

ACCURACY AND TIMELINESS IN DECISION-MAKING ORGANIZATIONS

by

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ABSTRACT

Two measures of performance, accuracy and timeliness of response, are introduced for information processing and decision-making organizations. Accuracy is computed by comparing the actual response of an organization to a given task to the desired response and assigning a cost to the discrepancy. Timeliness reflects the ability of the organization to produce a response within an allotted time determined by the task requirements. Delays in completing a task are due both to the time required for processing information and making decisions and to the time required to effect communications among decisionmakers. A simple model is introduced that models transmission delays. The method is applied to two organizational structures. The accuracy vs. expected response time locus is constructed and the accuracy-timeliness trade-off is investigated. The workload constraints on decisionmakers are considered in evaluating the two designs.

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1. INTRODUCTION

Organizations are formed when the task to be performed exceeds the capabilities of a single decisionmaker. Even when a single person can complete the task, he may not be able to produce a satisfactory response within the time limits imposed by the task. The organization designer is faced with the problem of designing an organization that will meet these design specifications and, in addition, assign subtasks or functions to members of the organization so that no one is overloaded. The design has to be robust to accommodate the different decisionmaking styles of different actual decisionmakers that may instantiate the organization at different times.

Consider, for example, the design of an air traffic control center for a busy airport area. The task cannot be done by a single controller; several controller stations may be required. The designer has to take into account the uncertainty that is inherent in the task and the need for accurate and timely responses by the controllers. But he also has to consider that different controllers will be on duty at any instant of time. While they are all well trained for their tasks, their actual information processing and decision making styles will differ.

The quantitative and qualitative analysis and evaluation of such task-oriented organizations has been the subject of recent research: Drenick (1986); Levis (1984). In the latter work, a model of the interacting decisionmaker with bounded rationality was introduced by Boettcher and Levis (1982) in which the individual members' cognitive workload was computed using n-dimensional information theory and the partition law of information (Conant, 1976). The organizational structure, i.e., the allowable interactions between decisionmakers and the protocols that govern them, is described using Petri Nets (Peterson, 1981; Tabak and Levis, 1985.) The use of Petri Nets has led to the development of an algorithm for the generation of all feasible organizational structures - organizations that meet certain structural and application-specific constraints (Remy, Levis, and Jin, 1987). It has also allowed the computation of organizational delays, the time from the moment a stimulus is sensed to the moment a response is produced (Jin, Levis, and Remy, 1986).

In this paper, a procedure is described for evaluating organizational designs and for carrying trade-off analyses. The approach is based on the ability to compute two measures of performance (MOPs): **Accuracy**, denoted by the performance index **J**, and **Timeliness**, denoted by **T**.

A method for the computation of the probability density function of the organization's response time is presented. The processing times associated with the individual functions are characterized by probability density functions. Therefore, the probability density function of the organization's response time is computed by performing convolutions for cascaded functions or processes and the appropriate computations for parallel processes. In this work, it is assumed that communication between decisionmakers is accomplished through electronic means and is, therefore, subject to jamming. A macroscopic model of communications jamming is presented, its effect on the transmission delays across communication links is computed, and its impact on the organization's response time is explored.

The methodology is applied to two organizational structures and the trade-off between accuracy and timeliness is investigated. The two organizations are evaluated taking into account the decisionmakers' workload (Levis and Boettcher, 1983)

2. ORGANIZATION MODEL

Decisionmaking organizations can be represented by Petri Nets [Peterson, 1981; Reisig, 1982]. In Petri Nets, there are two types of nodes: *places*, denoted by circles representing signals or conditions; and *transitions*, denoted by bars, representing processes or events. Places can only be connected to transitions, and transitions can only be connected to places. The execution of a Petri Net is controlled by tokens, which are denoted by dots in the circle nodes or places. A Petri net is said to execute when a transition fires. A transition can fire only when it is enabled. For a transition to be enabled, all its input places must contain at least one token each. When a transition fires it removes (consumes) one token from each input place and creates (deposits) a new token in each of the output places of that transition.

