine room {2}
>6" flooding, torpedo room {3}
>6" flooding, diesel room {4}
2-6" flooding, engine room {5}
2-6" flooding, torpedo room {6}
2-6" flooding, diesel {7}
<2", engine room {8}
<2", torpedo room {9}
<2", diesel room {10}

$x_2^d \rightarrow x_5^d$: same as inputs



u^d:	1	3	2
x_1^d:	0	0	z^{cd}
x_2^d:	s.p. angle	s.p. angle	(inactive)
x_3^d:	spc	spc	(inactive)
x_4^d:	speed	speed	speed
x_5^d:	depth	depth	depth

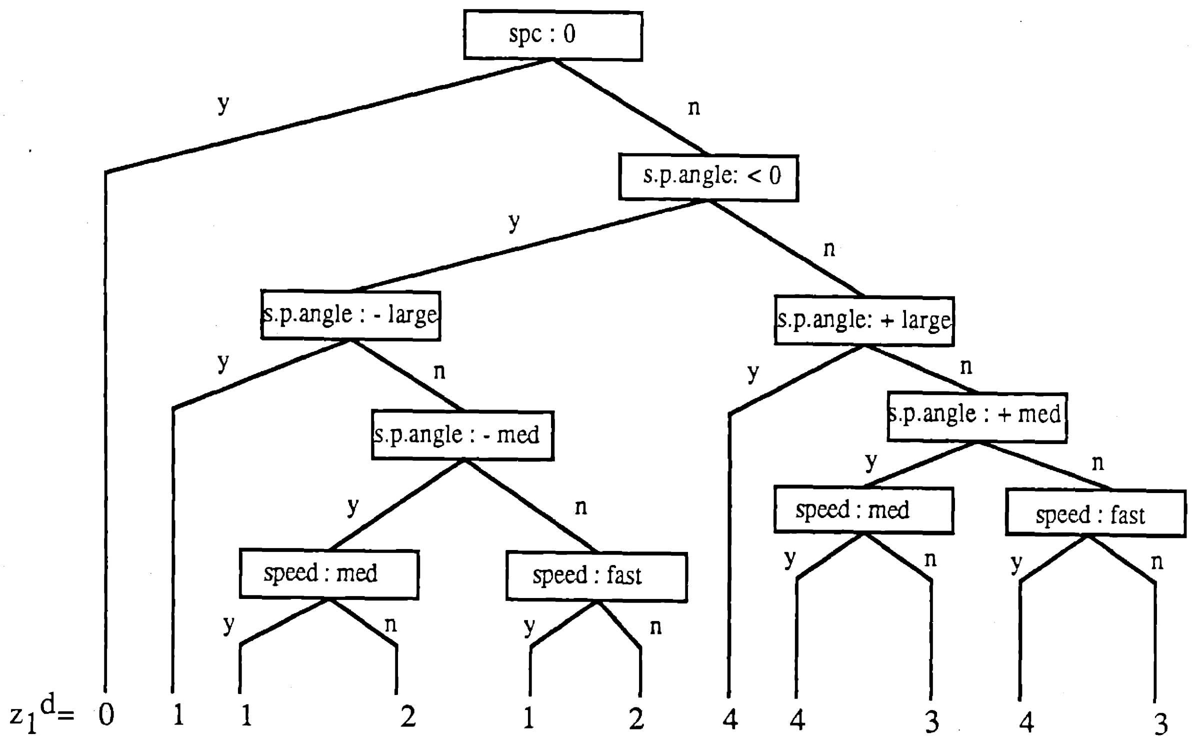
DOOW Situation Assessment

Inputs: $\underline{x}^d$: x_1^d casualty information
x_2^d s.p. angle
x_3^d stick position cue
x_4^d speed
x_5^d depth

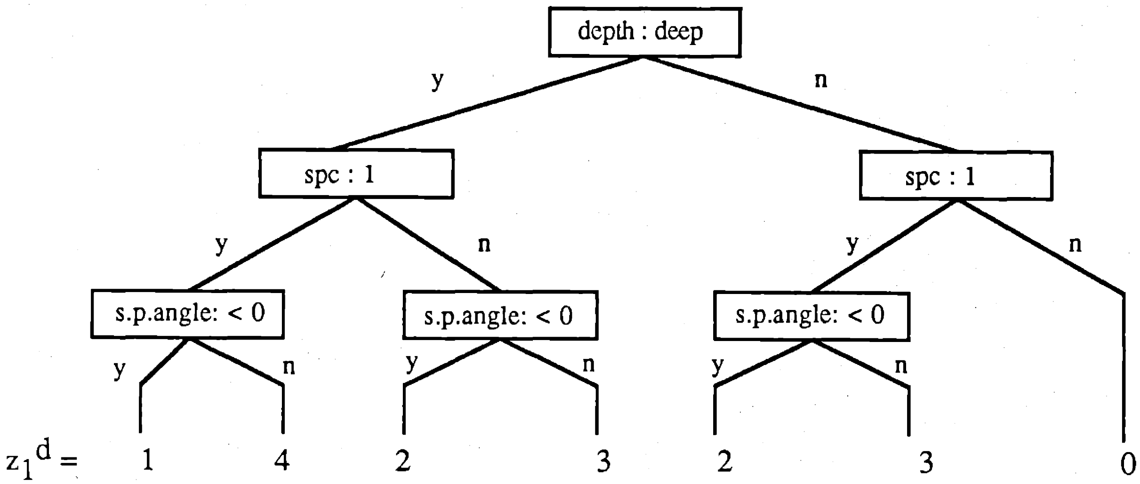
Outputs: $\underline{z}^d$
z_1^d : as below
normal/ind. flr. {0}
jam dive {1}
stuck dive {2}
stuck rise {3}
jam rise {4}
rudder failure {5}
fairwater plane failure {6}
> 6" pipe, eng. room {7}
> 6" pipe, not eng. room {8}
< 6" pipe, eng. room {9}
< 6" pipe, eng. room {10}

$z_2^d = x_4^d$; $z_3^d = x_5^d$

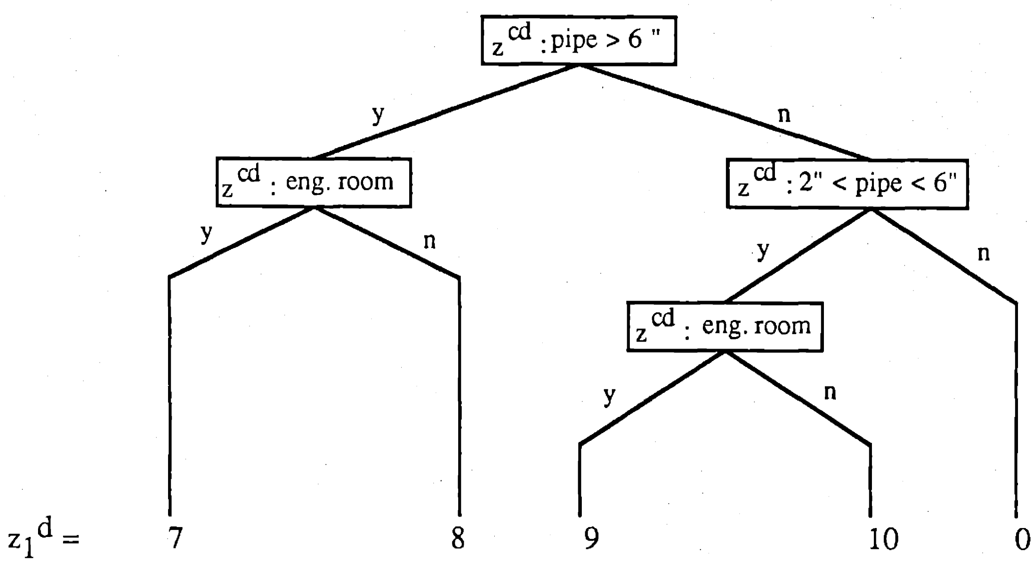
Algorithm f_1^d:



DOOW Situation Assessment, Algorithm $f_2{}^d$



Situation Assessment, Algorithm $f_3{}^d$



DOOW Information Fusion

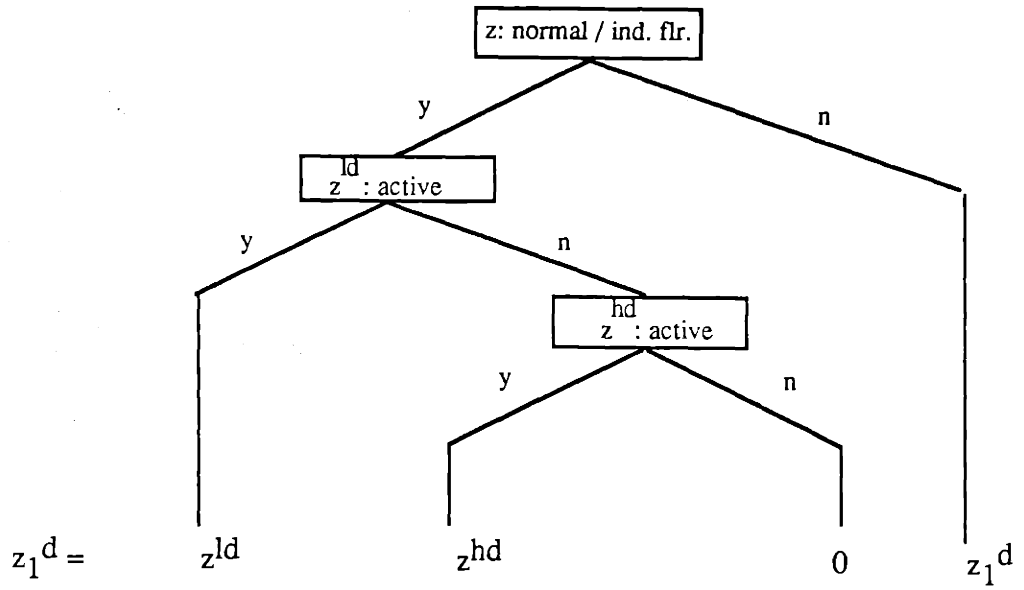
Inputs: $\underline{z}^d$, z^{ld}, z^{hd}

