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A design methodology for Command and Control organizations is introduced in which the data flow structure is determined first and then the decision-making organization design is obtained. The data flow structure design focuses on information processing schemata whereas the decision-making organization design focuses on the allocation of functions to the decisionmakers. Data flow structures are generated and are subsequently augmented and transformed into C^2 organizations. The candidate organizational designs are evaluated on the basis of their Measure of Effectiveness; and the design with the highest MOE value is selected. An example is used to illustrate the methodology.

I. INTRODUCTION

The design of Command and Control organizations must address a multitude of questions: specifically how to partition the task into subtasks; how many organization members to choose; how to allocate the subtasks to the various members; how to select the schema of information exchange among the members (protocols); what kind of communication harware is required for timely transmission of information and data in a given operating environment; what the structure of the required databases and the specifications of the respective harware should be; and how to design decision aids and allocate them to the decisionmakers (DMs). A methodology is presented that addresses these questions so that the design of Command and Control organizations becomes a structured process.

The properties that characterize a decision-making organization can be quantified by the corresponding Measures of Performance (MOPs). MOPs for C^2 organizations include accuracy, response time, task processing rate, and workload of the individual organization members.

Accuracy measures the degree to which the actual organization response matches the desired or ideal response. For each input task, a mapping known to the organization designer defines the desired response. A cost is assigned to the discrepancy between the actual and desired response. This cost is computed for each input task and each decision strategy. One accuracy measure is the expected value of the cost which is computed using the probability distribution of the input tasks [Levis, 1984].

Timeliness expresses the ability of C^2 organizations to respond to an incoming stimulus or task within the allotted time. The allotted time is a time interval (T_{min}, T_{max}) defined by the properties of the stimulus and the objectives of the C^2 organization. The threshold T_{max} is such that if the C^2 organization selects a response to the input after that threshold, there will not be enough time to execute (implement) the response.

The time elapsed between the instant an input is received and an output is produced by the C^2 organization is the Time delay or Response time. The expected time delay (expected response time) is a measure of performance that can be used to assess the timeliness of C^2 organizations. If the expected response time is within the interval (T_{min}, T_{max}), the C^2 organization's response is timely [Andreadakis and Levis, 1987].

The task processing rate of the C^2 Organization is defined as the processing rate that can be maintained without queueing of the input tasks, and without queueing of information at any stage of processing.

Workload represents the amount of mental effort expended by the individual decisionmakers in order to perform their assigned tasks. Since there is uncertainty associated with the stimuli (inputs) to the C^2 organization, decisionmakers must have available appropriate procedures to assess the situation and select a response. The model developed by Boetcher and Levis [1981, 1982] postulates that the decisionmaker is well trained and can select among several procedures in order to process the available information.

The analytical framework for workload computation is N-dimensional Information Theory. [Reisbeck, Shannon and Weaver, Conant]. A surrogate of the information processing workload is introduced which is quantified by the total activity. Since the decisionmakers are assumed to be limited in their capacity to process

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information and make decisions, a bounded rationality constraint has been introduced:

$$G/\tau \lesssim F_0 \quad [1]$$

where G is the total activity of the procedures performed by a decision-maker in bits/symbol, F_0 is the information processing rate that characterizes individual decisionmakers, in bits/sec, and τ is the mean time allocated to the decisionmaker to process each task in sec/symbol.

Measures of Performance (MOPs) are functions of the organization parameters. In the case of C^2 organizations, these parameters include the decisions of individual decisionmakers. If a decisionmaker has two procedures, Q_1 and Q_2, available for assessing the situation or selecting a response, his decision strategy is represented by the probabilities of using procedure Q_1 and Q_2, p_1 and $p_2 = 1-p_1$ respectively. These probabilities represent the relative frequency of use of the procedures.