A transition may have more than one output places. However, to model decisionmaking, it is necessary to introduce a special transition, a *decision switch*, in which the output places represent alternatives (Tabak and Levis, 1985). When the decision switch fires, a token is generated in only one of the output places. A decision rule associated with this special transition determines the place in which the token is generated. The rule can be deterministic or stochastic; it can be independent of the attributes of the tokens in the input places or it may depend on them.

The basic model of the interacting decisionmaker with bounded rationality is based on the assumption that information processing is done in stages. This particular model consists of four stages or processes: the situation assessment (SA) stage, the information fusion (IF) stage, the command interpretation (CI) stage and the response selection (RS) stage (Boettcher and Levis, 1982; Levis and Boettcher, 1983). The Petri net of the interacting decisionmaker is depicted in Figure 1. In the SA stage, external inputs - data from the environment or other members of the organization - are processed to assess the situation. This information is transmitted to the IF stage where it is fused with situation assessments communicated by other organization members. The resulting situation assessment is used to select a response in the RS stage. The exchange of information between the situation assessment and the information fusion stages of different decisionmakers constitutes information sharing among them. On the other hand, the transmission of information from the response selection stage to the information fusion stage constitutes result sharing. If the interaction is between the RS stage of one decisionmaker and the CI stage of another, then the former is issuing a command to the latter. This last interaction imposes a hierarchical relationship between the two DMs: one is the superordinate and the other is the subordinate. It is also allowed to have the output of the RS stage of one decisionmaker be the input to the SA stage of another; this leads to serial structures and serial processing.

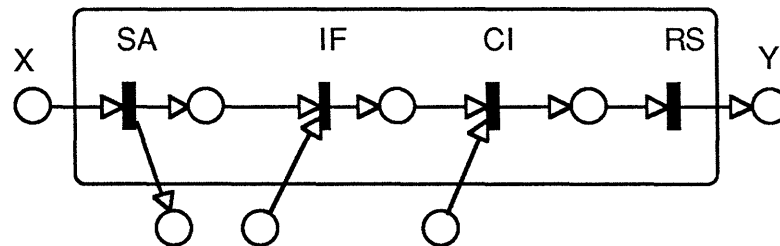


Fig. 1 Petri Net of the Interacting Decisionmaker

Workload represents the amount of mental effort expended by the decisionmakers in order to perform their assigned tasks. The analytical framework for the computation of a surrogate for workload is N-dimensional information theory (Reisbeck, 1963; Shannon and Weaver, 1963). This surrogate, denoted by G , is the total activity term in the partition law of information (Conant, 1976).

The value of G depends on several factors. First, it depends on the uncertainty of the organization's task, as modeled by the probability distribution $p(x)$ associated with the input set $\{x\}$. It depends also on the structure of the organization - the interactions among decisionmakers - and on the algorithms used to represent the various processing functions, such as situation assessment or information fusion. Finally, it depends on the internal decision strategies of each individual decisionmaker. Indeed, in the analysis of organizational performance that follows, for a given organizational design, the independent variables are the decisions of each decisionmaker and the dependent variables are the workload and the measures of performance.

The qualitative notion that the rationality of the human decisionmaker is not perfect, but is bounded (March, 1978), has been modeled as a constraint on the total activity G :

$$G \leq F \tau \quad (1)$$

where F is the information processing rate that characterizes individual decisionmakers and τ is the mean interarrival time of inputs or tasks. The designer's objective is to keep each organization member's workload below the threshold shown in eq. (1).

3. MEASURES OF PERFORMANCE

Two measures of performance are considered in this paper: accuracy and timeliness.