Outputs: $\underline{z}^d$

z_1^d: as below

z_2^d: z_2^d

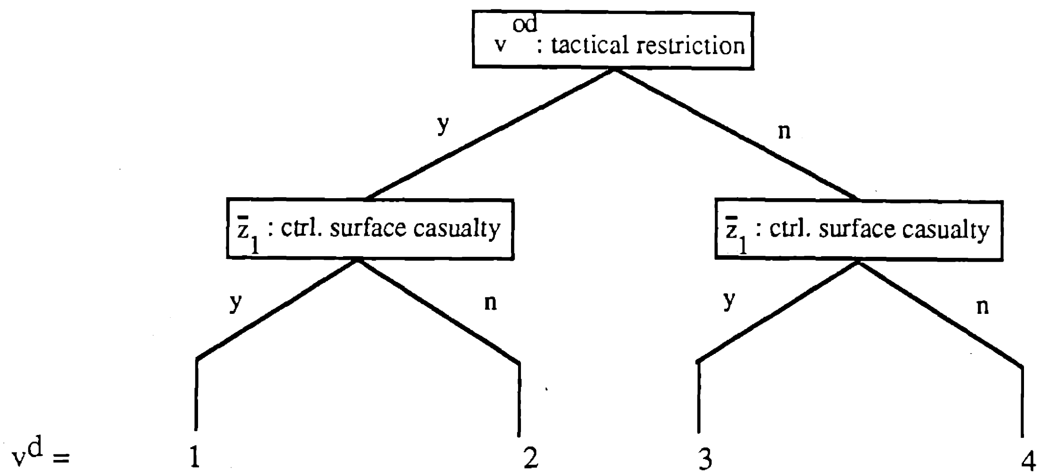
z_3^d: z_3^d



DOOW Command Interpretation

Inputs: $\underline{z}^d$, v^{od}

Outputs: v^d : {1,2,3,4}

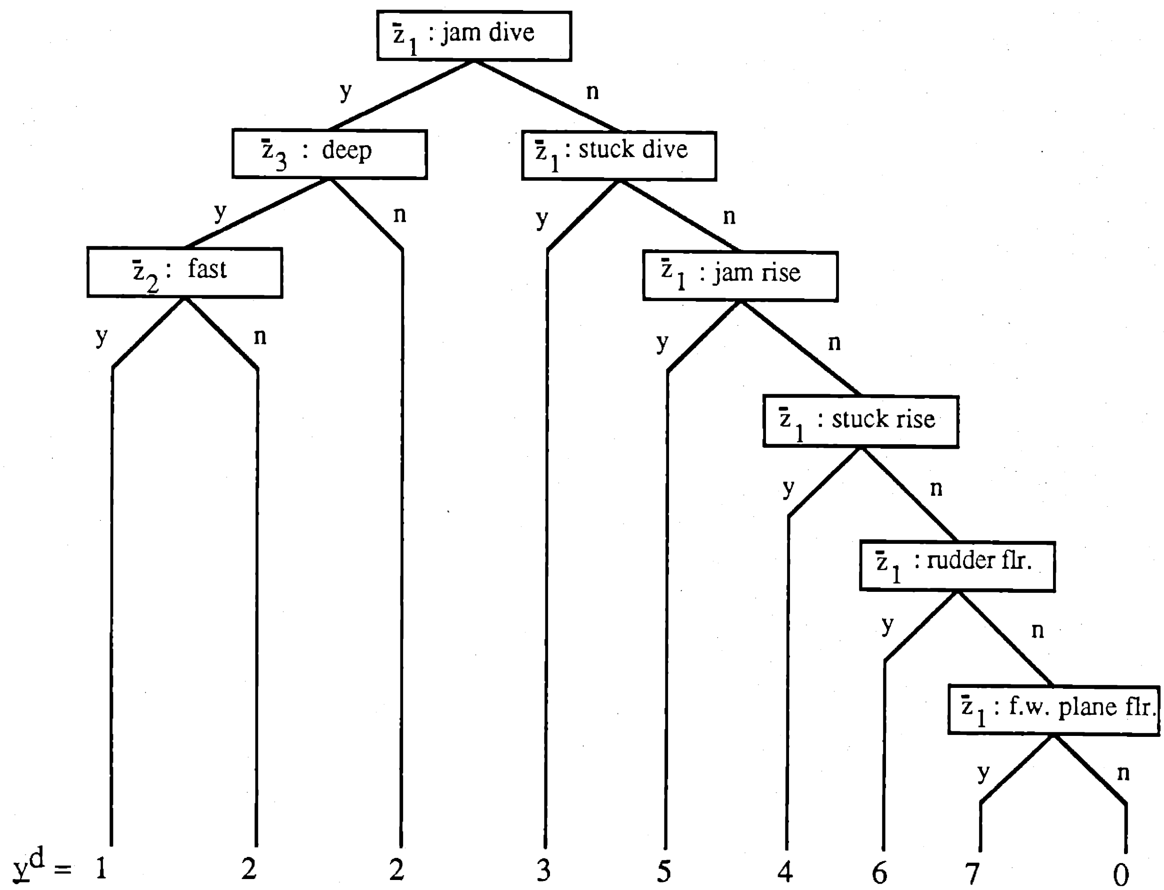


DOOW Response Selection

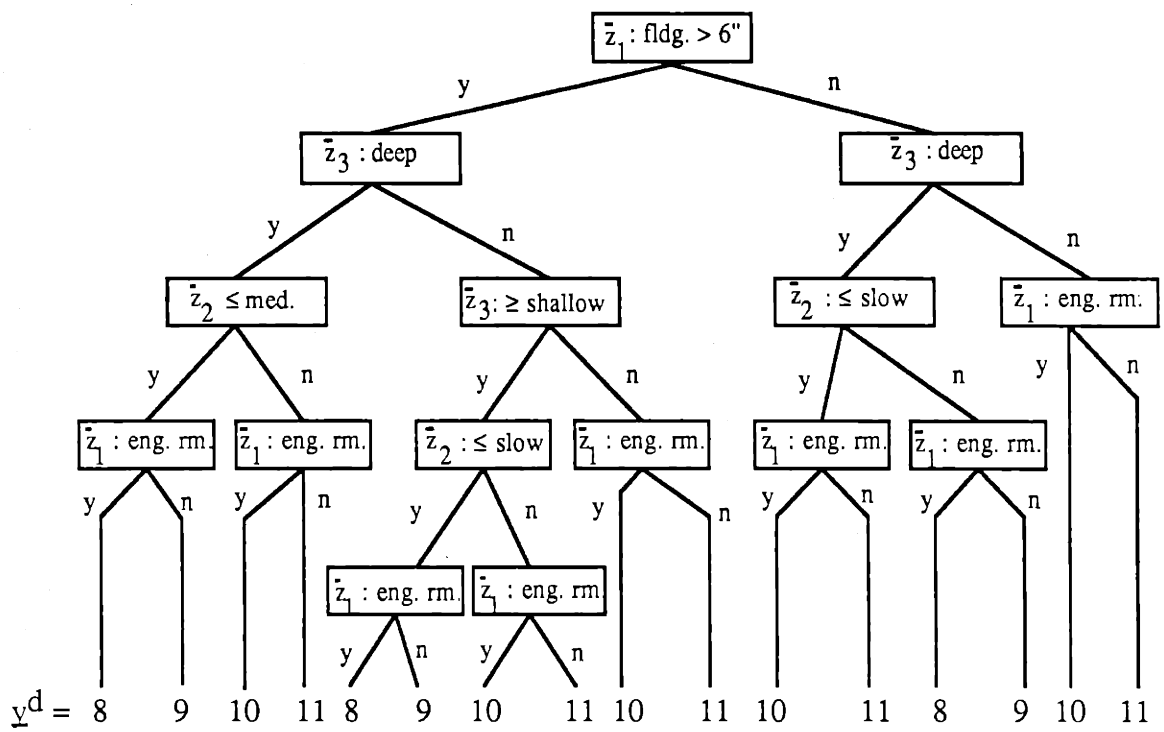
Inputs: $\underline{z}^d$

Outputs: $\underline{y}^d$: $\{y^{dc}, y^{dl}, y^{dh}\}$ as below; see also Table A.1

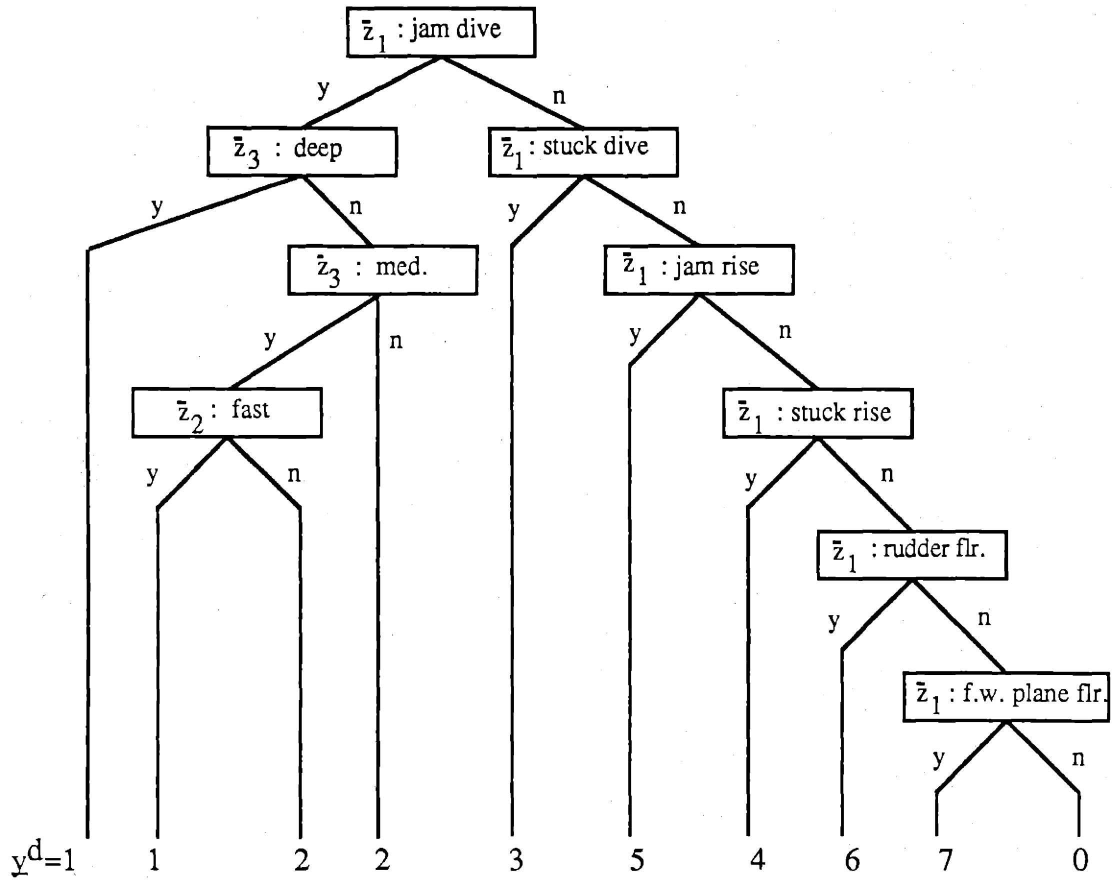
Algorithm h_1d:



DOOW Response Selection, Algorithm h_2^d



DOOW Response Selection, Algorithm h_3^d



DOOW Response Selection, Algorithm h_4^d

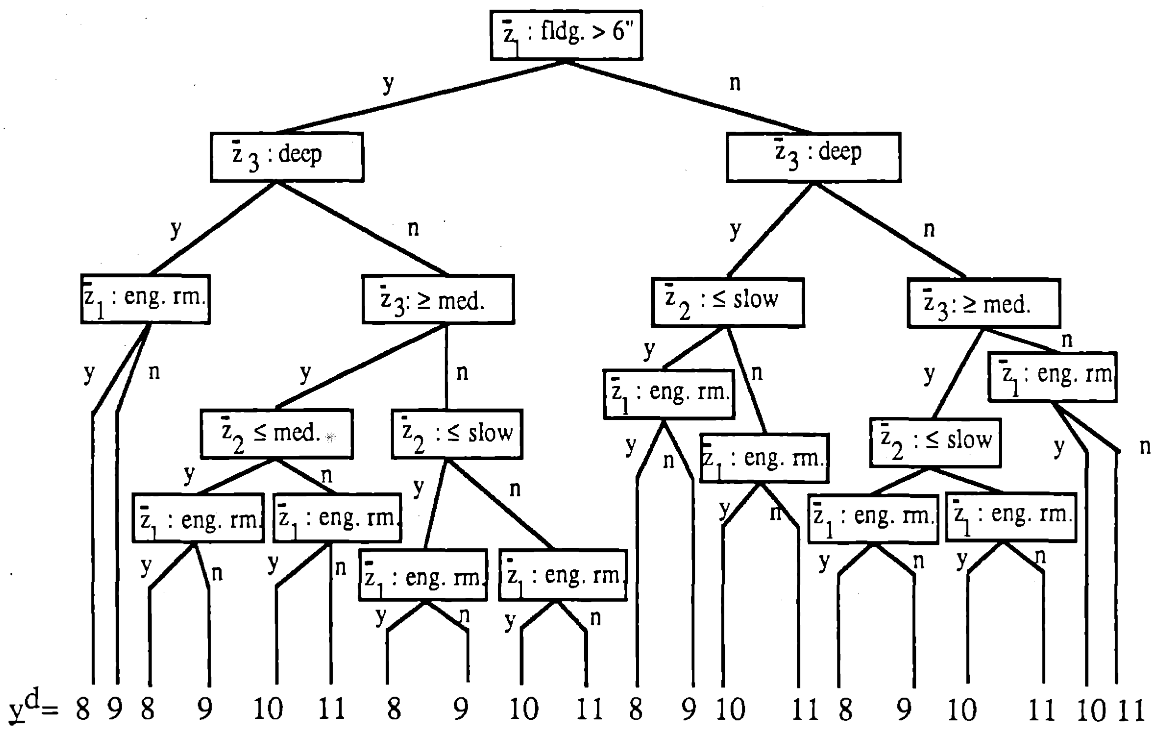


TABLE A.1

DEFINITION OF THE VECTOR $\underline{y}^d$

Code	Response	y^{dc}	y^{dl}	y^{dh}
0	ind. flr.	0	0	0
1	jam dive (unrestricted)	1	1	1
2	jam dive (restricted)	2	1	1
3	stuck dive	2	2	2
4	stuck rise	3	3	3
5	jam rise	3	4	4
6	rudder failure	0	0	5
7	fairwater plane failure	0	5	6
8	major flooding (engine room)	1	6	8
9	major flooding (not engine room)	1	6	7
10	minor flooding (engine room)	2	7	8
11	minor flooding (not engine room)	2	7	7

TABLE A.2

DEFINITION OF y^{dc}, y^{dl}, y^{dh}

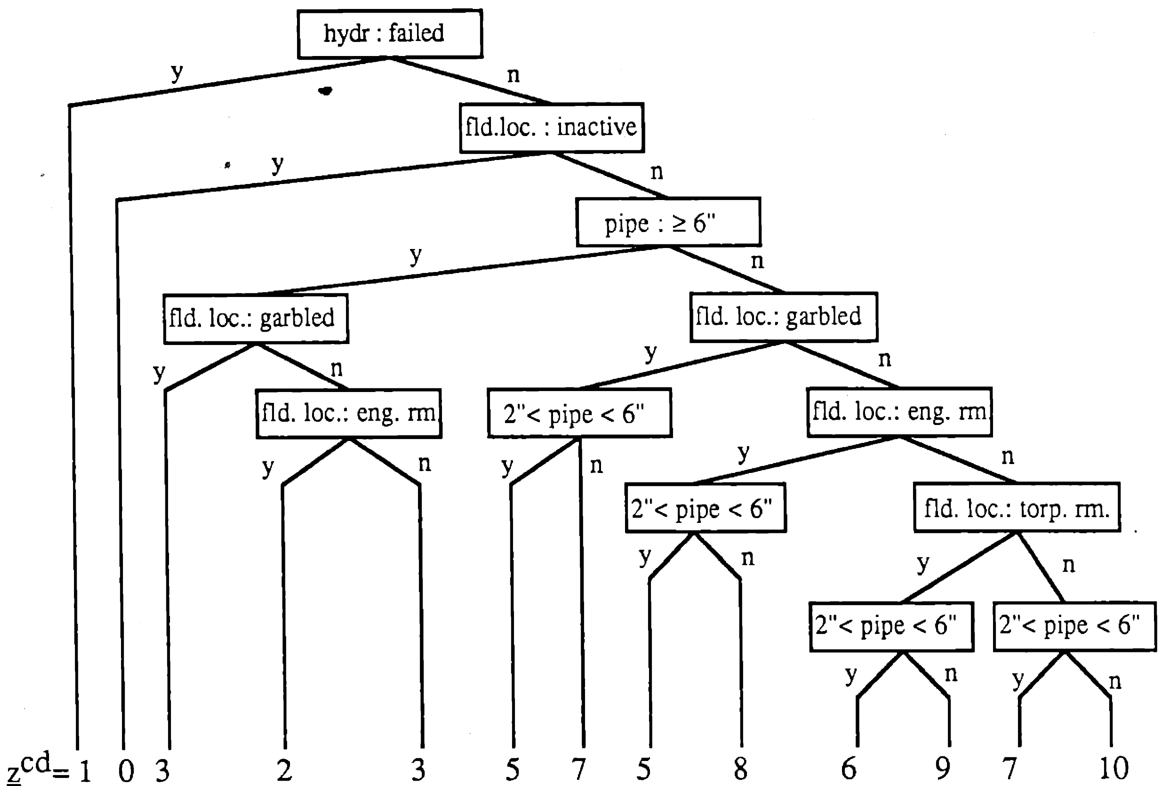
Code	y^{dc}	Definition: y^{dl}	y^{dh}
0	no response	no response	no response
1	EMBT blow	jam dive, f.w.pl. rise	jam dive, engine back 3/4, hard rudder
2	pump water overboard	stuck dive, f.w.pl. rise	stuck dive, eng. back 1/2, no rudder
3	line up to pump onbd.	stuck rise	eng. back 3/4, f.w.pl. on dive
4	-	jam rise	eng. back 1/2, f.w.pl. on dive
5	-	counter f.w.pl. w/st.pl.	slow; attempt emerg. ctrl. of rudder
6	-	st.pl. ang.<20; rise to 150'	slow;attempt emerg. ctrl. of f.w.pl.
7	-	st.plt.ang.<20;rise to 200'	1/2 speed; rise angle on f.w.planes
8	-	-	3/4 speed; rise angle on f.w.planes

A.3 CHIEF OF THE WATCH

Situation Assessment

Input: $\underline{x}^c$: $x_1{}^c$ hydraulic indicator
$x_2{}^c$ flooding location report
$x_3{}^c$ flooding pipe size report
$x_4{}^c$ speed
$x_5{}^c$ depth

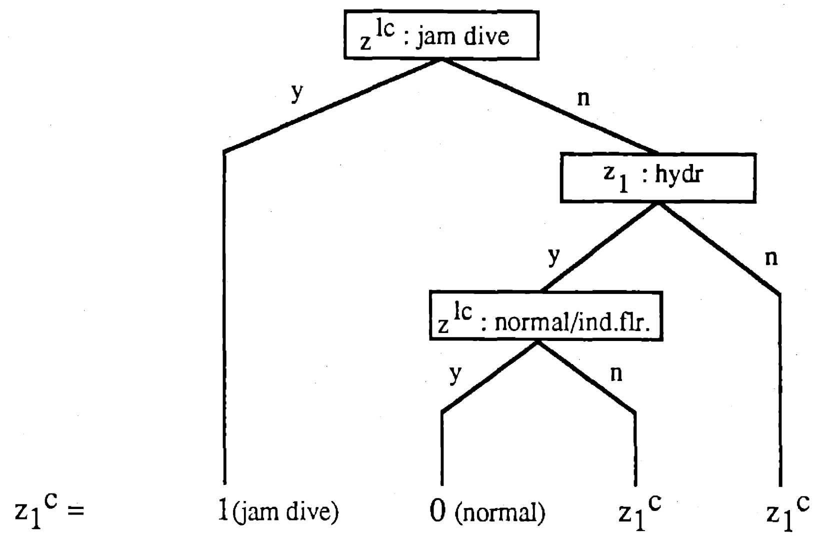
Output: $\underline{z}^c$: $z_1{}^c$ emergency situation
(defininition same as $x_1{}^c$)
$z_2{}^c$ (speed) = $x_4{}^c$
$z_3{}^d$ (depth) = $x_5{}^c$
$z^{cd} \equiv z_1{}^c$



