

MIGRATION OF CONTROL IN DECISION MAKING ORGANIZATIONS ¹

Alexander H. Levis ²

Sabina L. Skulsky

Laboratory for Information and Decision Systems
Massachusetts Institute of Technology
Cambridge, MA 02139 USA

ABSTRACT

In a distributed decision making organization supported by information processing and decision aiding systems, it is not always apparent whose decision affects the outcome the most. Often, control migrates away from the designated organization member in unexpected ways depending on the decisions of individual decision makers, on the structure of the organization, and on its operating procedures. A mathematical formulation of the concept of migration of control and of regions of dominance is given; the model and the computational procedure are illustrated by two simple examples. The point is made that the introduction of technologies that allow distributed decision making bring into focus dynamic phenomena that need novel approaches and new concepts to describe them.

¹ This work was supported in part by the Office of Naval Research under Contract No. N00014-84-K-0519.

² Corresponding Author:
Dr. Alexander H. Levis, MIT, 35-410/LIDS, Cambridge, MA 02139, USA

INTRODUCTION

M. Van Creveld in his book *Command in War* [13] makes the case that while the problem of command or management of an organization is not new, “its dimensions have grown exponentially in modern times, especially since 1939.” Indeed, the increase in the demands made on the information and decision systems supporting modern organizations can be attributed in part to the wide geographical distribution of the resources or assets managed by the organization, the complexity of the environment in which the organization functions, and the rate at which this environment changes, the so-called tempo of operations [7]. Another part of the problem has been caused by the technologies themselves, data processing and communications, that were introduced as a means for coping with the distributed nature of the organizations.

The interaction of organizations that try to carry out distributed decision making with the information and decision technologies introduced to aid them is either generating new classes of phenomena not previously observable, or is bringing to the fore organizational problems that were previously of secondary importance. Examples of the results of such interaction are the large amounts of data collected and processed, the proliferation of displays for presenting information in a form suitable for supporting decision making at different echelons of an organizational hierarchy or different levels of a functional hierarchy, or the massive exchange of data and information among the nodes of a distributed organization.

The development of effective systems that process data and convert it to information and then frame it to support decision making depends not only on the available technology - the sensors, the computers, the communications systems, and the displays and human-computer interfaces - but also on the structure of the decision making organizations themselves and the cognitive processes embedded in the organization members, the concept of operations that governs their interactions, and the intelligent machines that support them. The relationship between data and information, and information and the knowledge needed to make a decision are shown in Figure 1.[9]

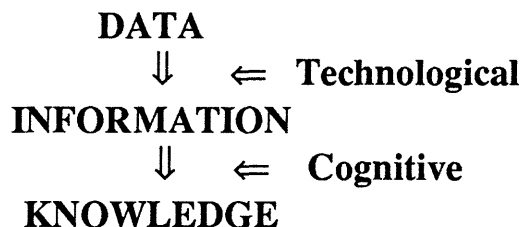


Figure 1. Data, Information, and Knowledge

Data are transformed to information primarily by technological processing: time series residing in a data base are presented in the form of a graph on the monitor of a workstation. Humans can also be part of the processing by executing comparable tasks. However, the transformation of information into knowledge is a cognitive process done primarily by humans. The introduction of intelligent decision support systems will shift these boundaries and will blur the demarkation lines between technological and cognitive processing.

In this context, the human decision maker continues to occupy a central role in distributed decision making organizations. The structure of the organization affects the human decision maker's ability to work effectively under time pressure in a stressful environment, such as the one experienced by air traffic controllers, bond or foreign exchange traders, military commanders in battle, or the operators of the control center of a power plant during an emergency. Furthermore, the organization may exhibit dynamic phenomena not anticipated by analyzing the formal organizational structure or the properties of the decision support system that is in place. One such phenomenon is the migration of control.

Control refers to the result of processing the externally produced statements of system requirements and analyzing system behavior in the presence of uncertainty. The migration of control in an organization refers to the movement of the control function through the information structure of a system. There is much anecdotal experience from large scale organizations that at times control may migrate in an unpredictable manner away from decision makers who have been assigned specific authority and responsibility to other organization members, usually at a lower echelon. Changes in the organization's structure, such as access to decision support systems, can change the sensitivity of the performance measures to the actions of different decision makers. Furthermore, the choice of strategies on the part of these decision makers affects which one has most impact on performance.

This migration of control can be viewed from both positive and negative perspectives. In the former sense, it is desirable for control to migrate in the event of a failure of a decision making node. Kahne [6] has highlighted this positive connotation while discussing control migration in a command, control, and communication system. To maintain system performance, the control function must be able to move (migrate) through a large scale system so that, if there are structural changes in the system, deterioration of function will be minimized.

However, from a negative perspective, control may migrate in an unforeseen or undesirable manner. For example, migration might occur away from executives, who should hold the positions of responsibility in favor of subordinates. The performance of an organization will deteriorate if what are seen to be efficient and effective means of processing information are altered upon migration of control. Even if the structure is designed so that the overall task is performed without

overloading organization members, that same structure can result in a wide range of performance depending on the strategies chosen by the decision makers. It is important to insure that strategies which are mutually acceptable will most likely be selected.

The main objective of this paper is to develop a model that shows the existence of migration of control in organizations and to examine the circumstances under which it can occur. It is also important from the analysis and design points of view to be able to determine how the migration occurs and which decision maker becomes dominant. Thus, the first goal is to determine for some candidate structures the sets of conditions for which a single decision maker becomes critical. The second goal is to identify the causes for migration of control in the organization so that rules can be developed for redesigning the protocols of the organization, or restructuring it, to avoid undesired migrations. One method for doing so is restructuring the organization so as to avoid undesirable control situations.

The technical approach that has been used in this paper consists of three steps. In the first step, the model of the organization is developed and expressed in the form of a Petri Net. Included in the specification of the problem is the set of tasks to be performed and the set of outputs that can be produced by the organization. Furthermore, the space of behavioral strategies and a performance index that assigns a value to each possible input-output pair are defined. The model of the organization is used to relate inputs and outputs in terms of the particular behavioral strategy chosen. In the second step, this relationship is made explicit by obtaining the mapping of the strategy space into the performance space. Thus, for each point in the strategy space, a corresponding value of the performance index is obtained. The key operation now is the determination of a set of sensitivity coefficients: the sensitivity of the performance to changes in the decisions of each decision maker. Thus, for each decision maker a value of his sensitivity coefficient is obtained for each point of the performance space. By comparing the values of the sensitivity coefficients of the different DMs at a point in the performance space, it is possible to determine who is dominant at that point: he who has more of an impact on the value of the performance, i.e., the one with the highest absolute value of the sensitivity coefficient. In this third and last step, the information on who is the dominant DM at each point on the performance space is mapped back to the strategy space to define the regions of dominance, if any, where certain decision makers are in control. Then the designer can assess whether this migration of control from one DM to another, as described by the regions of dominance, is desirable or not. He can then trace through the mappings and the models the reasons that dominance shifted from one to another and, if necessary, make design modifications.

The results of this work are directed toward practical methods for increasing the efficiency of information flow in large scale organizations.

PETRI NET MODELS AND ORGANIZATIONS

The mathematical framework that is used to model the structure of the organization and the interactions between the decision makers is that of Petri Nets. A very brief introduction to the formalism of Petri Nets follows.