Accuracy quantifies the degree to which the actual organization response, Y_j , matches the desired or ideal response, Y_{dj} . For each input task x_i , a mapping $L(x_i)$ defines the desired response Y_{di} . A cost $c(Y_j, Y_{di})$ is assigned to the discrepancy of Y_j and Y_{di} (Levis, 1984) as shown in Fig. 2. This cost is computed for each input task, x , and each decision strategy. The accuracy measure J is the expected value of the cost and is computed using the probability distributions of the input tasks:

$$J = \sum p(x_i) \sum c(Y_j, Y_{di}) p(Y_j | x_i) \quad (2)$$

For each decision strategy, there is a corresponding value of J . Thus, the mathematical model of accuracy maps the decision strategies into the performance space.

Timeliness expresses the ability of organizations to respond to the input within the allotted time. Defined in simple terms, the allotted time is a time interval (T_{min}, T_{max}) . T_{max} is a time threshold such that if the organization issues commands in response to the input after the threshold, there will not be enough time left for the implementation of the response.

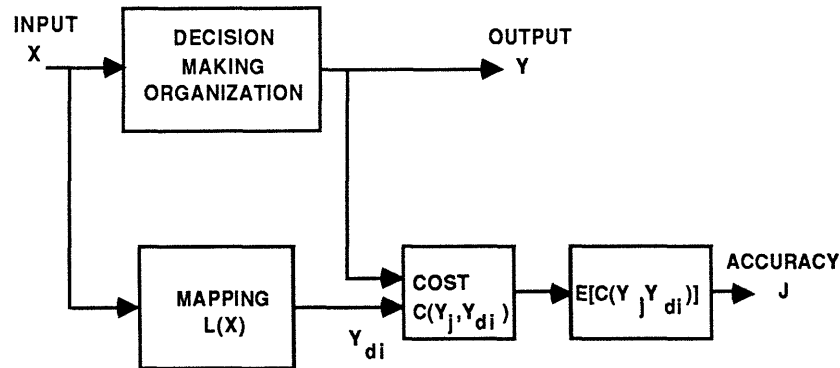


Fig. 2 Model for Evaluating the Accuracy Measure

The time delay or response time of an organization is the time elapsed between sensing the input and producing an output. The expected time delay (expected response time) is a measure of performance that can be used to assess the Timeliness of an organization's response. If the expected response time is within the interval (T_{\min}, T_{\max}) the performance is timely. However, this measure of performance does not take into account the variance of the response time. A better measure is the probability that the time delay, T_d , lies inside the interval (T_{\min}, T_{\max}) , i.e.

$$T = \text{Prob}(T_{\min} < T_d < T_{\max}) \quad (3)$$

This measure of performance is better than the expected time delay because it incorporates the effect of the time delay's variance. The probability density function (pdf) of the response time T_d must be computed in order to evaluate the measure T . To compute the pdf of the response time, all the information flow paths and the groups of concurrently active information flow paths in an organization must be identified.

In the Petri Net representation of an organization, the input (source) and output (sink) nodes are represented by places. Information flow paths are simple paths (Jin, Levis, and Remy, 1986) emanating from the input node and arriving at the output node. The presence of decision switches in the model of the decisionmaker, with the position of each switch determined by the internal decision strategies, results in some transitions being active during the processing of any task and in some being inactive. Therefore, for each decision strategy, some information flow paths are concurrently active while the other paths are inactive (not transmitting information). If each decision strategy D_i is implemented with a probability P_i representing its frequency of use, then each group of concurrently active paths, corresponding to a decision strategy D_i , is active with probability P_i . The simple paths and the concurrent paths are identified using an algorithm developed by Jin (Jin, Levis and Remy, 1986). If a pdf is assigned to the processing time of each processing algorithm (represented by a transition in the Petri Net), then the pdf of the response time of the organization is computed as follows:

For two cascaded algorithms with delay pdfs $f(t)$ and $g(t)$, the total delay is the sum of the two delays corresponding to the two algorithms. Therefore, the pdf of the total delay, $h(t)$, is given by the convolution of $f(t)$ and $g(t)$

$$h(t) = \int_0^t f(\tau) g(t-\tau) d\tau \quad (4)$$

For two algorithms with delay pdfs $f(t)$ and $g(t)$ on parallel concurrently active paths, the total delay is the maximum of the delays of the two algorithms. Hence, the pdf of the total delay, $h(t)$, is given by:

$$h(t) = f(t) G(t) + F(t) g(t) \quad (5)$$

where $F(t)$ and $G(t)$ are the cumulative distribution functions of $f(t)$ and $g(t)$ respectively.