COW Information Fusion

Inputs: $\underline{z}^c$, z^{lc}

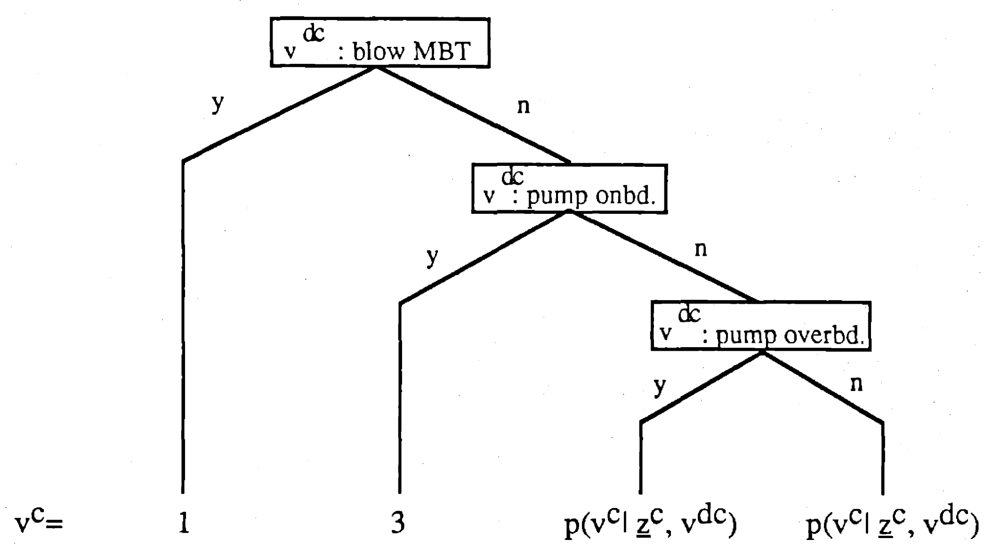
Outputs: $\underline{z}^c$



COW Command Interpretation

Inputs: $\underline{z}^c$, v^{dc}

Outputs: v^c



COW Response Selection

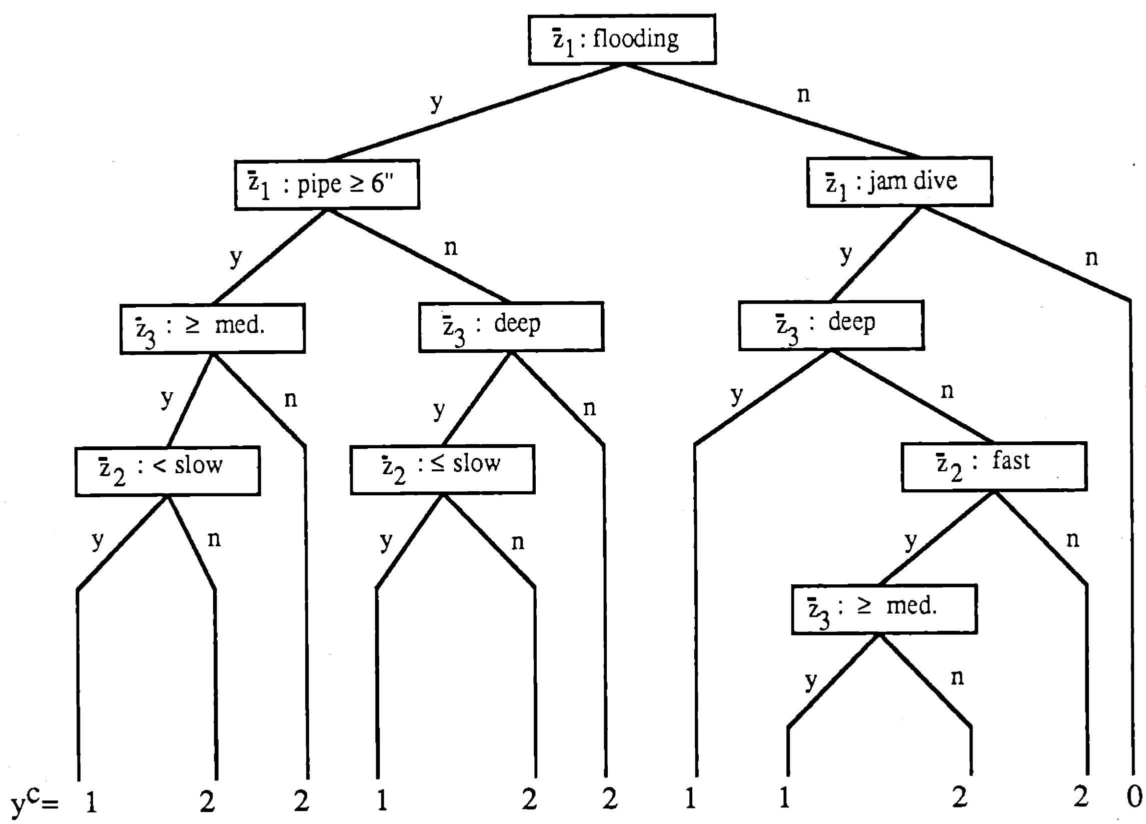
Inputs: $\underline{z}^c$ Outputs: y^c

Algorithm h_1^c: $y^c = y^{dc}$

Algorithm h_2^c: $y^c = y^{dc}$

Algorithm h_3^c: $y^c = y^{dc}$

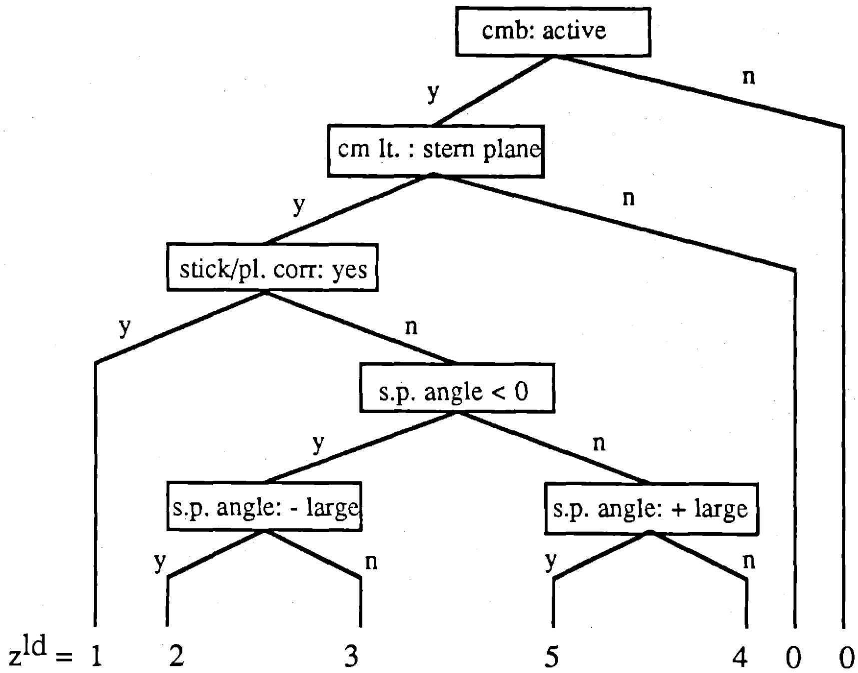
Algorithm h_4^c:



A.4 THE LEE HELM

Input: $\underline{x}^l$: x_1^l: control model buzzer
x_2^l: control model light
x_3^l: stern plane angle
x_4^l: stick pos. cue (stick/pl. corr.)

Output: z^{ld}



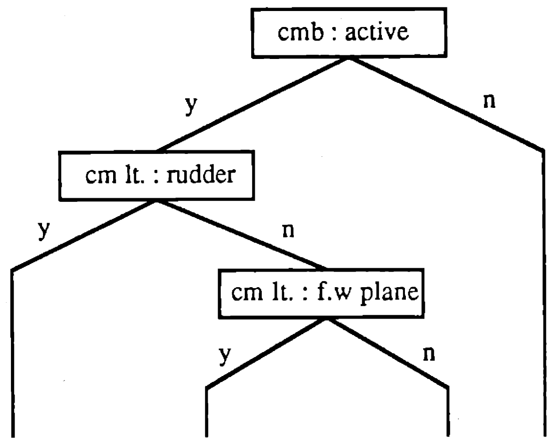
Lee Helm Response Selection Algorithm: $y^l = y^{dl}$

A.5 THE HELM

Helm Situation Assessment

Inputs: $\underline{x}^h$: x_1^h control mode buzzer Outputs: z^{hd}

x_2^h control model light



$z^{hd} =$ 6 (rudder flr.) 7 (f.w.pl. flr.) 0 0

Helm Response Selection Algorithm: $y^h = y^{dh}$

APPENDIX B

DERIVATION OF THE WORKLOAD EXPRESSIONS

In the derivations that follow, the algorithms have been assigned numbers in order to simplify the mathematical notation. The first SA algorithm of a DM is given the number 1, the second the number 2, and so on, through the last RS algorithm. In the case of the DOOW, the preprocessor receives the designation 0.

B.1 Workload Expressions for the OOD

B.1.1 Information Fusion Stage

The OOD was introduced in Chapter 5 as a simplified representation of one phase of an otherwise sophisticated decisionmaker. The "custom-made" nature of this DM model takes advantage of the descriptive flexibility of the methodology used. However, rather than customize the nomenclature, this algorithm is labeled as Information Fusion, since that seems to fit best.