A Petri Net - denoted by PN - is a bipartite directed graph represented by the quadruple $PN = (P, T, I, O)$, where P is a finite set of places, denoted by circle nodes, T is a finite set of transitions, denoted by bar nodes, and where I and O are mappings that correspond to the set of directed arcs from places to transitions (inputs) and from transitions to places (outputs). When I and O take values in $\{0, 1\}$, where 0 denotes the absence of an arc and 1 the presence with capacity 1, the resulting nets, called ordinary Petri Nets, are graphical tools used to model concurrent and asynchronous processes. They represent the decision makers working in parallel with one another and coordinating their activities. They can be used to model manufacturing processes, represent flow charts of computer software, and in numerous other applications. They are especially useful for modeling decision making organizations, since they show explicitly the interactions among decision makers. An introduction to Petri Nets can be found in Reisig[11].

Petri Nets can be used to study the dynamics of decision making organizations by introducing tokens in the places of the net and then analyzing the movement of these tokens as a result of the structure of the net and the protocols that it has embedded in its description. In the Petri Net model of the flow of information in an organization, the tokens represent information carriers, which wait to be processed in the places. These places are conditions which must be met before the information held in them can be processed. In turn, the transitions are events which process and transform the information. This transformation could include analysis, synthesis, transfer from one point to another, or computation.

The decision making organizations are those described by the mathematical framework proposed by Levis [8]. In these organizations, groups of well-trained decision makers execute well-defined tasks, each one constrained by his bounded rationality [10]. This constraint is a limit on the amount of information a human being can process in a given amount of time. In performing a task, a decision maker may be faced with several alternatives,, which may take the form of different algorithms to process the information, or different decision aids, such as intelligent terminals and mainframes. The strategies used to select among the alternatives have varying effects on the performance of the organization.

The basic component for constructing organizations is the model of the interacting decision maker (DM) with bounded rationality [3]. There are four basic stages in the model, as illustrated in the Petri Net of Figure 2.

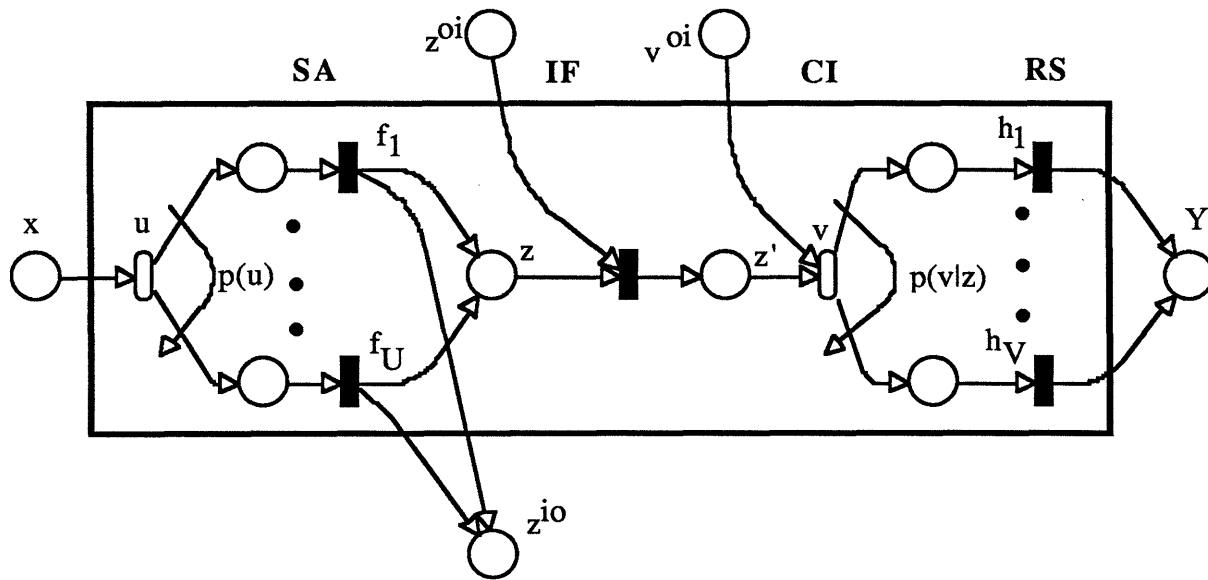


Figure 2 Petri Net Model of the Interacting Decision Maker

- **Situation Assessment (SA):** In this stage, the DM receives an input x from the environment and processes the information by using one of U algorithms f_1, \dots, f_U . The first switch, a special transition that places a token in only one of its output places when it fires, implements a decision rule $p(u)$, which controls the choice of algorithm. The result of the SA stage is z , the assessed situation. At this stage, some information z^{io} can be transmitted to the other organization members.
- **Information Fusion (IF):** The DM fuses his own situation assessment, z , with the information he obtains from the rest of the organization, z^{oi} . The revised assessment is z' .
- **Command Interpretation (CI):** The DM may receive commands, v^{oi} , from superiors that restrict his options in the response selection stage.
- **Response Selection (RS):** Finally, a response Y is generated, which depends on the assessed situation z' and the choice of response selection algorithm. The decision strategy associated with the switch is denoted $p(v | z)$. The response Y can go to the environment (output) or to other decision makers in the organization.

By interconnecting such models according to a prescribed set of rules [12] and by integrating the models of the decision support systems, complete models of organizations are obtained [2]. To carry out the analysis of such organizations requires defining measures of performance (MOPs) such as accuracy, response time, workload, and degree of coordination. These MOPs can be computed for different organizations using CAESAR (Computer Aided Evaluation of System

ARchitectures) a suite of algorithms and graphics tools designed and operated at the MIT Laboratory for Information and Decision Systems (LIDS).

Organizations can be seen as systems performing specific missions. These missions involve tasks with inputs x_i which have discrete probability distribution $\Pr(x_i)$ and cost function $C(y, y_{di})$. $\Pr(x_i)$ is the probability that the decision making organization (DMO) receives the input x_i , and has to perform the corresponding task, while $C(y, y_{di})$ assigns a cost to each response to this task. This is done by mapping x_i into an ideal or desired response y_{di} . Then, $C(y, y_{di})$ associates a value to the discrepancy between the actual response y and the desired response. Within this framework, an MOP which evaluates the organization's performance on a task can be introduced:

- **Measure of Performance, J**, measures how well the response of the organization corresponds to the desired response [1]. For each organizational strategy and each input, the cost C is computed. Unless the algorithms used are deterministic, there is more than one possible response for a given input x_i . The value of J for a strategy δ is:

$$J(\delta) = \sum_i p(x_i) \sum_h C(y_h, y_{di}) p(y_h | x_i) \quad (1)$$

Strategies can be categorized as pure and mixed [4]. Pure internal strategies of the r^{th} DM are those for which both the situation assessment strategy $p(u)$ and the response selection strategy $p(v | z)$ are pure. Pure means that one of the algorithms f_i is selected with probability 1 and one of the algorithms h_j is selected with probability 1, when the situation assessment is z . Thus:

$$D_k^r = \{p(u = i) = 1; p(v = j | z = z_m) = 1\} \quad (2)$$

for some i, j , and z_m in the set Z . There are U algorithms f for situation assessment, and V algorithms h for response selection. M is the dimension of the set Z . Therefore, for the r^{th} decision maker, there are n_r possible pure strategies

$$n_r = U (V^M) \quad (3)$$

The remaining internal strategies are the mixed strategies, which are convex combinations of pure strategies:

$$D^r(p_k) = \sum_{k=1}^{n_r} p_k D_k^r \quad (4)$$

where

$$\sum_{k=1}^{n_r} p_k = 1; p_k \geq 0 \quad \text{for all } k \quad (5)$$

A pure organizational strategy for a two person organization is a pair of pure strategies, one for each DM.