For two algorithms with delay pdfs $f(t)$ and $g(t)$, that are substitutes for one another, and are active with probability p_1 and $p_2=1-p_1$, the total delay is the weighted average of the delays of the two algorithms. Consequently, the pdf of the total delay, $h(t)$, is given by:

$$h(t) = p_1 f(t) + p_2 g(t) \quad (6)$$

It is further assumed that communications among decisionmakers are not perfect. One way to model the effect of imperfect communications is to assume the presence of jamming. Jamming is viewed macroscopically and is quantified by a parameter, α , the degree of jamming, which varies between 0, corresponding to the absence of jamming, and 1, corresponding to total jamming. As the degree of jamming increases, the delay in transmitting a message increases; this is modeled by multiplying all transmission times of the jammed communication links by a factor k , where $k \geq 1$:

$$k = 1 / (1-\alpha) \quad (7)$$

Consequently, the mean of the pdf of the communications delay is also multiplied by k and the variance by k^2 . For example, for $\alpha = 0.5$ the value of $k = 2.0$, and for $\alpha = 0.9$, $k = 10.0$, i.e. there is a twofold and a tenfold increase in communication delays.

Therefore, the decision strategies, which can be represented by a locus in the decision space, can be mapped into the a locus in the Performance space, i.e., the space (J, T) , or the Performance - Workload space (J, T, G) . Different organizational designs can be evaluated and compared on the basis of their corresponding loci.

4. APPLICATION AND RESULTS

The application of the methodology for evaluating and comparing organizational designs will be illustrated with a simple air defense task. This is a refined version of the example used by Levis and Boettcher (1983). The task model allows for two types of threats A or B, with the restriction of a maximum of two threats being present at any instant of time. For completeness, a third one, C, has been introduced to indicate the absence of a threat, i.e., the null threat. The available

resources to the organization designer are three decisionmakers, two or three sensor systems and two or three weapons systems. There are three possible responses to the threat: a fast weapon, a slow one, or no response at all (null). The cost $c(Y_j, Y_{di})$ assigned to the discrepancy between actual and desired response is presented in Table 1.

TABLE 1 The Cost Matrix

Threat Response	A	B	C
Fast	0	4	5
Slow	4	0	1
Null	5	1	0

Two organizational structures were selected; one parallel and one hierarchical. The Petri Net representation of the two organizations is depicted in Figs. 3 and 4. The nature of the task is such that the decisionmakers must interact (share information) in order to accomplish their mission.