Throughput:

$$\overset{o}{G}_t = T\,(x^o, \bar{z}^{do} ; v^{od}) \tag{B.1}$$

The definition of n-dimensional mutual information (3.6) applied to (B.1) yields:

$$\overset{o}{G}_t = H\,(v^{od}) - H_{x^o,\, \bar{z}^{do}}\,(v^{od}) \tag{B.2}$$

Except where switching between algorithms occurs, the algorithms are assumed to be deterministic. Therefore, v^{od} is fully determined by knowledge of the variables x^o and v^{od}. The second term in (B.2) is equal to zero and can be eliminated.

$$\overset{o}{G}_t = H\,(v^{od}) \tag{B.3}$$

Blockage:

The blockage expression is defined in the second term of (3.9) as the transmission between the input and the internal variables of a system; however the fact that rejection has been assumed to be zero, in Chapter 3, assumption (3), means that the PLI can be applied as follows:

$$\overset{o}{G_b} = H\,(x^o, \bar{z}^{do}) - G_t \qquad \text{(B.4)}$$

Substituting (B. 3) into (B.4) yields

$$\overset{o}{G_b} = H\,(x^o, \bar{z}^{do}) - H\,(v^{od}) \qquad \text{(B.5)}$$

Noise:

The noise present in the OOD is formally stated as :

$$\overset{o}{G_n} = H_{x^o, \bar{z}^{do}}\,(w^{o1}, w^{o2}, \ldots, w^{o8}, v^{od}) \qquad \text{(B.6)}$$

However, since all of the model algorithms that are not switches are deterministic by assumption, as per Chapter 3, assumption (2), the algorithm is noiseless by definition.

$$\overset{o}{G_n} = 0 \qquad \text{(B.7)}$$

Coordination:

A measure of the constraining relatedness among the internal variables of a system, the coordination for the OOD is defined as:

$$\overset{o}{G_c} = T\,(w_1 : w_2 : \ldots : w_8 : v^{od}) \qquad \text{(B.8)}$$

but can be rewritten, taking advantage of the n-dimensional mutual information (3.6), as:

$$G_c^o = \sum_{i=1}^{8} H(w_i) + H(v^{od}) - H(w_1, w_2, \ldots, w_8, v^{od}) \qquad (B.9)$$

Consider the last term, the joint entropy of the OOD's internal variables. Into the first two of these internal variables are mapped the inputs x^o and z^{do}, knowledge of which information removes any uncertainty in the remainder of the internal variables. Therefore (B.9) becomes:

$$G_c^o = \sum_{i=1}^{8} H(w_i) + H(v^{od}) - H(v^{od}) - H_{v^{od}}(x^o) \qquad (B.10)$$

Since the two variables in the last term are independent, that term is simply the entropy present in x^o. The coordination then becomes

$$G_c^o = \sum_{i=1}^{8} H(w_i) - H(x^o) \qquad (B.11)$$

and, since the equivalent of x^o is present in the summand and cancels with the second term, the final expression is:

$$G_c^o = \sum_{i=2}^{8} H(w_i) \qquad (B.12)$$

B.2 Workload Expressions for the DOOW

The derivations for the DOOW and the remainder of th SCP shall, when applicable, follow the development for the OOD. Any new manipulations will be introduced as the need arises.

B.2.1 Preprocessing Stage

Throughput:

$$g_t^{d\,pp} = T(\underline{x}^d, z^{cd} : \bar{\underline{x}}^d, u^d) \quad (B.13)$$

$$g_t^{d\,pp} = H(\bar{\underline{x}}^d, u^d) - H_{\underline{x}^d, z^{cd}}(\bar{\underline{x}}^d, u^d) \quad (B.14)$$

The deterministic nature of the preprocessor means that the arguments in the second term are known when the conditioning variables are known. This term can be eliminated.

$$g_t^{d\,pp} = H(\bar{\underline{x}}^d, u^d) \quad (B.15)$$

Blockage:

From the PLI, (3.9), and from the assumption that rejection is assumed to be zero, the blockage expression can be written in the following way:

$$g_b^{d\,pp} = H(x^d, z^{cd}) - G_t \quad (B.16)$$

This approach will be implicit in the blockage derivations that follow.

$$g_b^{d\,pp} = H(x^d, z^{cd}) - H(\bar{\underline{x}}^d, u^d) \quad (B.17)$$

Noise:

Although the noise is formally expressed as:

$$g_n^{d\,pp} = H_{\underline{x}^d, z^{cd}}(w^{d0}, \ldots, w^{d0}, u^d, \bar{\underline{x}}^d) \quad (B.18)$$

This algorithm is deterministic and, as described in Chapter 5 and illustrated in Appendix A, generates no noise. Knowledge of the conditioning variables leaves no uncertainty in the variable in parentheses.

$$g_n^{d\,pp} = 0 \tag{B.19}$$

B.2.2 Situation Assessment Stage

Throughput:

$$g_t^{d\,sa} = T(\underline{\bar{x}}^d, u^d : \underline{z}^d) \tag{B.20}$$

$$g_t^{d\,sa} = H(\underline{z}_d) - H_{\underline{\bar{x}}^d, u^d}(\underline{z}^d) \tag{B.21}$$

$$g_t^{d\,sa} = H(\underline{z}^d) \tag{B.22}$$

Blockage:

$$g_b^{d\,sa} = H(\underline{\bar{x}}^d, u^d) - G_t \tag{B.23}$$

$$g_b^{d\,sa} = H(\underline{\bar{x}}^d, u^d) - H(\underline{z}^d) \tag{B.24}$$

Noise:

$$g_n^{d\,sa} = H_{\underline{\bar{x}}^d, u^d}(W^{d1}, W^{d2}, W^{d3}, \underline{z}^d) \tag{B.25}$$

$$g_n^{d\,sa} = 0 \tag{B.26}$$

Coordination: PP ∪ SA

$$g_c^{d\,pp/sa} = T\,(\,W^{d0} \colon u^d : \underline{\bar{x}}^d \colon W^{d1} \colon W^{d2} \colon W^{d3} \colon \underline{z}^d\,) \tag{B.27}$$

$$g_c^{d\,pp/sa} = \sum_{i=0}^{3} \sum_{j=1}^{\alpha_i} H\,(\,w_j^{di}\,) + H\,(\,u^d\,) + H\,(\,\underline{\bar{x}}^d\,) + H\,(\,\underline{z}^d\,)$$

$$- H\,(\,W^{d0}, u^d, \underline{\bar{x}}^d, W^{d1}, W^{d2}, W^{d3}, \underline{z}^d\,) \tag{B.28}$$

Consider the joint entropy term in (B.28). Since the preprocessor is deterministic and generates deterministic output, selecting only pure strategies as discussed in Chapter 5, then knowledge of its inputs removes any uncertainty of subsequent variables in these two stages. The joint entropy term may be rewritten:

$$H\,(\,W^{d0}, u^d, \underline{\bar{x}}^d, W^{d1}, W^{d2}, W^{d3}, \underline{z}^d\,) = H\,(\,W^{d0}) \tag{B.29}$$

The term in parentheses on the left of (B.29) is the set of internal variables of the preprocessor. Noting that the inputs $\underline{x}^d$ and z^{cd} are mapped onto w^{di}, i = 1, 2, ..., 7, this term can be equivalently written as:

$$H\,(\,W^{d0}) = H\,(\,x^d, z^{cd}\,) \tag{B.30}$$

The coordination expression for the PP and SA stages of the DOOW may finally be expressed as:

$$g_c^{d\,pp/sa} = \sum_{i=0}^{3} \sum_{j=1}^{\alpha_i} H(W_j^{di}) + H(u^d) + H(\underline{\bar{x}}^d) + H(\underline{z}^d) - H(\underline{x}^d, z^{cd}) \tag{B.31}$$

B.2.3 Information Fusion

Throughput:

$$g_t^{d\,if} = T(\underline{z}^d, z^{ld}, z^{hd} : \underline{\bar{z}}^d, \bar{z}^{do}) \tag{B.32}$$

$$g_t^{d\,if} = H(\underline{\bar{z}}^d, \bar{z}^{do}) - H_{\underline{z}^d, z^{ld}, z^{hd}}(\underline{\bar{z}}^d, \bar{z}^{do}) \tag{B.33}$$

The fused assessed situation $\underline{\bar{z}}^d$ is fully determined by knowledge of z^d, z^{ld}, and z^{hd}. Furthermore, $\bar{z}^{do}$ is identical to $\bar{z}_1{}^d \in \underline{\bar{z}}^d$ and thus contributes no new information in either expression above. It may therefore be omitted in the expressions that follow.

$$g_t^{d\,if} = H(\underline{\bar{z}}^d) \tag{B.34}$$

Blockage:

$$g_b^{d\,if} = H(\underline{z}^d, z^{ld}, z^{hd}) - G_t \tag{B.35}$$

Which can be rewritten as

$$g_b^{d\,if} = H(\underline{z}^d, z^{ld}, z^{hd}) - H(\underline{\bar{z}}^d) \tag{B.36}$$

Noise:

$$g_n^{d\,if} = H_{\underline{z}^d,\, z^{ld},\, z^{hd}}(\bar{\underline{z}}^d) \tag{B.37}$$

$$g_n^{d\,if} = 0 \tag{B.38}$$

Coordination:

$$g_c^{d\,if} = H(w_1^{d4} : \ldots : w_5^{d4} : \bar{\underline{z}}^d : \bar{z}^{do}) \tag{B.39}$$

$$g_c^{d\,if} = \sum_{i=1}^{5} H(w_i^{d4}) + H(\bar{z}^d) + H(\bar{z}^{do}) - H(W^{d4}) -$$

$$H_{W^{d4}}(\bar{z}^d, \bar{z}^{do}) \tag{B.40}$$

Since the two variables in parentheses in the last term of (B.4 0) are fully determined by W^{d4}, this equation can be rewritten as

$$g_c^{d\,if} = \sum_{i=1}^{5} H(w_i^{d4}) + H(\bar{\underline{z}}^d) + H(\bar{z}^{do}) - H(W^{d4}) \tag{B.41}$$