$$\Delta_{ij} = \{D_i^1, D_j^2\} \quad (6)$$

where D_k^r is the k^{th} pure strategy for the r^{th} decision maker. Since the processes by which the DMs choose their strategies are independent, with no overlap, the organization's strategy space S^O is the direct sum of the individual strategy spaces. Whether the strategies are pure or mixed, they induce a behavioral strategy [4] for the organization:

$$\Delta = \sum_{i,j} p_i p_j \Delta_{ij} \quad (7)$$

Here, p_i and p_j are the probabilities that the first DM will use D_i and the second D_j . These strategies can yield a wide range of accuracy of performance for the organization. Once the method for computing performance is established, the organizational designer specifies a structure which allocates information processing and decision making tasks to members. The designer specifies the protocols for the proposed structure, and decides upon sets of procedures to be used by the members. Then, if a performance threshold J is set, specifications of this organizational design can be tested to see if the goal for accuracy is met.

MODELING OF MIGRATION OF CONTROL

In this section, a simple example of a two decision maker organization will be presented to illustrate the concepts and the application of the methodology. The migration of control can be seen by evaluating the measure of performance J as a function of the organization's behavioral strategy. If the decision strategies of all decision makers but one are held constant, varying that DM's strategies yields his marginal effect on performance. In this manner, for all points in the strategy space, the sensitivity of the accuracy of the organization to the choices of each DM can be determined. Because of the manner in which the individual strategies were defined, this is equivalent to varying the probability with which each pure strategy of each DM can occur. The more sensitive the performance of an organization is to the strategy choice of a certain DM, the more control the DM exerts in the organization. At various points in the strategy space, certain

DMs may assume control and then yield control to others at other points, when the accuracy grows less sensitive to their decisions. This is the phenomenon of migration of control.

Consider now the migration of control behavior in an organization consisting of two decision making entities, as shown in Figure 3.

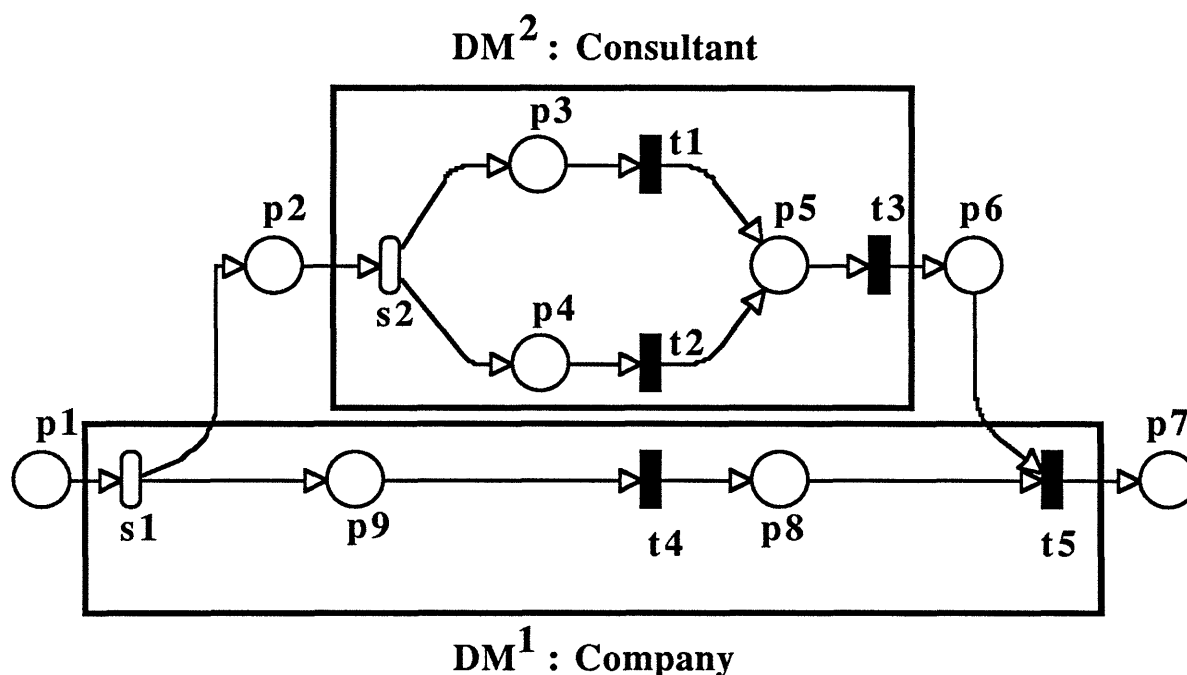


Figure 3 Petri Net of Company-Consultant Organization

A company (DM¹) must decide whether to invest some of its funds or not in support of basic research at a well known research university. The Petri Net in Figure 3 represents the initial dilemma denoted by the transition/switch s1: the company must decide whether to call in a consultant (DM²) for assistance in addressing the problem, or whether to tackle it alone. If the latter alternative is chosen, the company uses its own situation assessment to fuse the information (t3) and select a response (t5).

If the consultant option is chosen, the consultant receives the company's situation assessment and then is faced in turn with two choices, transition/switch s2: The first alternative is to send in a case team from the M* School of Management, whereas the second is to send in one from another school, say from H*. It is conceivable that to some the choice is clear cut. However, for the sake of illustrating the phenomenon, it is assumed that there is a legitimate choice. Once the case team is selected and a response prepared, either by process t1 or process t2, the consultant prepares his response (t4) and sends it to DM¹, who uses this to arrive at the company's response: to fund or

not to fund university research.

To evaluate the measure of performance for this organization, one must know the values that will result from the pure strategies outlined above. If the DM¹ chooses to analyze the case alone, the value of J will be 6 on a scale of 1 to 10, where the better the outcome the higher the value. If the consultant is called in, the value of J will be 8 if the case is handled by the capable M* team, and 5 if by the H* team. Thus, the performance measure takes the form:

$$J = 6p + (1-p)[8q + 5(1-q)] = 5 + p + 3q - 3pq \quad (8)$$

where p is the probability DM¹ will tackle the case alone and q is the probability that the M* team will be used. This J value is based on the organizational strategy, and is a measure of the closeness of the response yielded by this strategy to the ideal organizational response. A three-dimensional graph of J versus p and q (Figure 4) shows where in the strategy space performance is highest. One can see that in Figure 4, at (p, q) = (0, 0) where the consultant has been called in and he selects the H* team with probability 1, the accuracy will be 5. As the probability that the superior S* team will be put on the case is increased, as q is increased from 0 to 1, holding p fixed at 0, performance rises rapidly from 5 to 8. As the probability that the company will handle the case alone increases, i.e., as p is increased to 1, holding q fixed at 0, J rises to 6. Note that if p is set to unity, i.e., the company will handle the decision alone, the decision by the consultant as to whether to use the M* or the H* team is irrelevant. This is shown in Figure 4 by the constant value of J, at 6, for all values of q. One can also see graphically the effect on performance of incremental changes in the DMs' strategies.