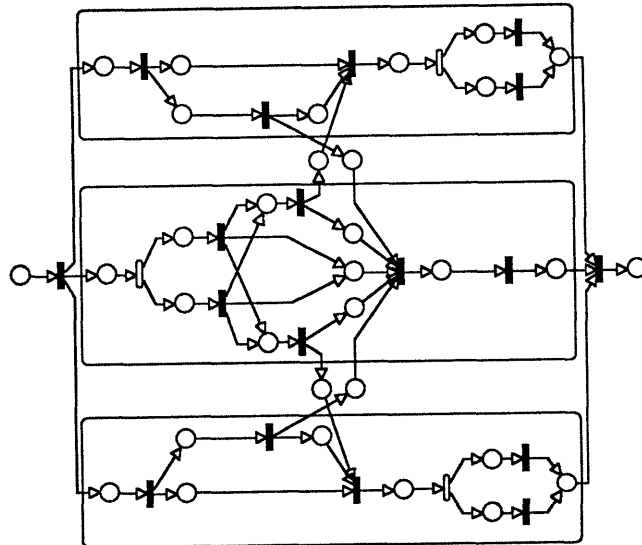


Fig. 3 Petri Net representation of the Parallel organization

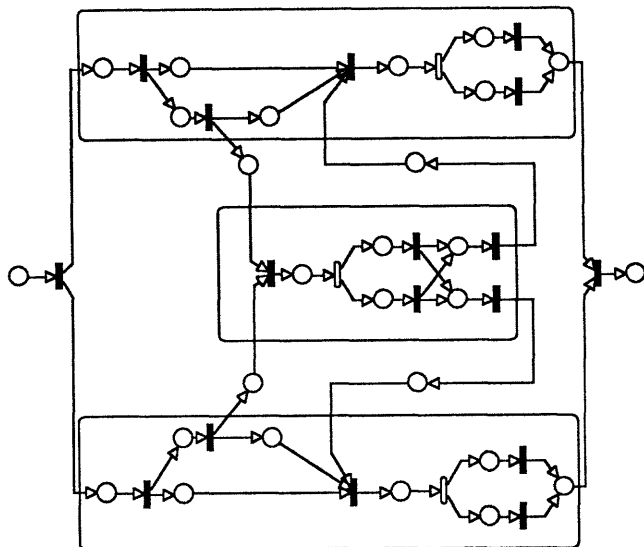


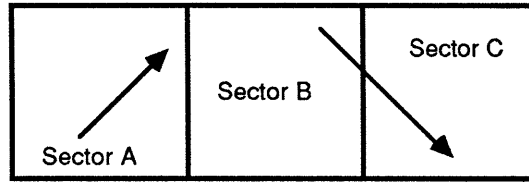
Fig. 4 Petri Net representation of the Hierarchical organization

In the parallel organization, the airspace has been divided into three sectors, with each decisionmaker assigned to one sector (Fig. 5a). Each decisionmaker can observe and engage threats in his sector. However, threats may move between sectors, therefore there is need for communications and information sharing between decisionmakers in adjacent sectors. In the hierarchical organization, the airspace is divided into two sectors and each sector is assigned to one decisionmaker (figure 5b). A center region is defined that straddles the two sectors and a supervisor is introduced, who does not observe the airspace directly, but receives information about the threats in the central region from the other two decisionmakers. He then processes the data and allocates the threats in the central region to either one of the decisionmakers, depending on the trajectory of the threat.

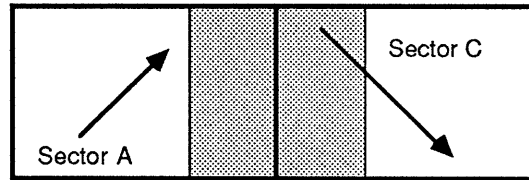
The accuracy J and workloads G of the three decisionmakers are computed for all decision strategies using algorithms, implemented in software, to simulate the decisionmaking process and the protocols in each organization.

The jamming model described in the previous section was used to study the effect of degradation in the communications on the timeliness of the two organizational structures. Software has been written to compute the probability density function of the transmission delay for several degrees of jamming (α) and then obtain the probability density function of the response time of both organizations for all decision strategies.

The computed pdfs of the response time for the two organization structures are depicted in Figures 6 and 7, for the decision strategies denoted by $p_1 = p_2 = p_3 = 0.5$, i.e., for use of the alternate algorithms in each DM model with probability 0.5.



