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ON THE DESIGN OF ORGANIZATIONAL STRUCTURES FOR COMMAND AND CONTROL*

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A quantitative approach to the evaluation of alternative organizational forms is presented. The method is extended to the case when the designer cannot assume that the organization members have the same perception of the task requirements as he does. Two three-person organizations are used to illustrate the approach.

1. INTRODUCTION

When the tasks which have to be performed exceed the capabilities of a single person, organizations are formed, consisting of individuals interacting with each other in specified ways. The most important characteristic of the organizations considered here is that their task involves information processing and decisionmaking. The qualitative and quantitative analysis of this class of organizations is carried out within an information theoretic framework and is a direct continuation of the work by R. F. Drenick [1], K. L. Boettcher, and A. H. Levis, [2], [3], [4].

In developing the model of organizations, several simplifying assumptions have been made: (a) designers and decisionmakers have identical knowledge of the tasks' uncertainty, i.e., the probability distribution of the tasks and (b) identical perception of the value of each task. These assumptions are very restrictive and often unjustifiable. In general, it is very difficult to assess the probability distribution of the tasks; it is also unlikely that the designer and the decisionmakers have the same perception of the tasks' probability distribution. In this paper, this assumption is relaxed. It is assumed that the designer knows the tasks' real probability distribution, while the decisionmaker's perception of this distribution is different. The second assumption that all tasks are of equal value is also improbable; usually, different tasks have different utilities, i.e., different weights are assigned to them by the designer. Therefore, the second assumption must be weakened, so that each task can be weighted differently. In order to pose these problems properly, two additional assumptions must be introduced: (a) there is no communication between the designer and the decisionmakers and (b) the designer knows the tasks' uncertainty as perceived by each decisionmaker in the organization, as well as the relative weights assigned by them to each task.

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2. THE DESIGN PROBLEM

2.1 Model of the Task

A task consists of receiving data (signals), processing that data, and producing an output in the form of actions or signals. The input data can originate from a single source or from many different sources. The data may be a single element or a set of elements. In general, it is modeled as a vector, x, generated by a single source. This vector signal is partitioned by partitioning matrices π and allocated to the appropriate decisionmakers. A task can be specified fully by its finite scheme, which consist of the task's alphabet and its probability distribution, i.e.,

$$\mathbf{X} = (X, P) = \begin{pmatrix} x_1, x_2 \dots x_m \\ p_1, p_2 \dots p_m \end{pmatrix} \quad (1)$$

2.2 Model of the Decisionmaker

The basic model of the memoryless decisionmaker with bounded rationality is based on the hypothesis of F. C. Donders [5] that information processing is done in stages. Specifically, it is assumed that the two stages are: (a) situation assessment, and (b) response selection. The structure of the basic model has been extended by Boettcher and Levis [2] to include interactions between decisionmakers as shown in Figure 1. It is assumed that the overall task x is partitioned by matrix π^n and that only the appropriate elements of x are allocated to the n-th decisionmaker. The decisionmaker processes the data using the algorithms in the SA stage in order to assess the situation. The assessed situation, $\bar{z}^n$, is then processed in the RS stage, where the decision of an appropriate action or response, y^n, is made. Which ones of the SA and RS algorithms a decisionmaker will use depends on his choice of internal decision strategy, D_k^n. For the situation assessment stage, it is assumed that the strategy u^n is independent of the input x^n, whereas in the response selection stage v^n depends on the value of the assesed situation $\bar{z}^n$. The assumption that the choice of u^n is not dependent on x^n has been relaxed in recent work by Chyen and Levis [6].

In order to make communication and interaction between decisionmakers possible, two additional functional elements are added to the model: (a) information fusion (IF), and (b) command interpretation (CI). The IF process allows sharing of information on the state of environment between decisionmakers. This functional element associates information on the assessed situation obtained by the n-th decisionmaker, z^n, and the corresponding information sent to him from the rest of organization, z^{on}, and gives the cumulative updated information on the state of environment $\bar{z}^n$. It is also possible for the n-th decisionmaker to communicate his knowledge on the state of environment z^{no} to other members of the organization, who accept and fuse that information with their own in the corresponding IF stage. Commands v^{on} received by the n-th decisionmaker from the rest of the organization can modify or even override his own decision v^n.