However, the ideal response changes with the inputs to the organization. Under different conditions, different responses will be optimal. In this case, the inputs into the organization that provide both DMs with the information they must consider in arriving at a decision are the students and faculty at the research university. If the current staff is up to par, certainly the ideal response would be to invest in university research. The sensitivity coefficient S¹ for the company is the percentage change that will occur in J in response to a one percent change in the probability p that characterizes the company's strategy. The sensitivity coefficient is defined as:

$$S^1 = \frac{p_0}{J(p_0, q_0)} \left. \frac{\partial J}{\partial p} \right|_{p_0, q_0} \quad (9)$$

and is evaluated at the point (p₀, q₀) of the strategy space. Similarly, for the consultant's

sensitivity coefficient:

$$S^2 = \frac{q_0}{J(p_0, q_0)} \left. \frac{\partial J}{\partial q} \right|_{p_0, q_0} \quad (10)$$

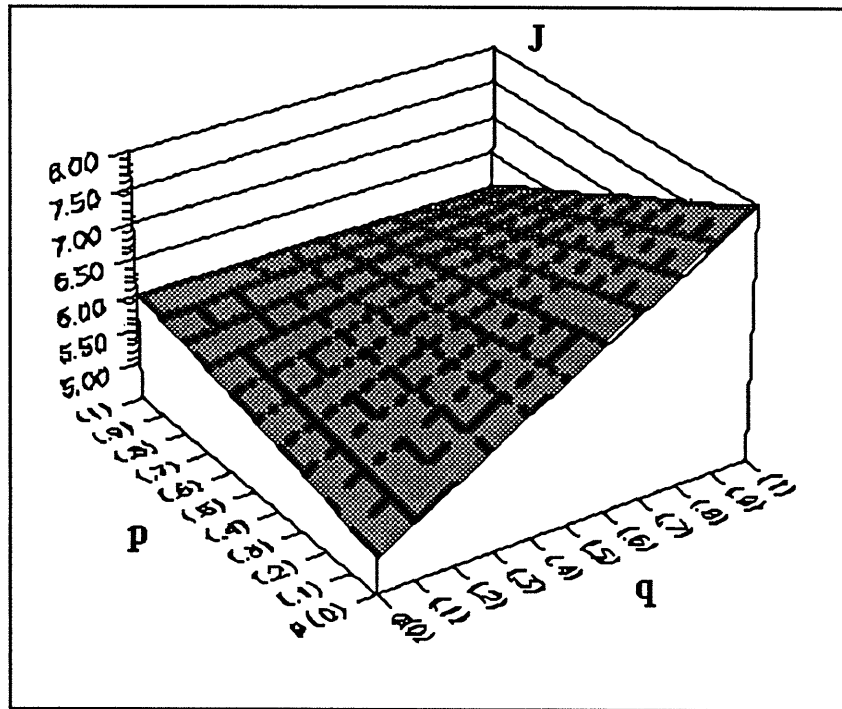


Figure 4 Performance versus strategies for DM¹ and DM²

A subscripted numeral represents the strategy number and a superscripted numeral represents the DM number. To find J and the sensitivity coefficient S^1 , q is set at zero, and p is varied from 0 to 1; then q is incremented and again p is varied from 0 to 1. For S^2 , p is set at zero, and q is varied from 0 to 1, then p is incremented and q is varied from 0 to 1. Sensitivity depends upon the direction in which the derivative is taken as well as the point in the strategy space (p_0, q_0) for which it is determined. Thus, at each point (p_0, q_0) , there are two sensitivity coefficients as defined in equations (9) and (10). For this very simple case, the actual expressions for the sensitivity coefficients can be derived:

$$\begin{aligned} S^1 &= (1-3q) p / J \\ S^2 &= 3(1-p) q / J \end{aligned} \quad (11)$$

The two sensitivity coefficients have been plotted as functions of the two strategies, p and q , as shown in Figures 5 and 6. By comparing these two plots, the regions in the strategy space where a decision maker has more control over the decision making process of the organization relative to the other DM are determined. The comparison is done on the basis of the absolute values of the sensitivity coefficients:

If $|S^1| > |S^2|$, then DM^1 is dominant; if $|S^2| > |S^1|$, then DM^2 is dominant.

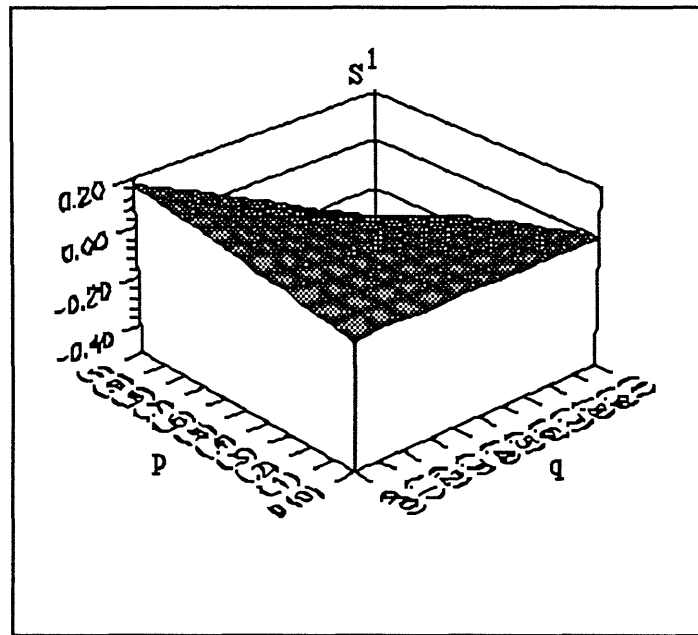


Figure 5. Sensitivity of performance to company's decisions

It is evident from the diagrams that DM^1 , the company, has most control on the situation when $(p, q) = (1, 0)$; that is, obviously, when the company handles the case alone. As p decreases, control is passed to the consultant, because the latter's decision as to whether to select the M^* or the H^* team has more impact on performance. Note, however, that if the consultant favors with very high probability the H^* team, the company may remain dominant. This occurs because the difference in performance between the company arriving at a decision alone and using a consultant with the H^* team is smaller (from 5 to 6) than if the M^* team is to be used (6 to 8). These results are summarized in the strategy space where the regions of dominance are shown (Figure 7). The shaded area shows for which points in the strategy space the company is dominant, while the unshaded area shows the region where the consultant is dominant.