The vector, whose elements are the decision strategies of all the decisionmakers of the organization, is the decision strategy of the C^2 organization. The set of all possible values of the decision strategies defines the decision space. To each such strategy corresponds a value of the vector of MOPs; the set of strategy values determines a set of values in the MOP space.

Measures of Effectiveness (MOEs) quantify the degree to which an organization (system) meets its requirements [Bouthonnier, 1982; Levis, 1986]. In order to assess the effectiveness of an organization, the organization's MOPs are compared to the organization's requirements for all decision strategies. Measures of Effectiveness (MOEs), quantities that result from this comparison, can be computed in the decision strategy space by identifying all decision strategies that satisfy the requirements. One possible Measure of Effectiveness is the ratio of decision strategies that satisfy the requirements to the total number of decision strategies.

II. PROBLEM FORMULATION

This paper introduces an approach to the design of Command and Control organizations using the following formulation of the design problem: Given a mission and a set of tasks to be performed, design a C^2 organization that is accurate, timely, exhibits a task processing rate that is higher than the task arrival rate, and whose decisionmakers are not overloaded.

These qualitative design requirements can be stated explicitly:

Accuracy greater than a threshold, or equivalently, expected cost J less than some threshold J_0 :

$$J < J_0 \quad [2]$$

Timeliness measure T less than some threshold T_0:

$$T < T_0 \quad [3]$$

Task processing rate R greater than task arrival rate R_0:

$$R > R_0 \quad [4]$$

The constraints that must be observed are that the decisionmakers not be overloaded, i.e the decisionmakers' information processing rate F be less than the rationality threshold F_0:

$$F < F_0 \quad \text{for every decisionmaker} \quad [5]$$

III. DESIGN METHODOLOGY

The design methodology has four phases (Fig. 1): in Phase 1 an algorithm for generating data flow structures produces a set of candidate designs, from which a few representative ones are selected. In Phase 2, the activity of the individual functions or processes, the accuracy, the processing time, and the processing rate of each data flow structure are computed. In Phase 3, each data flow structure is augmented and transformed into a C^2 organization in which the functions have been allocated to decisionmakers and the communication protocols have been designed. In Phase 4, the evaluation of the measures of performance of each C^2 organization is performed and then the respective measures of effectiveness are computed.

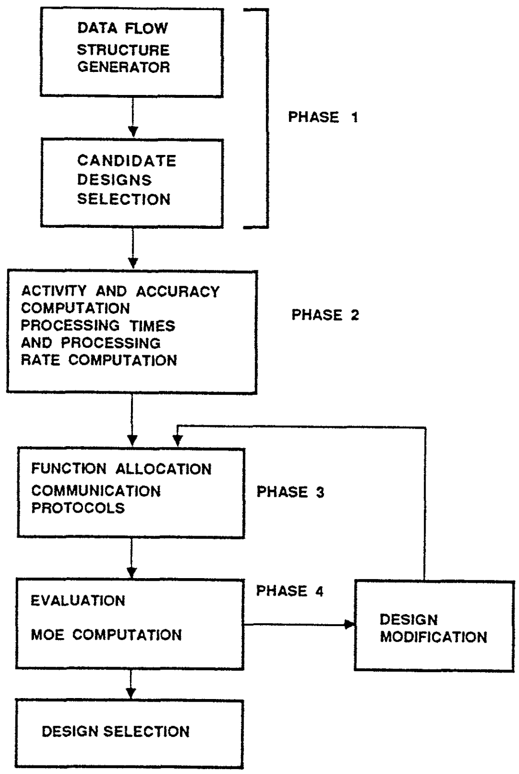

Figure 1. Design Methodology Flowchart

The designs obtained in this matter are revised to increase their measure of effectiveness by introducing decision aids, changing the function allocation, or modifying the protocols. The introduction of the hardware and its associated software (the command and control system), i.e. the specifications for the required decision aids and databases as well as for the communications links, transforms each decision-making organization into the corresponding Command and Control organization.