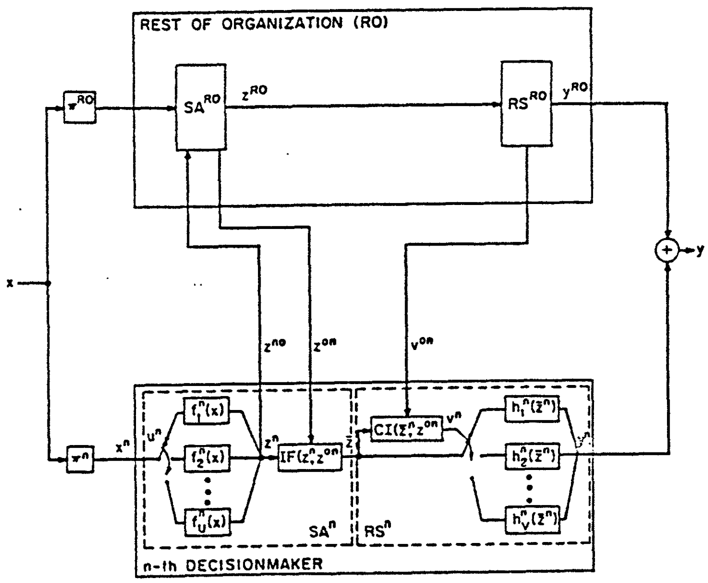

Figure 1. Model of the Single Decisionmaker with the Rest of the Organization

2.3 Acyclical Organizational Structure

An information processing organization receives, processes and produces signals or actions; it consists of a number of decisionmakers. The pattern in which the information is allowed to flow between the members within the organization is assumed to be acyclical in order to avoid deadlock or circulation of messages within the organization.

2.4 Workload and Performance

The two fundamental quantities describing decisionmakers (DMs) and decisionmaking organizations are the workload or the activity level of each indidivudal DM and the performance index of the organization. Both of them are functions of the input, the decisionmakers' internal structures, the organization's protocol or standard operating procedures and the decision strategy. For a specified input, a protocol and an internal structure (set of algorithms) both the performance and the workload depend parametrically on the organizational behavioral strategy which is defined as

$$\Delta = \{D^1(p^1) \;,\ldots,\; D^N(p^N)\}$$

$$= \sum_{k^1} \cdots \sum_{k^N} \Delta_{k^1 \ldots k^N} \; p^1_{k^1} \cdots p^N_{k^N} \tag{2}$$

where $D^n(p^n)$ is the n-th decisionmaker's mixed decision strategy, and $\Delta_{k^1,\ldots,k^N}$ denotes a pure strategy of the organization (see G. Owen [7], and Levis and Boettcher [3]).

The workload in the information theoretic framework is defined as the activity necessary to reduce uncertainty and arrive at a decision. For any arbitrary information processing system it is defined as

$$G = \sum_i H(w^i) = -\sum_i \sum_j p(w^i_j) \log p(w^i_j) \tag{3}$$

where w^i_j is the j-th value from the alphabet of the i-th internal variable. When the tasks' finite scheme $\mathbf{X}$, organizational structure (algorithms and protocols) and organization's behavioral strategy Δ, Eq. (2), are specified, it is then possible to evaluate the activity of each decisionmaker within the organization, i.e.,

$$G^n = G^n(\Delta) = -\sum_i \sum_j p(w^i_j) \log p(w^i_j) \tag{4}$$

where w denotes the internal variables of the n-th decisionmaker. It has been shown [2], [8] that the total activity G is the convex function of the decision strategy Δ in the sense that

$$G(\Delta) \geq \sum_{k^1} \cdots \sum_{k^N} G(\Delta_{k^1 \ldots k^N}) \; p_{k^1} \cdots p_{k^N} \tag{5}$$

where $G(\Delta_{k^1 \ldots k^N})$ is the workload corresponding to the pure strategy.

A limiting feature of the single decisionmaker is his bounded rationality. It is an expression of his cognitive limitations and has been modeled [2], [3] as a constraint on his total activity

$$G^n(\Delta) \leq F^n \tau \tag{6}$$

where F^n is the maximum rate at which the n-th decisionmaker can process information and τ is the mean interarrival time of tasks.

The organization's performance is defined as

$$J = E\{d(y,y')\} = \sum_i \sum_j d(y_j, y'_j) \; p(y_j | x_i) p(x_i) \tag{7}$$

where y is the actual output of the organization as a whole in response to the input x_i and where y' is the desired output as defined by the organization's designer. The comparison function d(y,y') can take any form appropriate to the particular problem; in its simplest form it is defined as

$$d(y,y') = \begin{cases} 0 \;, & y = y' \\ 1 \;, & y \neq y' \end{cases} \tag{8}$$

In that case, the performance index is reduced to the probability of producing an incorrect response, i.e., the probability of making an error.

The performance measure has meaning only for the organization as a whole and can be expressed as

$$J(\Delta) = \sum_{k^1} \cdots \sum_{k^N} J_{k^1 \ldots k^N} \, p^1_{k^1} \cdots p^N_{k^N} \qquad (9)$$

to show its dependence on the choice of an organizational strategy. The designer is the one who assigns the value of the performance threshold ($\bar{J}$) which the decisionmaking organization has to meet, i.e.,

$$J(\Delta) \leq \bar{J} \qquad (10)$$

This condition determines the set of strategies that yield satisficing performance.

2.5 Performance - Workload Locus

For each decision strategy, the organization's performance and the workload of each one of the N decisionmakers can be computed. The performance-workload locus, S_o, is defined in the (N+1)-dimensional space S as the set of all points $(J, G^1, \ldots, G^N)$ that correspond to the set of all admissible decisions strategies. Let $\sum$ be the set of all admissible strategies of the organization; then

$$\sum = \sum (\sum^1, \sum^2, \ldots, \sum^N) \qquad (11)$$

where $\sum^n$ is the set of admissible strategies of the n-th decisionmaker.