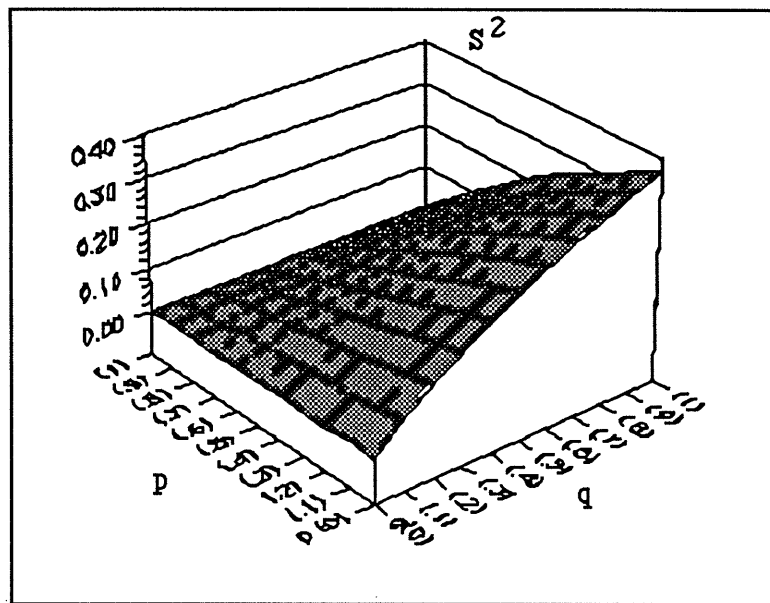


Figure 6. Sensitivity of performance to consultant's decisions

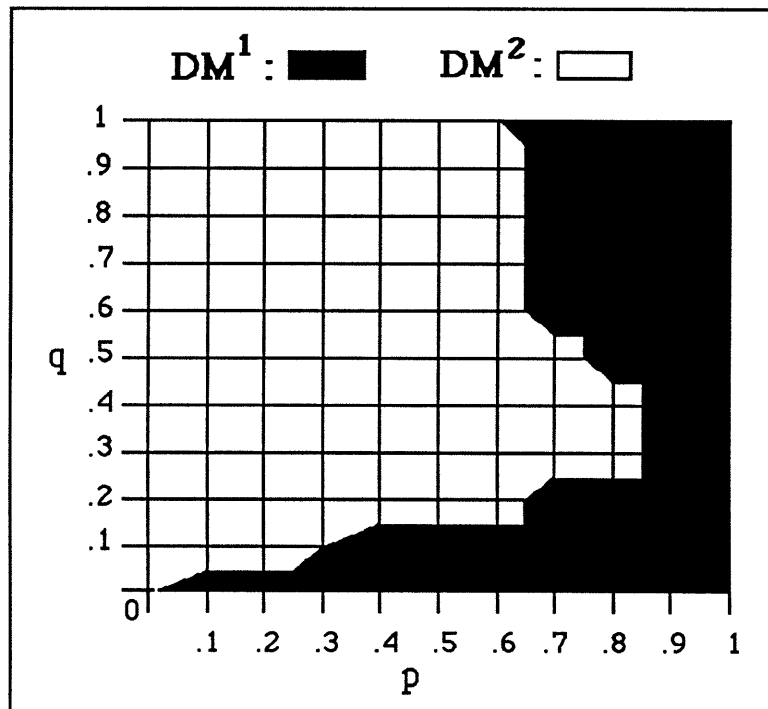


Figure 7. Regions of Dominance for Company-Consultant Organization

In this very simple case, each region of dominance is connected. The problem for the designer is to examine the boundary between the two regions and then to make modifications in the organizational structure and its rules of operation so that the boundary will be shifted as needed. In the general case, however, the region of dominance of a decision maker can consist of a number of disjoint subregions. When the regions are disjoint, the problem is more complex both in terms of understanding the dynamics of the organization (the mental models of its operation by the decision makers themselves may be too simplistic or incorrect) and in terms of organization redesign. Such a case is discussed in the following section.

MIGRATION OF CONTROL IN N-OPTION DECISION MAKING ORGANIZATIONS

This example of a two decision maker organization with a mission to detect enemy submarines was studied from the standpoint of coordinating the decision makers' activities by Grevet [5]. The two entities are a submarine (DM¹) and a surface ship (DM²). The Petri Net model for this organization is depicted in Figure 8.

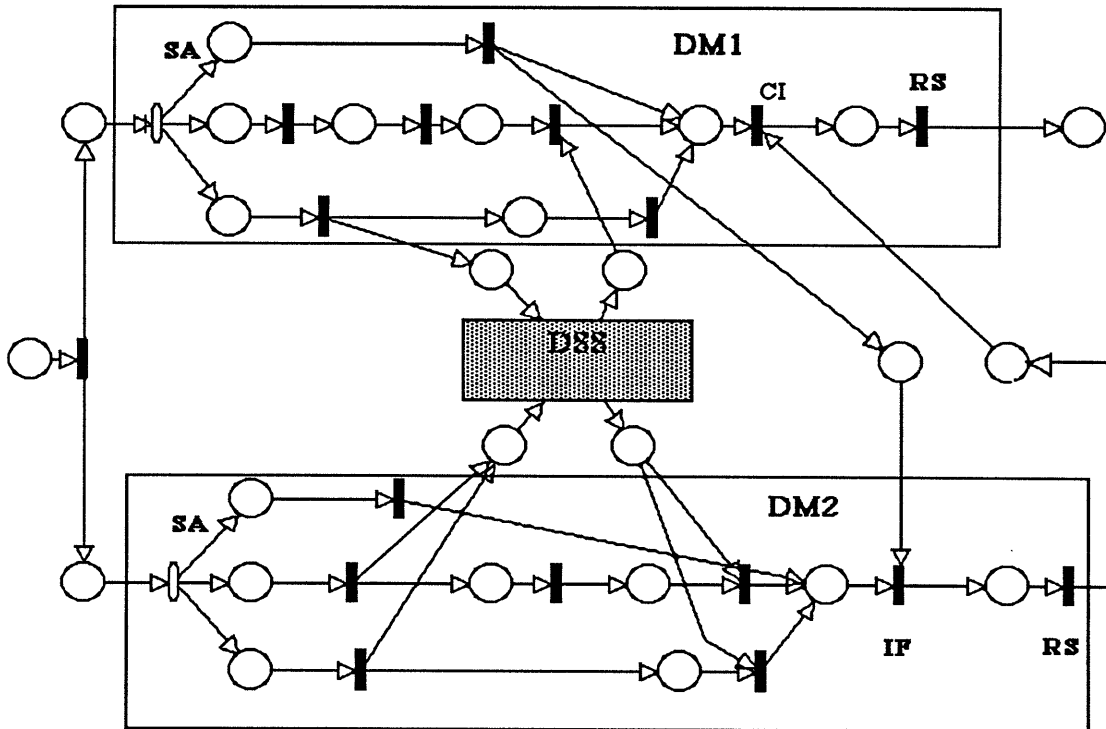


Figure 8. Two Decision Maker Organization Aided by Decision Support System

There are three decision making stages for each DM. In the SA (Situation Assessment) stage, the signals received from the environment are assessed by both DMs. There are three possible strategies for situation assessment for each DM to choose from:

- Strategy SA^i : DM^i processes the information alone without using a decision support system (DSS)
- Strategy IT^i : DM^i relies upon the response of an intelligent terminal
- Strategy MF^i : DM^i queries the mainframe DSS and compares its response to his/her own assessment.

and thus there are nine (3^2) pure strategies for the organization:

(SA1, SA2)	(SA1, IT2)	(SA1, MF2)
(IT1, SA2)	(IT1, IT2)	(IT1, MF2)
(MF1, SA2)	(MF1, IT2)	(MF1, MF2)

A mixed strategy δ_i for each DM^i is a combination of his pure strategies SA_i , IT_i , and MF_i weighted by the probability that each pure strategy will be selected. For DM^1 , the submarine, the probabilities for SA1, IT1, and MF1 respectively will be p_1 , p_2 , and p_3 . For DM^2 , the surface ship, the probabilities for SA2, IT2, and MF2 respectively will be q_1 , q_2 , and q_3 . An organizational behavioral strategy combines the mixed strategies of each DM. For this organization, the behavioral strategy is $(\delta_1(p_1, p_2, p_3), \delta_2(q_1, q_2, q_3))$.