(a) Three Sectors (Parallel)



(b) Two Sectors (Hierarchical)

Fig. 5 Division of Airspace

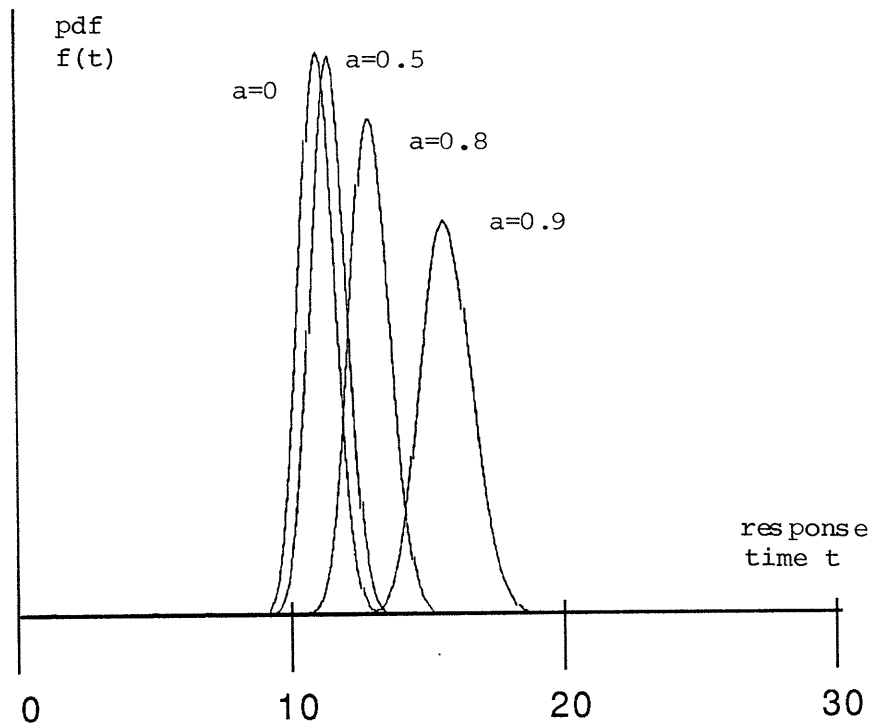


Fig. 6 Response time pdf for Parallel organization.

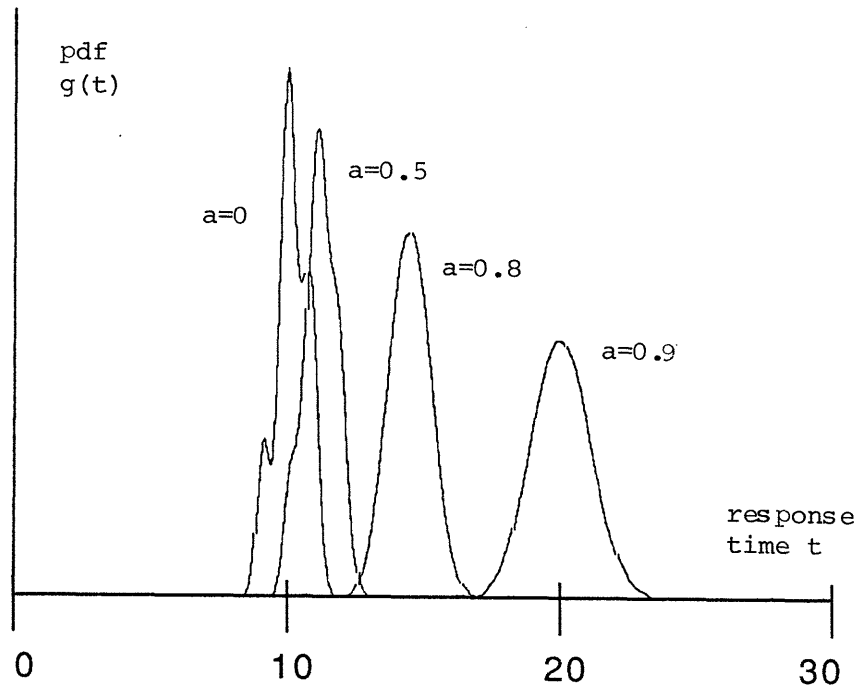


Fig. 7 Response time pdf for Hierarchical organization.

The results of the computations, i.e. the response time T , accuracy J , and the workloads G of the three decisionmakers, constitute a five dimensional vector for each decision strategy. As the decision strategy locus is swept, this vector traces the performance - workload locus of the organization. The locus can be seen by projecting it on any two or three dimensional subspaces.