The bounded rationality constraint for each DM, Eq. (6) is expressed simply as a bounding hyperplane in the performance-workload space; the satisficing constraint, Eq. (10), is also a bounding hyperplane that intersects the J axis at $\bar{J}$.

The performance-workload locus can be used to compare qualitatively two different organizational structures or designs that are to perform the same task. [4]. It can also be used to compare the effectiveness of the same organization in dealing with different degrees of uncertainty, i.e., for different probability distributions of the input alphabet X. This qualitative analysis is based on how well the locus S_o meets the requirements of Eqs. (6) and (10).

A quantitiave approach to the comparison and effectiveness analysis of organizational forms is based on comparisons not in the performance-workload space, but in the strategy space [4]. Bounded rationality constraints, Eq. (6), and performance requirements, Eq. (10), partition the space of organization strategies into a set of feasible strategies that lead the points in the performance-workload locus that satisfy constraints Eq. (6) and (10), and a set that does not. The set of feasible strategies is defined as follows:

$$\sum' = \sum \{\Delta | J(\Delta) \leq \bar{J}, \; G^1(\Delta) \leq F^1\tau, \ldots, G^N(\Delta) \leq F^N\tau\} \qquad (12)$$

Then, a measure of effectiveness, called the consistency measure, can be defined [4]:

$$Q = V(\sum')/V(\sum) \qquad (13)$$

where V is a volume in the N-dimensional strategy space. Therefore, Q denotes the fraction of all strategies that are feasible. The higher it is, the more consistent the decisions of the organization will be with the design specifications. A second interpretation of the measure is the following: if all organizational decision strategies are equally probable, then Q is the probability that the organization will make a decision that satisfies the individual bounded rationality constraints and leads to satisficing performance. Hence, Q is bounded increasing function of the performance threshold $\bar{J}$ and individual decisionmaker's activity threshold ($F^n\tau$, n = 1,...,N), i.e.,

$$0 \leq Q(\bar{J}, \tau) \leq 1 \qquad (14)$$

It is equal to zero if there is no decision strategy for which it meets the specifications of the task, while its value is equal to unity if all admissible decision strategies satisfy the requirements. It is evident that the higher value of the mutual consistency measure Q the better performance can be expected from that system. Therefore, the designer can compare systems with respect to Q and select the one with the highest value of Q for a given $\bar{J}$ and τ.

3.0 TWO POINTS OF VIEW

The basic premise in all previous work is that the designer knows the finite scheme, Eq. (1), and the performance index and that he assumes the decisionmakers in the organization will have the same knowledge. On that basis, he can design an organizational form and evaluate it. However, the question arises as to how robust the design is, i.e., how sensitive is the value of Q to the assumption that the decisionmakers have indeed the same knowledge. Suppose that they have different perceptions of the tasks' uncertainty and they assign different values to the individual tasks. The individual decisionmakers who only receive partial information about the organization's tasks may have a different perception of the probability distribution p(x). Furhtermore, their local objectives may distort the values of the weights assigned to each task by the designer who maintains a global perspective.

The designer can adopt two points of view in order to study the robustness of his design. First, he can assume that the DMs will operate on the basis of his perception of task uncertainty, p(x), and objective function J. Or, he can assume that the DMs will operate on the basis of a different perception of task uncertainty, e.g., q(x), and that they will assign different values, c(x), to the various tasks x_i.

These two points of view lead to the formulation of four problems that the designers must analyze.

Problem 1: (Basic Problem) The DMs know the objective probability distribution of the tasks, p(x), and the weighting coefficients for the various tasks. For simplicity, it is assumed that all the coefficients c(x) are equal to unity for the base case.

Problem 2: (Task Uncertainty) The DMs have their own perception of the probability distribution of the input, q(x) instead of p(x), but assign the same values to the tasks as the designer (c(x) = 1).

Problem 3: (Task Value) The DMs know the objective probability distribution to the tasks, p(x), but assign different values of the various tasks, i.e., their c(x) differs from the designer's (c(x) ≠ 1).

Problem 4: (General Problem) The DMs have their own perception of the probability distribution of the input, q(x), and the value of the tasks.

Problem 1 is the one that has been analyzed in detail in [2], [3], and [4] while Problem 4 is the general case; Problems 1, 2, and 3 are really special cases of 4. In this paper, Problem 2 is analyzed because it addresses the complex interrelationship between uncertainty and workload.

It is possible to develop the analytical expressions for the workload as a function of p(x) and of q(x). It is also possible to introduce weighted entropy, [9], and derive the expressions for the difference in the workload G^n due to the difference in the perception of the task uncertainty by the designer and the decisionmakers. However, the analytical expressions have not yielded yet any particular insight to the problem. Consequently, the sensitivity analysis will be described in terms of an example that has been introduced in an earlier study [3], [10].

4.0 THREE PERSON ORGANIZATIONS

Two three-person organizations have been used to illustrate the analysis and comparison of alternative organizational forms. The first one, Organization A, illustrates a parallel structure while Organization B is a hierarchical one. The two organizations are shown in Figures 2 and 3, respectively, where the Petri Net formalism is used [10]. Since the description of the organizations, their protocols and the air defense task that they model have been described in [3], they will not be repeated here. Only the task model will be described in some detail, since the probability distribution of the input x is the key issue in Problem 2.