B.2.4 Command Interpretation

Throughput:

$$g_t^{d\,ci} = H(\bar{\underline{z}}^d, v^{od} : \bar{v}^d) \tag{B.42}$$

$$g_t^{d\ ci} = H(\bar{v}^d) - H_{\bar{\underline{z}}^d, v^{od}}(\bar{v}^d) \tag{B.43}$$

$$g_t^{d\ ci} = H(\bar{v}^d) \tag{B.44}$$

Blockage:

$$g_b^{d\ ci} = H(\bar{\underline{z}}^d, v^{od}) - g_t^{d\ ci} \tag{B.45}$$

$$g_b^{d\ ci} = H(\bar{\underline{z}}^d, v^{od}) - H(\bar{v}^d) \tag{B.46}$$

Noise:

$$g_n^{d\ ci} = H_{\bar{\underline{z}}^d, v^{od}}(\bar{v}^d) \tag{B.47}$$

$$g_n^{d\ ci} = 0 \tag{B.48}$$

B.2.5 Response Selection

Throughput::

$$g_t^{d\ rs} = H(\bar{\underline{z}}^d, \bar{v}^d : \underline{y}^d) \tag{B.49}$$

$$g_t^{d\ rs} = H(\underline{y}^d) - H_{\bar{\underline{z}}^d, \bar{v}^d}(\underline{y}^d) \tag{B.50}$$

$$g_t^{d\ rs} = H(\underline{y}^d) \tag{B.51}$$

Blockage:

$$g_b^{d\ rs} = H(\bar{\underline{z}}^d, \bar{v}^d) - g_t^{d\ rs} \tag{B.52}$$

$$g_b^{d\ rs} = H(\bar{\underline{z}}^d, \bar{v}^d) - H(\underline{y}^d) \tag{B.53}$$

Noise:

$$g_n^{d\ rs} = H_{\bar{z}^d, \bar{v}^d}(y^d) \tag{B.54}$$

$$g_n^{d\ rs} = 0 \tag{B.55}$$

Coordination: $CI \cup RS$

$$g_c^{d\ ci/rs} = T(W^{d5}: \bar{v}^d: W^{d6}: \ldots W^{d9}: \underline{y}^d) \tag{B.56}$$

$$g_c^{d\ ci/rs} = \sum_{i=0}^{4} \sum_{j=1}^{\alpha_i} H(w_j^{d5+i}) + H(\bar{v}^d) + H(\underline{y}^d) -$$

$$H(W^{d5}, \bar{v}^d, W^{d6}, \ldots, W^{d9}, \underline{y}^d) \tag{B.57}$$

The joint uncertainty term becomes:

$$H_{W^{d5}}(\bar{v}^d) + H_{W^{d5}, \bar{v}^d}(W^{d6}) + H_{W^{d5}, \bar{v}^d, W^{d6}}(W^{d7}) + \ldots$$

$$+ H_{W^{d5}, \bar{v}^d, W^{d6}, \ldots, W^{d8}}(W^{d9}) + H_{W^{d5}, \bar{v}^d, W^{d6}, \ldots, W^{d9}}(\underline{y}^d) \tag{B.58}$$

The first and last terms are zero, as the arguments are determined by the conditioning variables.

Knowledge of W^{d5} is sufficient to determine v^d and whether or not each particular algorithm internal variable set, W^{di}, i = 16,7,8,9 is active. Hence, the expression may be rewritten as :

$$H_{W^{d5}}(W^{d6}) + H_{W^{d5}}(W^{d7}) + H_{W^{d5}}(W^{d8}) + H_{W^{d5}}(W^{d9}) \qquad \text{(B.59)}$$

The coordination expression is finally:

$$g_c^{d\ ci/rs} = \sum_{i=0}^{4} \sum_{j=1}^{\alpha_i} H(w^{d5+i}) + H(\bar{v}^d) + H(\underline{y}^d) - \sum_{i=6}^{9} H_{W^{d5}}(W^{di}) \qquad \text{(B.60)}$$

B.2.6 DOOW Workload Totals

Total Throughput:

$$G_t^d = H(\bar{\underline{x}}^d, u^d) + H(\underline{z}^d) + H(\bar{\underline{z}}^d) + H(\bar{v}^d) + H(\underline{y}^d) \qquad \text{(B.61)}$$

Total Blockage:

$$G_b^d = H(x^d, z^{cd}) - H(\underline{z}^d) + H(\underline{z}^d, z^{ld}, z^{hd}) - H(\bar{\underline{z}}^d)$$

$$+ H(\bar{\underline{z}}^d, v^{od}) - H(\bar{v}^d) + H(\bar{\underline{z}}^d, \bar{v}^d) - H(\underline{y}^d) \qquad \text{(B.62)}$$

Total Noise:

$$G_n^d = 0 \qquad \text{(B.63)}$$

Total Coordination:

The total coordination for a decisionmaker is not a simple sum of the coordination terms associated with each decisionmaking stage, but must take into account the variable interactions between the stages as well:

$$G_c^d = g_c^{pp/sa} + g_c^{if} + g_c^{ci} + g_c^{rs} + T(pp \cup sa : if : ci \cup rs) \quad \text{(B.64)}$$

$$T(pp \cup sa: if: ci \cup rs) = T(pp \cup sa: if) + T(pp \cup sa, if : ci \cup rs) \quad \text{(B.65)}$$

The following development is after that given in [22], which showed that in evaluating an expression like (B.65), it is necessary to consider only those variables which determine the others in any given stage.

$$T(pp \cup sa: if) = H(\underline{z}^d, z^{ld}, z^{hd}) - H_{\underline{x}^d, z^{cd}}(\underline{z}^d, z^{ld}, z^{hd}) \quad \text{(B.66)}$$

Knowledge of $\underline{x}^d$ determines $\underline{z}^d$.

$$T(pp \cup sa: if) = H(\underline{z}^d, z^{ld}, z^{hd}) - H_{\underline{x}^d, z^{cd}}(z^{ld}, z^{hd}) \quad \text{(B.67)}$$

$$T(pp \cup sa, if : cirs) = H(\underline{z}^d, v^{od}) - H_{\underline{x}, z^{cd}, \underline{z}^d, z^{ld}, z^{hd}}(\underline{z}^d, v^{od}) \quad \text{(B.68)}$$

The fused situation assessment, $\underline{z}^d$, is determined by the conditioning variables; in turn, the initial situation assessment, $\underline{z}^d$, is known when $\underline{x}^d$, z^{cd} are known. These two variables may therefore be eliminated:

$$T(pp \cup sa, if : cirs) = H(\underline{z}^d, v^{od}) - H_{\underline{x}^d, z^{cd}, z^{ld}, z^{hd}}(v^{od}) \quad \text{(B.69)}$$

Summing the terms from (B.64):

$$G_c^d = \sum_{i=0}^{3} \sum_{j=1}^{\alpha_i} H(W_j^{di}) + H(u^d) + H(\underline{x}^d) + H(\underline{z}^d) - H(x^d, z^{cd})$$

$$+ \sum_{i=1}^{5} H(w^{d4}) + H(\bar{z}^d) + H(\bar{z}^{do}) - H(W^{d4})$$

$$+ \sum_{i=0}^{4} \sum_{j=1}^{\alpha_i} H(w^{d5+i}) + H(\bar{v}^d) + H(\underline{y}^d) - \sum_{i=6}^{9} H_{W^{d5}}(W^{d9})$$

$$+ H(\underline{z}^d, z^{ld}, z^{hd}) - H_{\underline{x}^d, z^{cd}}(z^{ld}, z^{hd}) + H(\bar{\underline{z}}^d, v^{od})$$

$$- H_{\underline{x}^d, z^{cd}, z^{ld}, z^{hd}}(v^{od}) \qquad (B.70)$$

B.2.6 Workload Expressions for the Aided DOOW

In this section are derived the expressions for the DOOW workload when that DM is aided in the manner discussed in section 5.3. The presence of the aid in the model intoduces new variables and changes the interpretation of some original ones. The superscript "aid" will be used to distinguish any variable of this type. Those variables without this superscript should be interpreted as they are in the unaided case. This convention shall allow the substitution of expressions that are not changed, or are changed only indirectly, when an aid of the type considered in this work is introduced.

Throughput:

Recall that in the aided DOOW, no preprocessing function points to a desired decision strategy. The first two terms, then, are a restatement of the first term in (B.61) with the aid information, x^{aid}, entering as the inputs $\underline{x}^d$ and z^{cd} do. The remainder of the expression is identical to the unaided case.

$$G_t^{d\ aid} = H(\underline{z}^d) - H_{\underline{x}^d, z^{cd}, x^{aid}}(\underline{z}^d) + H(\bar{\underline{z}}^d) + H(\bar{v}^d) + H(\underline{y}^d) \qquad (B.71)$$

Blockage:

The blockage expression is simply a restatement of (B.62) with x^{aid} included as one of the DOOW's inputs and the first two terms of (B.71), the aided SA throughput, substituted for (B.62)'s first two.

$$G_t^{d\ aid} = H(\underline{x}^d, z^{cd}, x^{aid}) - H(\underline{z}^d) + H_{\underline{x}^d, z^{cd} x^{aid}}(\underline{z}^d) + H(\underline{z}^d, z^{ld}, z^{hd})$$

$$- H(\bar{z}^d) + H(\bar{\underline{z}}^d, v^{od}) - H(\bar{v}^d) + H(\bar{\underline{z}}^d, \bar{v}^d) - H(\underline{y}^d) \qquad \text{(B.72)}$$

Noise:

Since the unaided DOOW was noiseless, the entropy of the single stochastic decision variable in the aided case, u^{aid}, comprises the entire expression for noise:

$$G_n = H(u^{aid}) \qquad \text{(B.73)}$$

Coordination:

$$G_c^{d\ aid} = \sum_{i=1}^{3} p(u=1)\, g_c^{di} + \alpha_i \boldsymbol{H}\,[p(u=i)] + H(\underline{z}^d)$$

$$+ \sum_{i=1}^{5} (w_i^{d4}) + H(\bar{\underline{z}}^d) - H(W^{d4})$$

$$+ \sum_{i=5}^{9} \sum_{j=1}^{\alpha i} H(w_j^{di}) + H(\bar{v}^d) + H(\underline{y}^d) - \sum\sum H_{W^{d5}}(w_j^{di})$$

$$+ g^{d\ if} + g^{d\ ci\cup rs}$$

$$+ H(\underline{z}^d, z^{ld}, z^{hd}) - H_{\underline{x}^d, z^{cd}, x^{aid}}(z^{ld}, z^{hd})$$

$$+ H(\bar{\underline{z}}^d, v^{od}) - H_{\underline{x}^d, z^{cd}, x^{aid}, z^{ld}, z^{hd}}(v^{od}) \quad \text{(B.74)}$$

where: $g_c^{d1} \equiv g_c^{pp/sa}$ (coordination of $pp \cup sa$ in unaided case)

$$g_c^{d2} \equiv g_c^{pp/sa} + H(w_z^{d\ aid}) + H(w_c^{d\ aid}) + H(\underline{z}^d) - H_{\underline{x}^d, z^{cd}}(x^{aid})$$