The projections of the organization locus on the accuracy - timeliness dimensions for the parallel and hierarchical structures are shown in Figure 8. From the study of these projections it is observed that the hierarchical structure exhibits more timely response in the absence of jamming. As jamming increases, both organizations have comparable timeliness measures. For high degrees of jamming, the hierarchical has less timely response than the parallel structure. The reason is that there are two communication links on some information flow paths of the hierarchical structure and only one link on some information flow paths of the parallel structure.

Accuracy is comparable for both structures. The hierarchical can achieve slightly better accuracy. However, the approach illustrated in this section is based on comparing two organizational structures not on the basis of optimal performance (when each organization is using the optimal decision strategy,) but by comparing the whole performance locus. Indeed, comparison of optimal performance will lead to the conclusion that the hierarchical is better, since it can achieve higher accuracy than the parallel one. It can also achieve much worse accuracy, as shown in Figure 8. The parallel one, however, can achieve slightly lower accuracy at its optimal point, but its performance does not degrade very much with respect to the strategies used by the decisionmakers; it is a more robust design with respect to the variability in human decisionmaking.

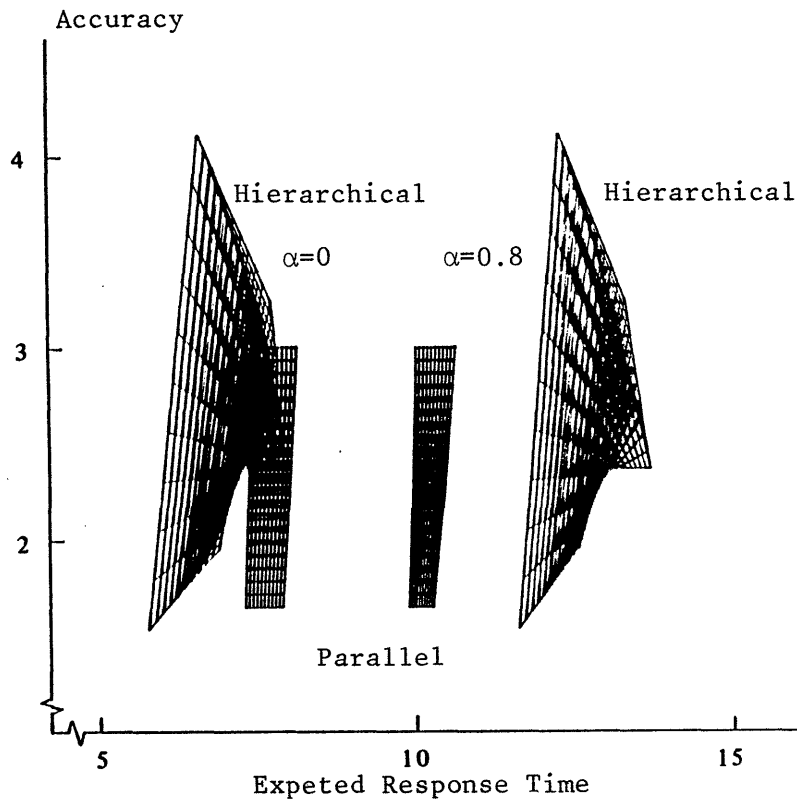


Fig. 8 Accuracy-Timeliness locus for Parallel and Hierarchical organization for degree of jamming $\alpha = 0$ and $\alpha = 0.8$.

The projection of the locus on the workload of decisionmaker A and decisionmaker B dimensions for the two structures are depicted in Figure 10. It should be noted that decisionmaker A and decisionmaker C perform identical tasks and have identical strategies and algorithms. Consequently, their workloads are identical, and the projections shown in Figure 9 contain all the information with respect to workload. The hierarchical is better than the parallel because the workload is more evenly distributed among the three decisionmakers. Decisionmaker B in the parallel organization is overloaded because he must communicate with both decisionmakers A and C, and process his own information. For stringent bounded rationality constraints, fewer operating points of the parallel organization satisfy the workload requirements than of the hierarchical one. At some threshold, the parallel has no admissible points, whereas, the hierarchical still has.