A threat is modeled by an ordered pair of points in a two dimensional space. The two points are assumed to be measurements defining the trajectory of the threat. It is also assumed that time interval between the points is known, so that the speed of the threat can be calculated. In the parallel organization, A, the threat area is divided into three sectors, each one assigned to one of the three decisionmakers. If a threat lies entirely within a sector, i.e., both points are in one sector, then the corresponding DM assesses the situation and generates a response. If a threat crosses the boundary between two sectors, then the DM with the sector within which the second (or latter) point lies is expected to provide the response. However, the adjacent DM must communicate information: the data about the first (or earlier) point. In order to avoid complex protocols, it is assumed that no more than one threat can be in each sector and there can be only one threat that crosses sectors at a time. These assumptions avoid two conflicts: (a) one DM having to decide about two threats at the same time and (b) the center DM receiving simultaneously data from the other two DMs and having to assess two threats simultaneously. Actually, the second assumption can be relaxed so that two threats that cross boundaries can be present provided they do so on different boundaries and the net result is such that a single DM does not have to respond to both of them.

Fourteen different threat configurations are possible. If one distinguishes between fast or slow threats, then a total of forty two configurations are possible.

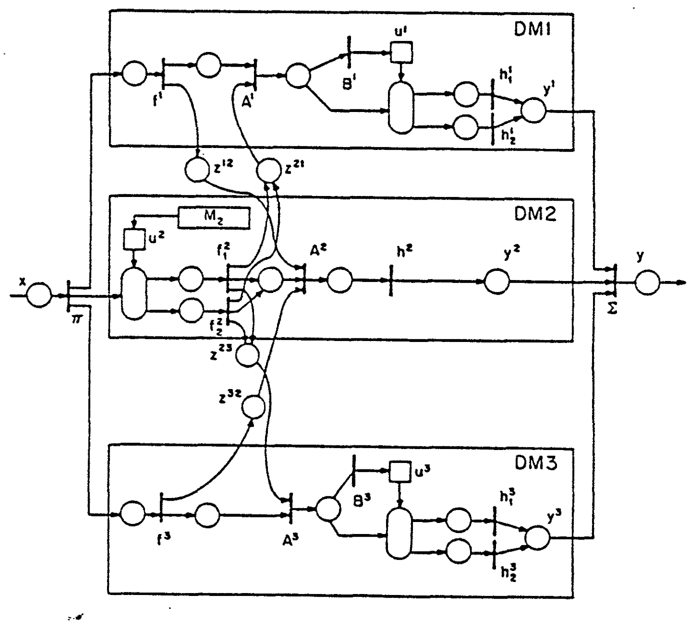

Figure 2. Organization A: Parallel Structure

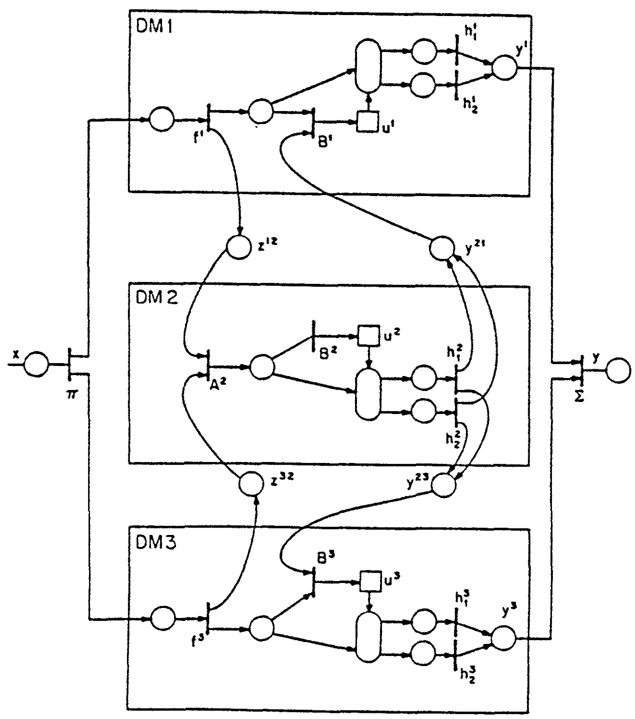

Figure 3. Organization B: Hierarchical Structure

In organization B, the situation is rather different. There are two main sectors with DM^1 and DM^3 being responsible for the threats in each sector, respectively. The two DMs, however, do not share information directly. Instead, they pass information about threats at or near their common boundary to the coordinator (DM^2) who assesses the situation and assigns the threat to the appropriate DM.

For the evaluation of the performance-workload locus, forty five threat sets were used representing seventeen of the forty-two possible configurations. The objective probability distribution p(x) was assumed to be uniform, i.e., each one of the forty five threat sets was equally likely.