$g_c^{d3} = 0$ (coordination of the identity algorithm mapping x^{aid} into $\underline{z}^d$)

$w_z^{d\ aid}$ ≡ the variable into which the DOOW's own assesment is mapped in algorithm $h^{d2\ aid}$

$w_c^{d\ aid}$ ≡ the worst case situation comparison matrix (defined in Chapter 5)

B.3 Workload Expressions for the COW

B.3.1 Situation Assessment

$$g_t^{c\ sa} = T(\underline{x}^c : z^{cd}, \underline{z}^c) \quad \text{(B.75)}$$

$$g_t^{c\ sa} = H(z^{cd}, \underline{z}^c) - H_{\underline{x}^c}(z^{cd}, \underline{z}^c) \quad \text{(B.76)}$$

Since z^{cd} is identical to $z_1^c \in \underline{z}^c$, and since the arguments of the second term are determined by the input, $\underline{x}^c$, upon wich they are conditioned, the throughput may be expressed as:

$$g_t^{c\,sa} = H(\underline{z}^c) \tag{B.77}$$

Blockage:

$$g_b^{c\,sa} = H(\underline{x}^c) - g_t^{c\,sa} \tag{B.78}$$

$$g_b^{c\,sa} = H(\underline{x}^c) - H(\underline{z}^c) \tag{B.79}$$

Noise:

$$g_n^{c\,sa} = H_{\underline{x}^c}(z^{cd}, \underline{z}^c) \tag{B.80}$$

$$g_n^{c\,sa} = 0 \tag{B.81}$$

Coordination:

$$g_c^{c\,sa} = T(W^{c1} : \underline{z}^c : z^{cd}) \tag{B.82}$$

$$g_c^{c\,sa} = \sum_{i=1}^{17} H(w^{c1}) + H(\underline{z}^c) + H(z^{cd}) - H(W^{c1}, \underline{z}^c, z^{cd}) \tag{B.83}$$

Consider the joint entropy term. The symbol W^{c1} denotes the set of internal variables of the situation assessment algorithm. The first five elements of this set receive the values of the arriving vector $\underline{x}^c$, knowledge of which vector removes the uncertainty of the assessed situation. The coordination may thus be restated:

$$g_c^{c\,sa} = \sum_{i=1}^{17} H(w^{c1}) + H(\underline{z}^c) + H(z^{cd}) - H(\underline{x}^c) \tag{B.84}$$

B.3.2 Information Fusion

Transmission:

$$g_t^{c\,if} = H(\underline{z}^c, z^{lc} : \bar{\underline{z}}^c) \qquad \text{(B.85)}$$

$$g_t^{c\,if} = H(\bar{\underline{z}}^c) - H_{\underline{z}^c, z^{lc}}(\bar{\underline{z}}^c) \qquad \text{(B.86)}$$

$$g_t^{c\,if} = H(\bar{\underline{z}}^c) \qquad \text{(B.87)}$$

Blockage:

$$g_b^{c\,if} = H(\underline{z}^c, z^{lc}) - g_t^{c\,if} \qquad \text{(B.89)}$$

$$g_b^{c\,if} = H(\underline{z}^c, z^{lc}) - H(\bar{\underline{z}}^c) \qquad \text{(B.90)}$$

Noise:

$$g_n = H_{\underline{z}^c, z^{lc}}(\bar{\underline{z}}^c)$$

$$g_n^{c\,if} = 0 \qquad \text{(B.92)}$$

Coordination:

$$g_c^{c\,if} = T(W^{c2} : \bar{\underline{z}}^c) \qquad \text{(B.93)}$$

$$g_c^{c\,if} = H(\bar{\underline{z}}^c) - H_{W^{c2}}(\bar{\underline{z}}^c) \qquad \text{(B.94)}$$

The internal variables which condition the second term determine the assessed situation $\underline{z}^c$.

$$g_c^{c\,if} = H(\bar{\underline{z}}^c) \qquad \text{(B.95)}$$

B.3.3 Command Interpretation

Throughput:

$$g_t^{c\,ci} = H(\bar{v}^c) - H_{\underline{z}^c,\, y^{dc}}(\bar{v}^c) \tag{B.96}$$

$$g_t^{c\,ci} = H(\bar{v}^c) \tag{B.97}$$

Blockage:

$$g_b^{c\,ci} = H(\bar{\underline{z}}^c, y^{dc}) - g_t^{c\,ci} \tag{B.98}$$

$$g_b^{c\,ci} = H(\bar{\underline{z}}^c, y^{dc}) - H(\bar{v}^c) \tag{B.99}$$

Noise:

$$g_n^{c\,ci} = H_{\bar{\underline{z}}^c,\, y^{dc}}(W^{c3}, \bar{v}^c) \tag{B.100}$$

The set of variables W^{c3} is fully determined by the conditioning variables.

$$g_n^{c\,ci} = H_{\bar{\underline{z}}^c,\, y^{dc}}(\bar{v}^c) \tag{B.101}$$

Coordination:

$$g_c^{c\,ci} = H(W^{c3}: \bar{v}^c) \tag{B.102}$$

$$g_c^{c\,ci} = \sum_{i=1}^{3} H(w_i^{c3}) + H(\bar{v}^c) - H(w_1^{c3}) - H_{w_1^{c3}}(w_2^{c3})$$

$$- H_{w_1^{c3},\, w_2^{c3}}(w_3^{c3}) - H_{W^{c3}}(v^c) \tag{B.103}$$

Knowledge of w_1^{c3} and w_2^{c3} determines w_3^{c3}, therefore

$$g_c^{c\,ci} = \sum_{i=1}^{3} H (w^{c3}) + H (\bar{v}^c) - H (w_1^{c3}, w_2^{c3}) - H_{W^{c3}} (\bar{v}^c) \qquad \text{(B.104)}$$

B.3.4 Response Selection

Throughput:

$$g_t^{c\,rs} = H (y^c) - H_{\underline{z}^c, \bar{v}^c} (y^c) \qquad \text{(B.105)}$$

$$g_t^{c\,rs} = H (y^c) \qquad \text{(B.106)}$$

Blockage:

$$g_b^{c\,rs} = H (\bar{\underline{z}}^c, \bar{v}^c) - g_t \qquad \text{(B.107)}$$

$$g_b^{c\,rs} = H (\bar{\underline{z}}^c, \bar{v}^c) - H (y^c) \qquad \text{(B.108)}$$

Noise:

Although the switching among the algorithms comprising this stage is probabilistic, the noise this switching generates is accounted for in the command interpretation stage, where the switching decision is made. The RS algorithms themselves are deterministic, therefore the following is true:

$$g_n^{c\,rs} = 0 \qquad \text{(B.109)}$$

Coordination:

$$g_c^{c\,rs} = T (\underline{z}^c : \bar{v}^c : W^{c4} : W^{c5} : W^{c6} : y^c) \qquad \text{(B.110)}$$

Using the result obtained by Boettcher [6]:

$$g_c^{c\,rs} = \sum p_j\, g_c\, p(\bar{z}^c \mid \bar{v}^c = j) + \alpha_j \boldsymbol{H}(p_j) + H(y^c) \tag{B.111}$$

where: $\boldsymbol{H}(p) \equiv -p \log p - (1-p) \log (1-p)$

$p_j \equiv p(\bar{v}^c = j)$

$g_c \equiv$ coordination of algorithm j, j= 4, 5,..., 8

$\alpha_j \equiv$ number of variables in algorithm j

Appendix A showed that all algorithms but the fourth are identity algorithms. The coordination of these, defined as the information mutually transmitted between all the internal variables, is zero by inspection.

$$g_c^{cj} = 0, \quad j = 4, 5, 6, 8 \tag{B.112}$$

The coodination for the fourth RS algorithm is derived as follows:

$$g_c = T(w^{c7} : w^{c7} : \ldots : w^{c7} : y^c) \tag{B.113}$$

$$g_c^{c7} = \sum_{i=1}^{10} H(w^{c7}) + H(y^c) - H(W^{c5}, y^c) \tag{B.114}$$

The response y^c is fully determined by knowledge of W^{c7}

$$g_c^{c7} = \sum_{i=1}^{10} H(w_i^{c7}) + H(y^c) - H(W^{c5}) \tag{B.115}$$

$$g_c^{c\,rs} = p(\bar{v}^c = 4) \left\{ \sum_{i=1}^{10} H(w^{c7}) + H(y^c) - H(W^{c5}) \right\} p(\bar{z}^c \mid \bar{v}^c = 4)$$

$$+ \alpha_j \boldsymbol{H} (p_j) + H (y^c) \tag{B.116}$$

Total Throughput:

$$G_t^c = H (\underline{z}^c) + H (\underline{\bar{z}}^c) + H (\bar{v}^c) + H (y^c) \tag{B.117}$$

Total Blockage:

$$G_b^c = H (\underline{x}^c) - H (\underline{z}^c) + H (\underline{z}^c, z^{lc}) - H (\underline{\bar{z}}^c) + H (\underline{\bar{z}}^c, y^{dc})$$

$$- H (\bar{v}^c) + H (\underline{\bar{z}}^c, \bar{v}^c) - H (y^c) \tag{B.118}$$

Total Noise:

$$G_n^c = H_{\underline{\bar{z}}^c,\, y^{dc}} (\bar{v}^c) \tag{B.119}$$

Total Coordination:

$$G_c^c = g_c^{sa} + g_c^{if} + g_c^{ci} + g_c^{rs} + T (sa: if: ci: rs) \tag{B.120}$$

$$T (sa: if: ci: rs) = T (sa: if) + T (sa, if: ci) + T (sa, if, ci: rs) \tag{B.121}$$

$$T (sa: if) = H (\underline{z}^c, z^{lc}) - H_{\underline{x}^c} (\underline{z}^c, z^{lc}) \tag{B.122}$$