Finally, a Command and Control organization is selected from the candidate designs on the basis of the greatest MOE value.

Phase 1: Data flow structure generation

The Petri Net formalism is used to represent the data flow structures. The processing stages are represented by transitions, whereas the data or information that are input or output of the processing stages are represented by places. The availability of data or information at specific places of the Petri Net is represented by the existence of tokens in the respective places. In order to describe the information processing, the following stages are introduced:

Initial processing [IP]: this stage receives data from the sensors and performs preliminary situation assessment.

Data fusion [DF]: this stage receives and combines (fuses) the results of IP.

Middle processing [MP]: this stage follows the DF stage and performs situation assessment.

Results fusion [RF]: this stage combines the results of several MP stages.

Final processing [FP]: this stage operates on the outcome of the RF stage and selects a response, i.e., it produces an output.

Interactions between stages

In order to design a data flow structure, the permissible interactions among processing stages must be established. These are:

IP → DF or IP → RF
DF → MP or DF → FP
MP → RF
RF → FP

It should be noted that more than one IP node can be connected to one DF node or one RF node and more than one MP node can be connected to one RF node, whereas exactly one MP node can follow each DF node and exactly one FP node can follow each RF node or DF node.

Thus, the permissible information flow types are (Fig. 2):

IP → DF → MP → RF → FP	flow type 1
IP → DF → FP	flow type 2
IP → RF → FP	flow type 3

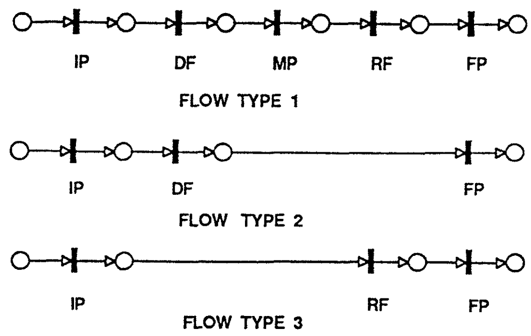

Figure 2. Information Flow Types

Classification of data flow structures

The classification is performed on the basis of the data flow types that are present in the data flow structure. The feasible combinations and the corresponding classes thus defined are:

pure flow type 1: class 1
pure flow type 2: class 2
pure flow type 3: class 3
combination of flow type 1 and flow type 2: class 12
combination of flow type 1 and flow type 3: class 13 (indistinguishable from 12)
combination of flow type 1, flow type 2, and flow type 3: class 123.

The combination of flow type 2 and flow type 3 is not feasible. Given a class and the number of inputs, the data flow structures of the class are characterized by two parameters: the degree of complexity and the degree of redundancy.

Degree of complexity of a data fusion [DF] node (or results fusion [RF] node) is the number of initial processing [IP] nodes (middle processing [MP] nodes) that are connected to the fusion node. The term complexity is justified by the observation that the more data that are fed to a data fusion [DF] node, the more complex the middle processing [MP] is. Similar considerations apply to the results fusion [RF] and final processing [FP] nodes.

Degree of complexity of the DF stage (or RF stage) is the maximum of the degrees of complexity of the individual DF (RF) nodes.

Degree of redundancy of an initial processing [IP] node (or middle processing [MP] node) is the number of data fusion [DF] nodes (result fusion [RF] nodes) that receive data (results) from the same initial processing IP (middle processing MP) node. The term redundancy is justified by the observation that the same information is communicated to more than one processing paths of the data flow structure.

Degree of redundancy of the DF stage (or RF stage) is the maximum of the degrees of redundancy of the individual IP (MP) nodes corresponding to the DF (RF) stage.

If the structure has both data fusion and results fusion stages, two degrees of complexity and two degrees of redundancy are required for its characterization. Figures 3 and 4 depict two class 2 structures, with seven inputs each. In Fig. 3 the degree of complexity c is 2 and the degree of redundancy r is 2, whereas in Fig. 4 the degree of complexity c is 3 and the degree of redundancy r is 3. In both cases, all fusion nodes have the same degree of complexity and the same degree of redundancy. This need not be the case, in general.