In order to provide some contrast and also represent a plausible situation, the probability distribution perceived by the decisionmakers, q(x), was assumed to be non-uniform. Specifically, it was assumed that the DMs did not take into account that threats could cross sectors (they assigned almost zero probability to these events), but assumed uniform probability distribution for threat sets that did not include trajectories crossing sector boundaries.

The level of activity, measured by whether a decisionmaker expects to respond to a threat or not, is shown in Table 1.

TABLE 1. Expected Activity by DMs for p(x) and q(x)

DM	STATUS	p(x)		q(x)	
		ORG A	ORG B	ORG A	ORG B
1	Active	49%	91%	76%	82%
	Inactive	51	9	24	18
2	Active	84%	82%	38%	38%
	Inactive	16	18	62	62
3	Active	51%	89%	59%	64%
	Inactive	49	11	41	36

The active status denotes either autonomous operation — the DM receives a threat in his sector and responds to it — or interaction with another DM by sharing situation assessment information.

5.0 RESULTS

The consistency measure Q for the parallel organization A and task probability distribution p(x) and q(x) is shown in Figures 4 and 5, while Figures 6 and 7 are the corresponding plots for a hierarchical Organization B.

Figure 4 shows that there are no strategies that the organization members can use that will not lead to overload, if the interarrival time τ is less than 32 units of time. Furthermore, if τ is more than 52 units then no strategy will overload the DMs. The fraction of strategies that satisfy the bounded rationality constraints is a non-decreasing function of τ, as shown by the gradual, step like increases in Q. Now consider Figure 5. This shows the effect of underestimating the task requirements by the decisionmakers. By neglecting to take into consideration the common occurence of threats that cross over from one sector to another and the resulting need for communication and coordination, they perceive that they can handle threats arriving every 22 units of time on the average. All strategies are feasible, if the threats arrive every 42 or more units of time. On that basis, they can choose strategies they believe to be feasible, but which in reality will cause overload and, consequently, a degradation of performance, possibly a severe one. Very similar observations can be made by comparing the Q loci of organization B, Figs. 6 and 7. In that case, too, the Q locus for the objective probability is farther from the origin than the locus resulting when the perceived uncertainty by the decisionmakers is used. The decisionmakers have underestimated the need for coordination to handle threats that occur near or on the boundary between the two sectors.

The assumption that a decisionmaker may select any of the admissible, but not necessarily feasible, strategies with equal probability is not a realistic one. If the DM thinks that a certain subset Σ_s' of the decision strategy space Σ will meet the performance and workload constraints, then he will choose strategies from that set only and ignore the rest. This can be modeled by assuming a uniform probability distribution for the strategies in Σ_s' and assigning zero probability to the strategies not in Σ_s'. If a decisionmaker's perception of the task's probability distribution q(x) is such that Σ_s' is the null set, then a uniform probability distribution is assumed for selecting a strategy from the set Σ.

If the decisionmaker's q(x) is the same as the designer's, the objective probability distribution p(x), then the feasible strategy set is denoted by Σ_o'. The relative position of the two strategy sets, the one due to q(x), Σ_s', and the one due to p(x), Σ_o', may be such that the two sets are disjoint, overlapping, or identically the same. Therefore, in selecting a strategy from Σ_s', the decisionmaker may be selecting a strategy that meets the specifications of the task as seen by the designer or he may not. In order to analyze the relationship between Σ_s' and Σ_o', the consistency measure introduced in Eq. (13) is modified as follows:

$$\bar{Q}(\bar{J},\tau) = \begin{cases} V(\Sigma_o')/V(\Sigma) & \text{for } V(\Sigma_s') = 0 \\ \dfrac{V(\Sigma_s') \quad V(\Sigma_o')}{V(\Sigma_s')} & \text{for } V(\Sigma_s') > 0 \\ 1 & \text{for } V(\Sigma_o') = V(\Sigma) \end{cases} \tag{15}$$

where $V(\cdot)$ is again the volume in the strategy space. The quantity $\bar{Q}$ can be interpreted as the probability that a decisionmaker, who perceives the probability distribution of the tasks as being q(x), will select a decision strategy that satisfies the requirements $(\bar{J},\tau)$.

The example of Organizations A and B and the probability distributions p(x) and q(x) introduced in Section 4 are used now to illustrate the modified consistency measure $\bar{Q}$. From plots of the consistency measures of Q, Figures 4 and 5 and the plot of the modified consistency measure in Figure 8, the following observations can be made. For very low threshold values, $\bar{J} < 2.4$ and $\tau < 22$, there are no strategies for which DMs can meet the workload and performance requirements. For values of the thresholds