The input vector, $\underline{x}^c$, determines the assessed situation, $\underline{z}^c$.

$$T (sa: if) = H (\underline{z}^c, z^{lc}) - H_{\underline{x}^c} (z^{lc}) \tag{B.123}$$

$$T (sa, if: ci) = H (\underline{\bar{z}}^c, y^{dc}) - H_{\underline{x}^c,\, \underline{z}^c,\, z^{lc}} (\underline{\bar{z}}^c, y^{dc}) \tag{B.124}$$

Again, the fact that $\underline{x}^c$ determines $\underline{z}^c$ can be invoked. Also, knowledge of $\underline{z}^c$ and z^{lc}

determine $\underline{z}^c$. This term becomes

$$T\,(\text{sa, if: ci}) = H(\bar{\underline{z}}^c, y^{dc}) - H_{\underline{x}^c,\ z^{lc}}(y^{dc}) \qquad \text{(B.125)}$$

$$T\,(\text{sa, if, ci: rs}) = H(\bar{\underline{z}}^c, \bar{v}^c) - H_{\underline{x}^c,\ \underline{z}^c,\ z^{lc},\ y^{dc}}(\bar{\underline{z}}^c, \bar{v}^c) \qquad \text{(B.126)}$$

The second term may, according to the same reasoning used to obtain (B.112), be rewritten as:

$$T\,(\text{sa, if, ci: rs}) = H(\bar{\underline{z}}^c, \bar{v}^c) - H_{\underline{x}^c,\ z^{lc},\ y^{dc}}(\bar{v}^c) \qquad \text{(B.127)}$$

The expression for the total coordination of the COW is thus:

$$G_c^c = \sum_{i=1}^{17} H(w^{c1}) + H(\underline{z}^c) + H(z^{cd}) - H(\underline{x}^c) + H(\bar{\underline{z}}^c)$$

$$+ \sum_{i=1}^{3} H(w^{c3}) + H(\bar{v}^c) - H(w_1^{c3}, w_2^{c3})$$

$$+ p(\bar{v}^c{=}4)\ \{\sum_{i=1}^{10} H(w^{c7}) + H(y^c) - H(W^{c5})\}\ p(\bar{\underline{z}}^c \mid \bar{v}^c = 4) +$$

$$+ \alpha_j \boldsymbol{H}(p_j) + H(y^c)$$

$$+ H(\underline{z}^c, z^{lc}) - H_{\underline{x}^c}(z^{lc}) + H(\bar{\underline{z}}^c, y^{dc}) - H_{\underline{x}^c,\ z^{lc}}(y^{dc}) + H(\bar{\underline{z}}^c, \bar{v}^c)$$

$$- H_{\underline{x}^c,\ z^{lc},\ y^{dc}}(\bar{v}^c) \qquad \text{(B.128)}$$

B.4 Workload Expressions for the Lee Helm

B.4.1 Situation Assessment

As with the OOD, the Lee Helm (and the Helm) do not incorporate the full complement of DM model stages, but each possesses only a single SA algorithm and a single RS (identity) algorithm.

Throughput:

$$g_t^{l\,sa} = H(z^{ld}) - H_{\underline{x}^l}(z^{ld}) \qquad (B.129)$$

Since z^{ld} is a deterministic function of $\underline{x}^l$, the second term may be omitted.

$$g_t^{l\,sa} = H(z^{ld}) \qquad (B.130)$$

Blockage:

$$g_b^{l\,sa} = H(\underline{x}^l) - g_t \qquad (B.131)$$

$$g_b^{l\,sa} = H(\underline{x}^l) - H(z^{ld}) \qquad (B.132)$$

Noise:

$$g_n^{l\,sa} = H_{\underline{x}^l}(W^{l1}, z^{ld}) \qquad (B.133)$$

$$g_n^{l\,sa} = 0 \qquad (B.134)$$

Coordination:

$$g_c^{l\,sa} = T(w_1^{l1} : w_2^{l1} : \ldots : w_{10}^{l1} : z^{ld}) \tag{B.135}$$

$$g_c^{l\,sa} = \sum_{i=1}^{10} H(w_i^{l1}) + H(z^{ld}) - H(w_1^{l1}) - H_{w_1^{l1}}(w_2^{l1})$$

$$- H_{w_1^{l1}, w_2^{l1}}(w_3^{l1}) - H_{w_1^{l1}, w_2^{l1}, w_3^{l1}}(w_4^{l1}) - \ldots$$

$$- H_{w_1^{l1}, w_2^{l1}, \ldots, w_{10}^{l1}}(z^{ld}) \tag{B.136}$$

As in previous such cases, the input variables are mapped into internal variables, the first four in this instance. Knowledge of these determines all subsequent variables in this deterministic algorithm. Equation B.122 may be rewritten as:

$$g_c^{l\,sa} = \sum_{i=1}^{10} H(w_i^{l1}) + H(z^{ld}) - H(w_1^{l1}, w_2^{l1}, \ldots, w_4^{l1}) \tag{B.137}$$

As the last term is equivalent to $H(\underline{x}^{l})$, the coordination is finally written as:

$$g_c^{l\,sa} = \sum_{i=1}^{10} H(w_i^{l1}) + H(z^{ld}) - H(\underline{x}^{l}) \tag{B.138}$$

B.4.2 Response Selection

Transmission:

$$g_t^{l\,rs} = T(y^{l} : v^{dl}) \tag{B.139}$$

$$g_t^{l\,rs} = H(v^{dl}) - H_{y^l}(v^{dl}) \tag{B.140}$$

$$g_t^{l\,rs} = H(v^{dl}) \tag{B.141}$$

Blockage:

$$g_b^{l\,rs} = H(y^l) - g_t \tag{B.142}$$

$$g_b^{l\,rs} = H(y^l) - H(v^{dl}) \tag{B.143}$$

Since the algorithm is defined as an identity algorithm, the two terms in (B.130) are equal, so the blockage becomes

$$g_b^{l\,rs} = 0 \tag{B.144}$$

Noise:

$$g_n^{l\,rs} = 0 \tag{B.145}$$

Coordination:

$$g_c^{l\,rs} = T(y^{dl}) = 0 \tag{B.146}$$

Total Throughput:

$$G_t^{l} = H(z^{ld}) + H(v^{dl}) \tag{B.147}$$

Total Blockage:

$$G_b^{l} = H(\underline{x}^l) - H(z^{ld}) \tag{B.148}$$

Total Noise:

$$G_n^{l} = 0 \tag{B.149}$$

Total Coordination:

$$G_c^{l} = g^{l\,sa} + g^{l\,rs} + T(sa : rs) \tag{B.150}$$

$$T(sa : rs) = H(y^d) - H_{\underline{x}}l(y^d) \tag{B.151}$$

$$G_c^{l} = \sum_{i=1}^{10} H(w_i^{l1}) + H(z^{ld}) - H(\underline{x}^l) + H(y^d) - H_{\underline{x}}l(y^d) \tag{B.152}$$

B.5 Workload Expressions for the Helm

B.5.1 Situation Assessment

Throughput:

$$g_t^{h\,sa} = T(\underline{x}^h : z^{hd}) \tag{B.153}$$

$$g_t^{h\,sa} = H(z^{hd}) - H_{\underline{x}}h(z^{hd}) \tag{B.154}$$

$$g_t^{h\,sa} = H(z^{hd}) \tag{B.155}$$

Blockage:

$$g_b^{h\,sa} = H(\underline{x}^h) - g_t \tag{B.156}$$

$$g_b^{h\,sa} = H(\underline{x}^h) - H(z^{hd}) \tag{B.157}$$

Noise:

$$g_n^{h\,sa} = H_{\underline{x}}h (W^{h1}, z^{hd}) \tag{B.158}$$

$$g_n^{h\,sa} = 0 \tag{B.159}$$

Coordination:

$$g_c^{h\,sa} = T (w_1^{h1} : w_2^{h1} : \ldots : w_5^{h1} : z^{hd}) \tag{B.160}$$

$$g_c^{h\,sa} = \sum_{i=1}^{5} H (w_i^{h1}) + H (z^{hd}) - H (w_1^{h1}, w_2^{h1}, \ldots , w_5^{h1}, z^{hd}) \tag{B.161}$$

By analogy to the coordination expression for the Lee Helm SA stage, (B.161) may be rewritten as:

$$g_c^{h\,sa} = \sum_{i=1}^{5} H (w_i^{h1}) + H (z^{hd}) - H (\underline{x}^h) \tag{B.162}$$

B.5.2 Response Selection

Throughput:

$$g_t^{h\,rs} = T (y^{dh} : y^h) \tag{B.163}$$

$$g_t^{h\,rs} = H (y^{dh}) - H_y h (y^{dh}) \tag{B.164}$$

$$g_t^{h\,rs} = H (y^{dh}) \tag{B.165}$$

Blockage:

$$g_b^{h\,rs} = H(y^h) - g_t \tag{B.166}$$

By analogy with (B.131)

$$g_b^{h\,rs} = 0 \tag{B.167}$$

Noise:

$$g_n^{h\,rs} = 0 \tag{B.168}$$

Coordination:

As in (B.142)

$$g_c^{h\,rs} = 0 \tag{B.169}$$

Total Throughput:

$$G_t^h = H(z^{hd}) + H(y^{dh}) \tag{B.170}$$

Total Blockage:

$$G_b^h = H(\underline{x}^h) - H(z^{hd}) \tag{B.171}$$

Total Noise:

$$G_n^h = 0 \tag{B.172}$$

Total Coordination:

$$G_c = g^{h\,sa} + g^{h\,rs} + T(sa:rs) \quad (B.173)$$

$$T(sa:rs) = H(y^{dh}) - H_{\underline{x}^h}(y^{dh}) \quad (B.174)$$

$$G_c^h = \sum_{i=1}^{5} H(w_i^{h1}) + H(z^{hd}) - H(\underline{x}^h) + H(y^{dh}) - H_{\underline{x}^h}(y^{dh}) \quad (B.175)$$

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