After the SA stage, the submarine sends its assessment to the surface ship, which compares it to its own assessment in the IF (Information Fusion) stage. Then, based on this fusion, the surface ship identifies the signal and sends an order to the submarine. In turn, the latter interprets this order in the CI (Command Interpretation) stage, and based on this interpretation, selects the organization's response.

The task is modeled as follows: Each input x_i consists of an ordered string of six bits. The submarine receives the first three bits a_i , b_i , c_i and the surface ship receives the last three bits d_i , e_i , f_i . The task is described by the alphabet, X , with probability distribution $p(x)$:

$$X = \{x_i = a_i, b_i, c_i, d_i, e_i, f_i \mid \{0, 1\}^6 \supseteq \{a_i, b_i, c_i, d_i, e_i, f_i\}\}$$

There are 64 equiprobable inputs representing the signals that the team must identify to produce a response. There are four responses possible: R_1 , R_2 , R_3 , and R_4 .

- **CASE 1:** If bits a_i and d_i both equal 0, the signal is not from an enemy sub, and the submarine should not counteract. This response is R_1 , and the probability of the corresponding input is $1/4$.
- **CASE 2:** If case 1 does not hold and bits b_i and e_i both equal 0, (input probability $3/16$) the signal comes from an enemy sub testing submarine DM^1 . Here, DM^1 should confuse the enemy sub by under reacting (response of R_2 .)
- **CASE 3:** If cases 1 and 2 do not hold and bits c_i and f_i equal 0, a moderately threatening enemy submarine is present. DM^1 should over-react, to deter the enemy. This response is R_3 , and the probability of the corresponding input is $9/64$.
- **CASE 4:** If none of the above cases hold, then the signal comes from an enemy submarine which is threatening DM^1 . Now, the submarine DM^1 should over-react more forcefully than in case 3. This input probability is $27/64$. The response is R_4 .

The cost matrix giving the costs associated with the discrepancies between the actual and ideal responses is shown in Table 1.

TABLE 1: Cost Matrix

actual R ideal R	R1	R2	R3	R4
R1	0	2	3	4
R2	4	0	1	2
R3	6	4	0	2
R4	8	4	3	0

The different strategies vary in effectiveness of processing information. When the DMs assess the input without the DSS, they identify correctly the first two of their three bits. Therefore, for an input $x_i = (a_i, b_i, c_i, d_i, e_i, f_i)$, the result of the situation assessment when DM^1

uses the SA strategy is (a_i, b_i, u_i) where u_i is what DM¹ produces as the value for the third bit. This value has a probability of 0.5 of being equal to c_i (the actual value). Similarly, for DM², the result is (d_i, e_i, v_i) where v_i is equal to f_i with probability 0.5. When the IT strategy is used, the first bit of each DM's three bits is identified correctly all the time, while the other two are identified correctly with probability 0.5. And for the MF strategy, all bits are identified correctly all the time. Thus, the organization is guaranteed to perform correctly at all times only if the organizational strategy is (MF1, MF2). The performance measure J for this organization is the expected value of the cost for not identifying the string x_i correctly, i.e., inaccuracy, and is obtained by multiplying the cost of each pure strategy by the probability of its occurrence:

$$J = [p_1 \ p_2 \ p_3] \underline{J} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix}$$

where

$$\underline{J} = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix} = \begin{bmatrix} .53 & .98 & .35 \\ .98 & 1.2 & .83 \\ .35 & .83 & 0 \end{bmatrix} \quad (12)$$

Note that up to the situation assessment phase, the two DM's actions and options are identical: they operate in parallel. Thus, the J matrix is symmetric. Furthermore, since in the (MF1, MF2) case the costs are zero, the corresponding term in the J matrix is also zero.

When analyzing migration of control in the consultant-client case, only one parameter was needed to characterize the strategy of each DM, since their choices were binary. Here, however, each switch has three branches indicating three options. However, since the parameters characterizing the points in the strategy space are probabilities, the 3-option case can be expressed in terms of 2 parameters, as shown in equation (13).

$$J = \begin{bmatrix} p_1 & p_2 & 1-p_1-p_2 \end{bmatrix} \begin{bmatrix} .53 & .98 & .35 \\ .98 & 1.2 & .83 \\ .35 & .83 & 0 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ 1-q_1-q_2 \end{bmatrix} \quad (13)$$

By reducing to two dimensions, J may be written in general form as:

$$J = [p_1 \ p_2] \begin{bmatrix} -.17 & -.2 \\ -.2 & -.46 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \end{bmatrix} + [.35 \ .83] \begin{bmatrix} p_1 \\ p_2 \end{bmatrix} + [.35 \ .83] \begin{bmatrix} q_1 \\ q_2 \end{bmatrix} + \text{const.} \quad (14)$$

In this case, the constant is zero because of the zero value of J_{33} . The sensitivity coefficients for each DM are defined as follows:

$$S^1 = [p_1/J \ p_2/J] \begin{bmatrix} \frac{\partial J}{\partial p_1} \\ \frac{\partial J}{\partial p_2} \end{bmatrix}; \quad S^2 = [q_1/J \ q_2/J] \begin{bmatrix} \frac{\partial J}{\partial q_1} \\ \frac{\partial J}{\partial q_2} \end{bmatrix} \quad (15)$$

Again, in this case, a closed form expression can be obtained for the two sensitivities:

$$S^1 = [p_1/J \ p_2/J] \begin{bmatrix} -0.17q_1 - 0.2q_2 + 0.35 \\ -0.2q_1 - 0.46q_2 + 0.83 \end{bmatrix}$$

$$S^2 = [q_1/J \ q_2/J] \begin{bmatrix} -0.17p_1 - 0.2p_2 + 0.35 \\ -0.2p_1 - 0.46p_2 + 0.83 \end{bmatrix} \quad (16)$$

where J is as defined in equation (14). At this point, the calculations can be done efficiently using a spreadsheet; the values for the sensitivity coefficient for each DM at all points in the strategy space can be determined and plotted as a function of the strategies (p_1, p_2) and (q_1, q_2).

The computations for the antisubmarine warfare case, with three options, can be easily extended analytically to the n -option case with a reduction; however, the graphical representation of the regions of dominance becomes much more complex.