$$2.4 \leq \bar{J} < 4.9 \quad ; \quad 22 \leq \tau < 32$$

the DMs think that there are strategies that satisfy

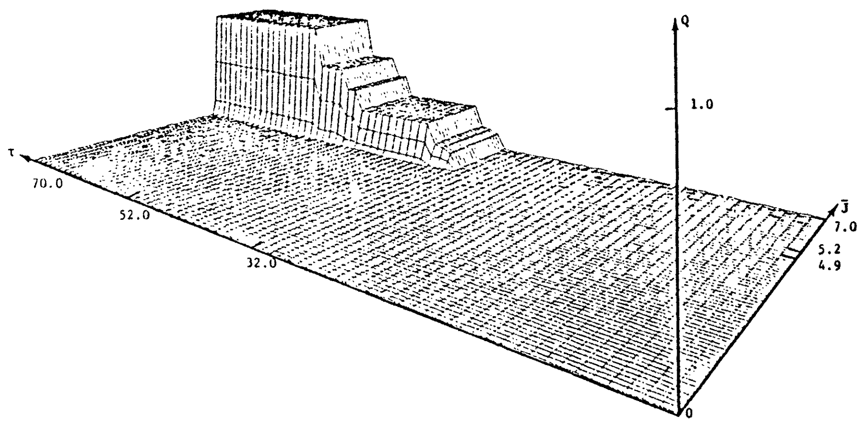

Figure 4. Consistency Measure Q for Organization A: p(x)

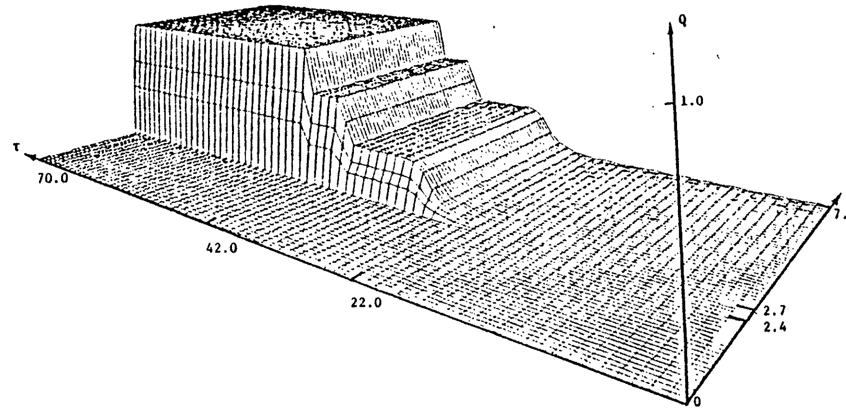

Figure 5. Consistency Measure Q for Organization A: q(x)

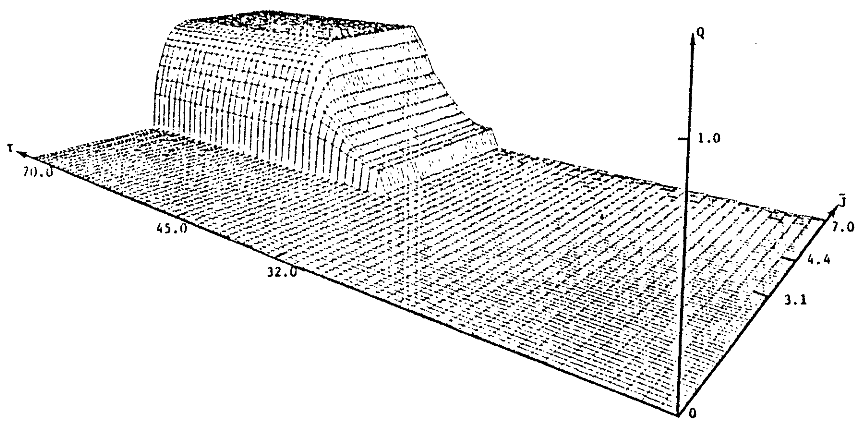

Figure 6. Consistency Measure Q for Organization B: p(x)

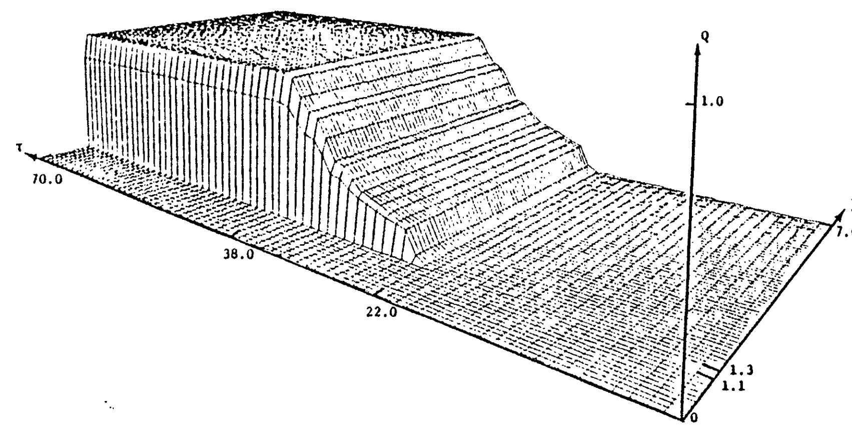

Figure 7. Consistency Measure for Organization B: q(x)

the requirements, but in reality there are not: $\bar{Q}$ remains zero because the intersection of Σ_s' and Σ_o' is null. For values of τ between 32 and 52, the probability with which they will select a feasible (from the designer's point of view) strategy varies. For values of $\bar{J} \geq 5.2$ and $\tau \geq 52$, the measure $\bar{Q}$ is unity, i.e., all admissible strategies are feasible.