5. CONCLUSIONS

A method to compute the probability density function of the response time of decisionmaking organizations has been presented. A model to quantify the effect of jamming on the probability density function of the response time has been introduced. The approach used to simulate the decisionmaking process of organizations and to compute their accuracy and workload has been described.

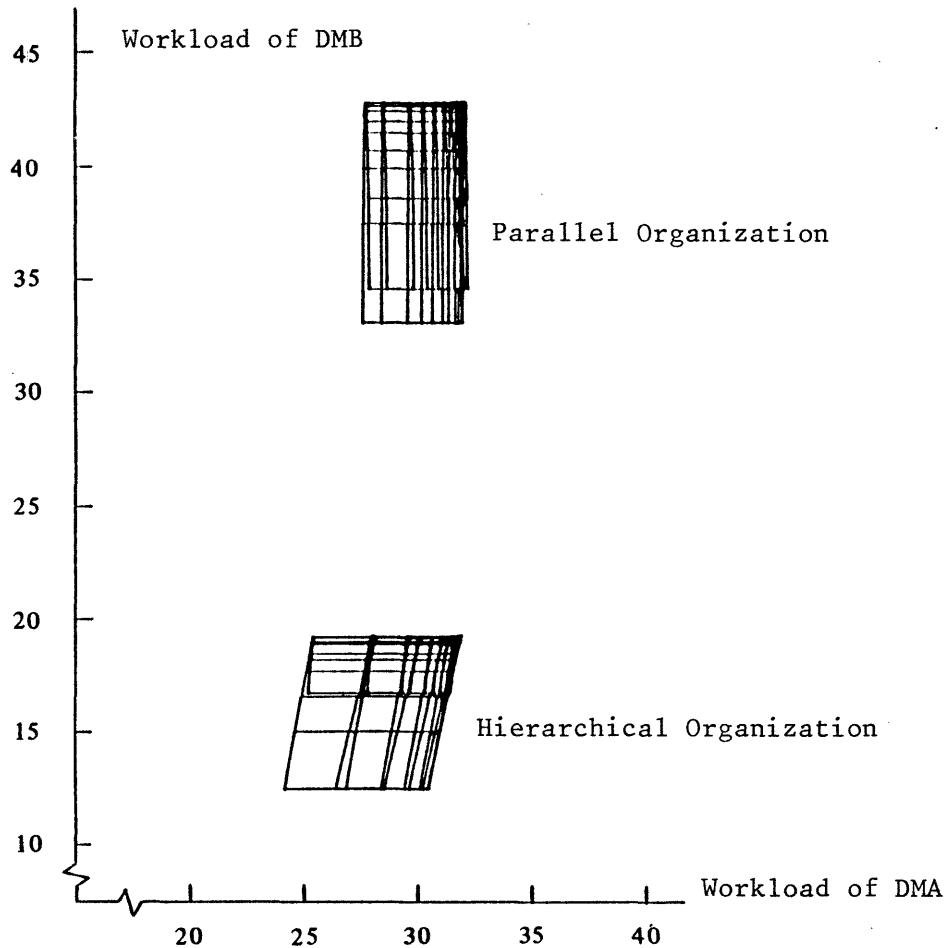


Fig. 9 Workload locus for Parallel and Hierarchical organizations

Two three-person organizations, one with a hierarchical and the other with a parallel structure, have been selected to illustrate the approach. The qualitative analysis of the results shows that it is not possible to determine the "optimal" organizational structure. Each structure has advantages and disadvantages; the choice of a particular design depends on the values of the parameters that characterize the task to be performed. For certain environments, the hierarchical is better; for others, the parallel is better. Comparing the two loci allows a clear view of the resulting tradeoffs.

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