Given the versatility of spreadsheet software for the Macintosh™, there are many formats in which to analyze the migration of control. Each reveals a different perspective of how the structure of an organization impact on the relative control of its members. The various plots that can be made include:

- The sensitivity coefficient for each DM is obtained as a function of the organization's behavioral strategies. That requires to plot a surface in the five-dimensional space: S vs (p_1, p_2, q_1, q_2) . One way to accomplish that is discretize the two-dimensional strategy space of each DM in terms of a rectangular grid and then order the pairs. Then a three-dimensional plot, a surface, can be obtained of S vs. (p_1, p_2) and (q_1, q_2) .
- The regions of dominance for each DM in the four dimensional behavioral strategy space. Again, in this case, if the discretization of the strategy space is carried out, including the ordering of the pairs, a two dimensional strategy space is obtained in which the regions of dominance can be depicted. Note, however, that the manner in which the pairs (p_1, p_2) and (q_1, q_2) are ordered will affect the appearance of the regions.

Of course, it is always possible to parametrize the strategy space and plot the sensitivity due to one DMs changes in strategies for a fixed strategy of the other DM. For example, observing how S^1 varies in the strategy space of DM^1 for incremental changes in the DM^2 's strategies provides some interesting insights on the effect on control of using a less efficient strategy.

As illustrated in Figure 9, where both q_1 and q_2 equal zero, the strategy choice of DM^2 being querying the mainframe, results in perfect accuracy on his part. Therefore, the performance measure is most sensitive to the decisions of DM^1 throughout his entire strategy space (except when p_1 and p_2 are also both zero). DM^1 gains control, shown by a larger sensitivity coefficient S^1 , as p_1 and p_2 increase, and loses control as q_1 and q_2 increase. This can be observed in the shaded areas of the plots, in which $p_1 + p_2 \leq 1$. Strategy 1, assessing the situation without aid, SA1, and 2, using the intelligent terminal, IT1, yield larger values of J (and thus worse accuracy) than strategy 3, querying the mainframe, MF1. Therefore, increased likelihood of a DM using either of the two less effective strategies has more effect on accuracy than increased likelihood of the DM using strategy 3. This is intuitively appealing: when performance is very poor, small changes can yield substantial performance improvements. Thus, the actions of DM^1 when p_1 and p_2 are large have greater impact than when p_3 is large. The fact that strategy 2 is the least effective explains why. In the plots where either q_1 or q_2 is nonzero, the S^1 surface slopes gently upward as p_1 is increased, and rises more dramatically when p_2 is increased. Comparison of the three plots in Figure 9 shows that, when q_1 and q_2 are large, DM^2 gains control just as DM^1 does when p_1 and p_2 are large. And since there are only two DMs, when one DM dominates, the other recedes.

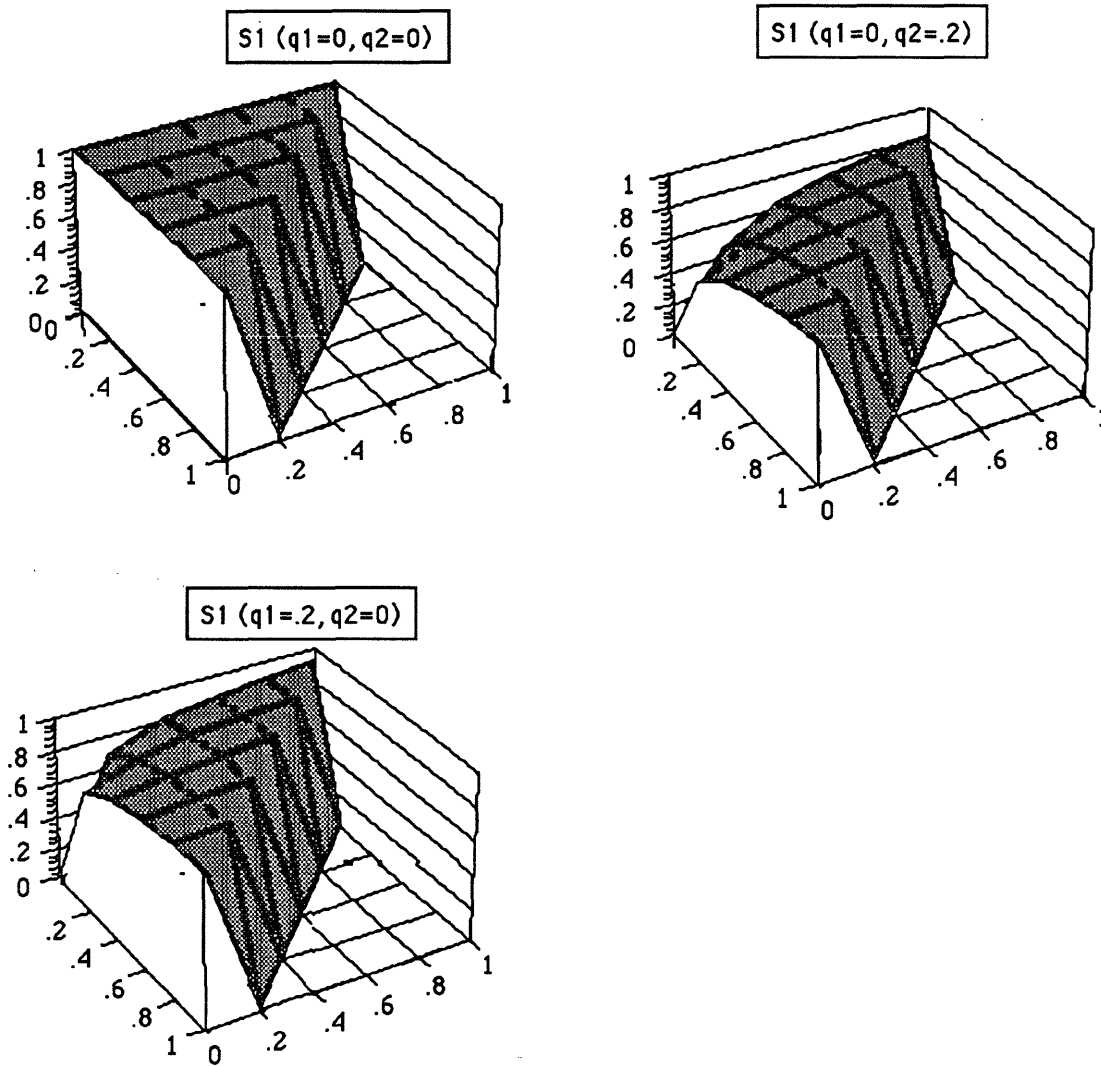


Figure 9. Migration of Control in Strategy Space of DM^1

Given the information obtained from the calculation of the sensitivity coefficients, two for each point in the organization's behavioral strategy space, regions of dominance are determined by comparing the absolute values of the sensitivity coefficients. The resulting plot, analogous to that of Figure 7, is shown on Figure 10.