From the plots of Q in Figures 6 and 7 and the plot of the modified consistency measure $\bar{Q}$, Figure 9, similar observations can be made for Organization B. For $\bar{J} \leq 1.1$ and $\tau < 22$, there are no feasible decision strategies. For

$$1.1 \leq \bar{J} < 3.1 \quad \text{and} \quad 22 \leq \tau < 32$$

there are strategies that appear to the DMs to be feasible, as shown in Figure 7, but in reality they are not. Consequently, while Q is nonzero, $\bar{Q}$ is zero. In the region $32 \leq \tau \leq 45$, in contrast to Organization A, the intersection $\Sigma_s' \cap \Sigma_o'$ is increasing faster than Σ_s'. For $\bar{J} > 4.4$ and $\tau > 45$, all strategies are feasible. Interesting insights are obtained, if the assumptions of p(x) and q(x) are reversed. Suppose that the actual threat set does not include threats that cross boundaries, i.e., $p^1(x)=q(x)$, but that the DMs assume that there are, $q^1(x)=p(x)$. While the Q plots for Organization A remain the same, but with Fig. 5 representing the designer's point of view and Fig. 4 the DMs, the $\bar{Q}$ plot is quite different. For

$$0 \leq \bar{J} < 2.4 \quad \text{and} \quad 0 \leq \tau < 22$$

there are no decision strategies with which the organization can meet the performance requirements and the workload constraints, and the DMs are aware of that. For

$$2.4 \leq \bar{J} < 4.9 \quad \text{and} \quad 22 \leq \tau < 32$$

there exist feasible strategies, but the DMs are not aware of them. Since Σ_s' is null, the DMs may choose strategies from Σ at random and, therefore, the probability of selecting a feasible one is equal to the value of Q (Figure 5). For larger values of the thresholds $\bar{J}$ and τ, the two sets Σ_s' and Σ_o' intersect; at the point $\bar{J} = 4.9$ and $\tau = 3.2$, Σ_s' is within Σ_o' and stays within it from then on.

Similar behavior is observed for Organization B, as indicated by the $\bar{Q}$ locus in Figure 11.

Finally, comparison of the $\bar{Q}$ plots for Organization A, Figures 8 and 10 (or Organization B, Figures 9 and 11) shows that the effectiveness of each organization structure is sensitive to the knowledge of the input. If the decisionmakers underestimate the task requirements, degradation of performance will occur, while if the designer underestimates the workload requirements of the task, but the decisionmakers are aware of them, then the organization will be as effective as it can be.