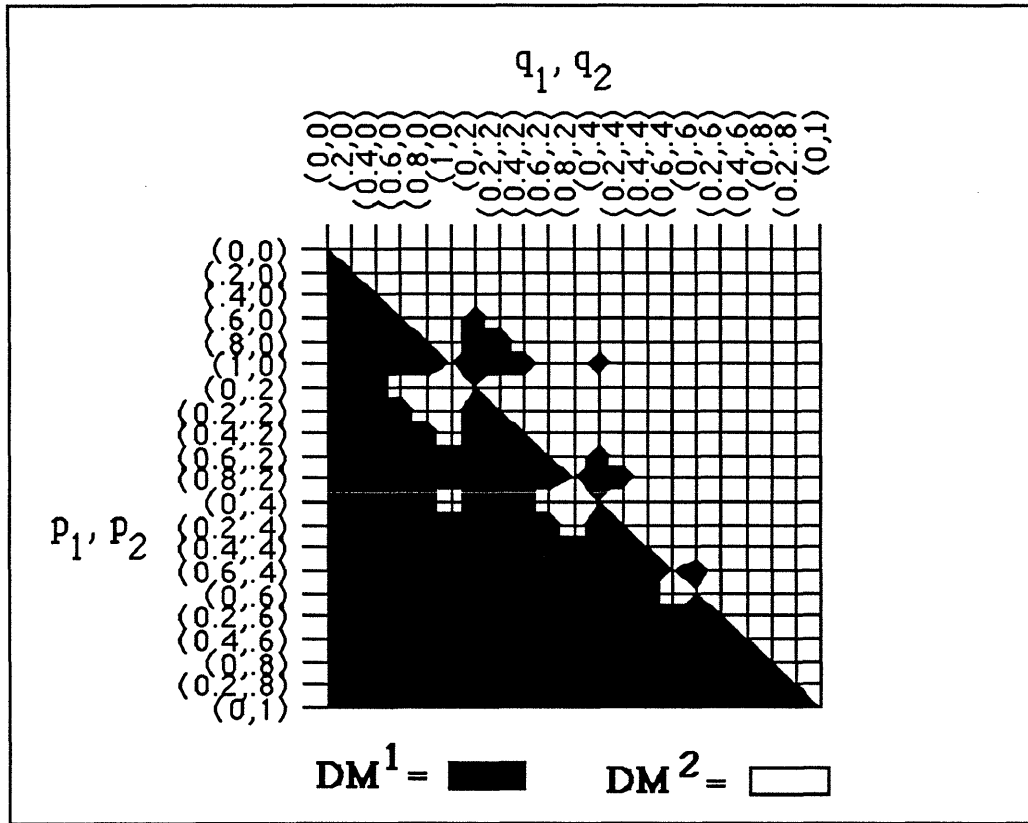


Figure 10. Regions of Dominance in the strategy space

The points in the strategy space have been so ordered that the resulting areas are connected as possible. As a result, Figure 10 illustrates the fact that in a parallel organization with a symmetric matrix for the costs, one would expect a symmetry in the areas of dominance by the two decision makers. In this case, the line of symmetry is from the diagonal: areas which are to the left of the line $(p_1, p_2) = (q_1, q_2)$ in which one DM is in control match areas on the right in which the other retains control. Wherever DM^1 gains control on one side, its mirror image yields DM^2 gaining control on the opposite side. Given the earlier reasoning, it makes sense that when the probability of choosing one strategy is the same for both DMs, and the probability of one DM choosing the least effective strategy is greater than that of the other, the former is in control, since he has the power to make a significant change in the organization's performance.

This display of migration of control provides a starting point for redesigning of organizations so as to optimize the flow of control. Redesigning the organization becomes of crucial importance when, because of a hierarchical organizational structure, it is necessary that those members in higher echelons retain control under various operating conditions. Here, although the actions and

options of the DMs are identical up to their situation assessment stage, the organization is hierarchical. The submarine DM¹, the subordinate, will send the result of its assessment to the commander, DM², who will fuse this with its own assessment, identify the signal, and produce a directive which is sent to the subordinate. In turn, the subordinate interprets this order and produces the organizational response. However, the situation as analyzed reveals no such hierarchy. Therefore, it is desirable to redesign the concept of operations so that DM² retains control in most cases.

It is possible to develop rules for redesigning the organization for specific operating conditions. For example, suppose that DM², the commander, finds that although not as accurate as the other assessment alternatives, the intelligent terminal (IT) provides better performance with respect to speed and ease of use, and so he decides to choose this alternative, strategy IT2, at all times. Then, $q_2 = 1$. This structure preserves the commander's control: for every mixed strategy of the submarine, DM¹, the commander DM² retains control.

CONCLUSION

A methodology, and the associated models, have been described that allow designers of information processing and decision systems to investigate the effect their designs have on the properties of decision making organizations. Specifically, a quantitative model of a property that becomes very important when distributed decision making is considered, the migration of control, has been described and illustrated with application to two simple examples. The concepts used and the computational procedures presented are not limited to simple examples; they apply to arbitrary size organizations. The depiction of the complete results in simple graphs depends, however, on the dimensionality of the problem; use of the specific features of individual problems may help reduce the dimensionality of the strategy space, as was illustrated with the second example. This work is continuing, as part of an effort to understand the dynamics of organizations that function through the use of decision support systems.

REFERENCES

- [1] S. K. Andreadakis and A. H. Levis, Accuracy and timeliness in decision making organizations. Proc. 10th IFAC World Congress (Pergamon Press, Oxford, 1987).
- [2] S. K. Andreadakis and A. H. Levis, Synthesis of distributed command and control for the outer air battle. Proc. 1988 Symposium on C2 Research (SAIC, McLean, VA, 1988)

- [3] K. L. Boettcher and A. H. Levis, Modeling the interacting decision maker with bounded rationality. *IEEE Transactions on Systems, Man, and Cybernetics*, SMC-120 (3) (1982) 334-344.
- [4] K. L. Boettcher and A. H. Levis, Modeling and Analysis of Teams of Interacting Decisionmakers with Bounded Rationality," *Automatica*, Vol. 19, No. 6, pp. 703-709, 1983.
- [5] J. L. Grevet, Decision Aiding and Coordination in Decision-Making Organizations, MS Thesis, Laboratory for Information and Decision Systems, MIT, Report LIDS-TH-1737, (1988).
- [6] S. Kahne, Control Migration: A Characteristic of C3 Systems, *IEEE Control Systems Magazine*, 3 (1) (1983) 15-19.
- [7] J. S. Lawson, Jr., Command control as a process. *Control Systems Magazine* 1 (1) (1981) 5-11.
- [8] A. H. Levis, Information Processing and Decision-Making Organizations: a Mathematical Description, *Large Scale Systems*, 7, (1984) 151-163.
- [9] A. H. Levis and M. Athans, The quest for C3 theory: dreams and realities, in S. E. Johnson and A. H. Levis (Eds.), *The Science of Command and Control: Coping with Uncertainty* (AFCEA, Fairfax, VA, 1988).
- [10] A. A. Louvet, J. T. Casey and A. H. Levis, Experimental investigation of the bounded rationality constraint, in S. E. Johnson and A. H. Levis (Eds.), *The Science of Command and Control: Coping with Uncertainty* (AFCEA, Fairfax, VA, 1988).
- [11] W. Reisig, *Petri Nets: An Introduction* (Springer-Verlag, Berlin, 1985).
- [12] P. A. Remy and A. H. Levis, On the generation of organizational architectures using Petri Nets, in: G. Rozenberg (Ed.), *Advances in Petri Nets 1988* (Springer-Verlag, Berlin, 1988).
- [13] M. Van Creveld, *Command in War* (Harvard University Press, Cambridge, MA, 1985).