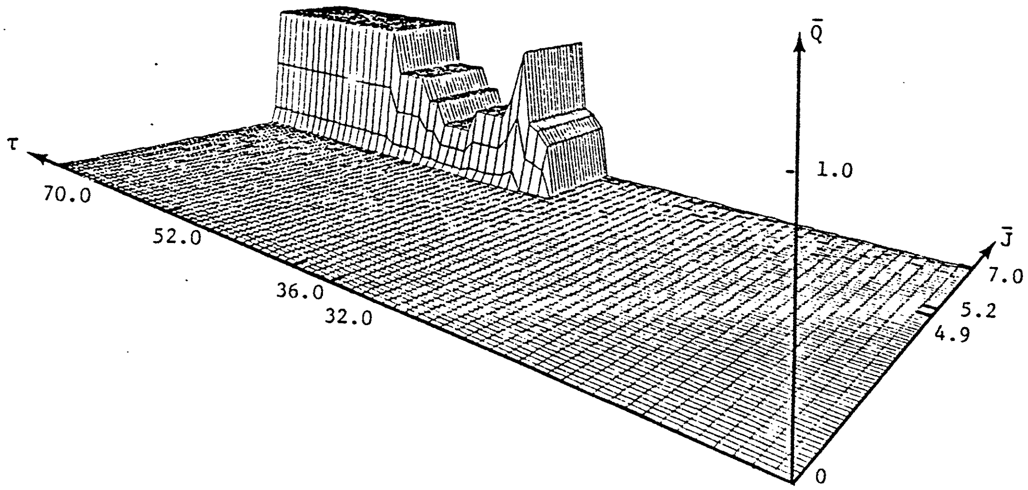

Figure 8. Modified Consistency Measure $\bar{Q}$ for Organization A

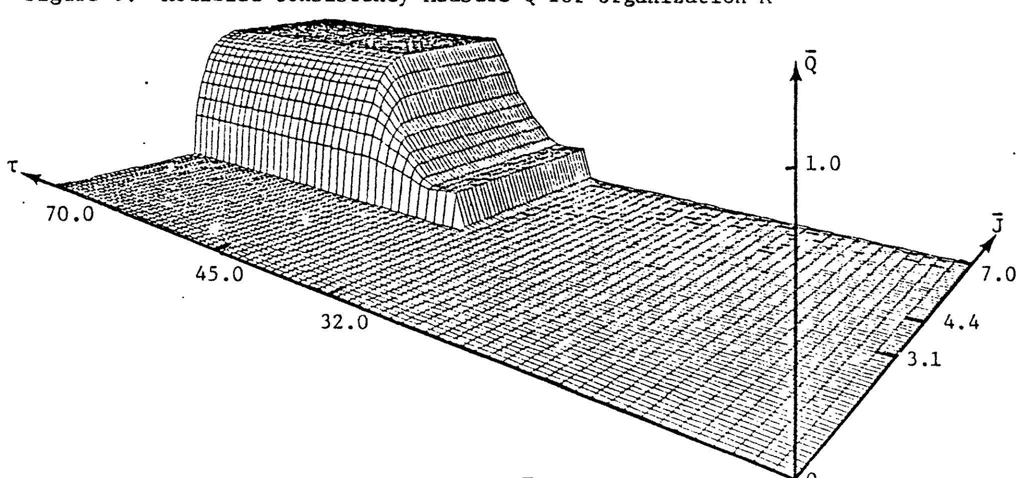

Figure 9. Modified Consistency Measure $\bar{Q}$ for Organization B

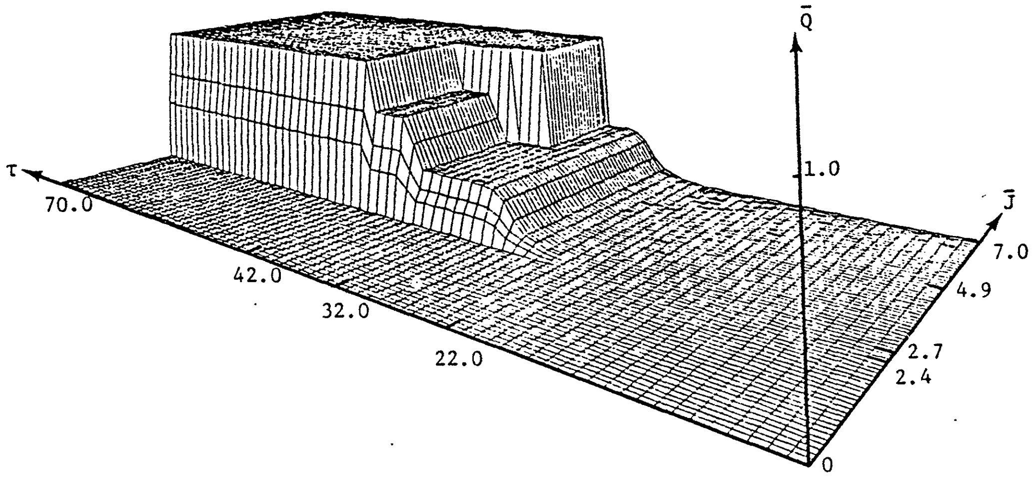

Figure 10. Modified Consistency Measure $\bar{Q}$ for Organization A: $p^1=q$; $q^1=p$

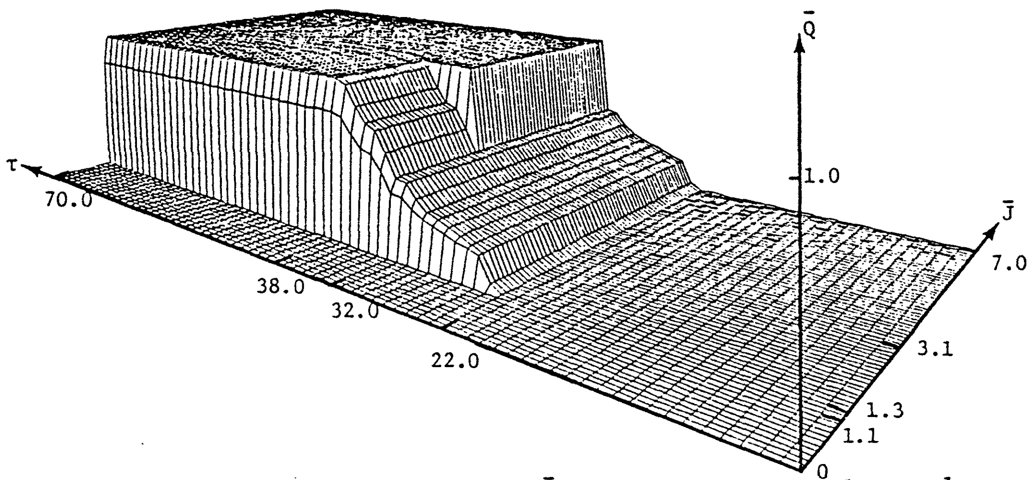

Figure 11. Modified Consistency Measure $\bar{Q}$ for Organization B: $p^1=q$; $q^1=p$

6.0 CONCLUSION

An approach to the evaluation of alternative organizational designs has been presented. The issues that arise when the designer's and the decisionmakers' knowledge of the tasks and of their relative value differ have been discussed. A measure of organizational effectiveness has been introduced for the case when the designer and the decisionmakers differ in their perception of the uncertainty associated with the inputs or tasks. Two three-person organizations, one with parallel structure and one with a hierarchical one, have been used to illustrate the approach.

One weakness of the procedure is that it requires substantial computational effort. Current research is focussed on analytical and computational properties that may yield efficient algorithms for determining the modified consistency measures.

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