In order to generate candidate data flow structures from each class, the ranges of the degree of complexity and the degree of redundancy for the DF and RF stages must be specified. These are selected by considering the adaptability of the data processing functions required by the task to the processing schema represented by the data flow structure, as well as the minimum connectivity requirements to meet survivability.

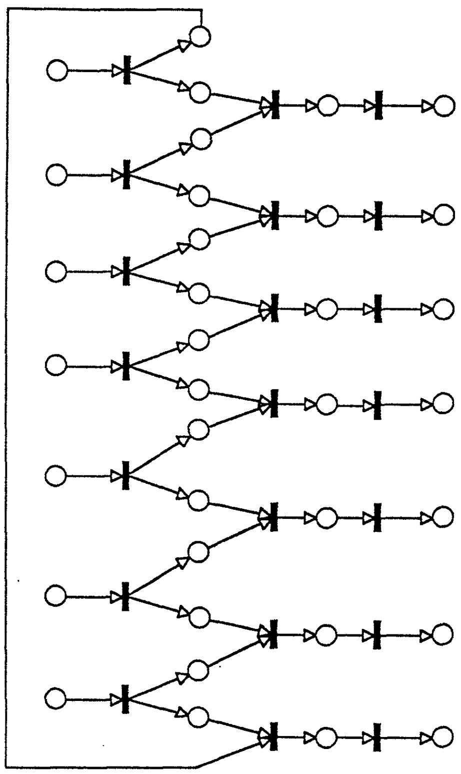

Figure 3. Class 2 Structure, c=2, r=2

Once these ranges (c_{df1}, c_{df2}), (r_{df1}, r_{df2}), (c_{rf1}, c_{rf2}) and (r_{rf1}, r_{rf2}), have been selected, all structures with

$$r_{df1} \leq r_{df} \leq r_{df2} \quad [6a]$$

$$c_{df1} \leq c_{df} \leq c_{df2} \quad [6b]$$

$$r_{rf1} \leq r_{rf} \leq r_{rf2} \quad [6c]$$

and

$$c_{rf1} \leq c_{rf} \leq c_{rf2} \quad [6d]$$

are generated. Having selected the candidate data flow structures, the design proceeds with Phase 2 which computes the MOPs of the data flow structures.

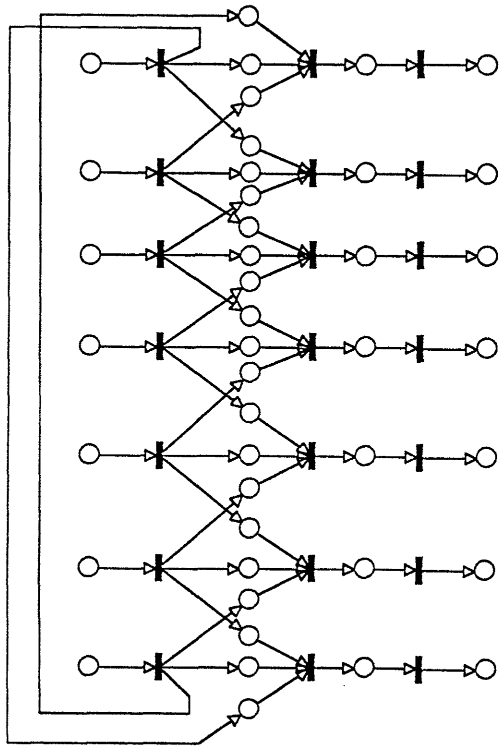

Figure 4. Class 2 Structure, c=3, r=3

Phase 2: MOP computation for the data flow structures.

The objectives of the second phase are to compute the total activity and, therefore, an estimate of the processing time of each function, the accuracy of the response, and an estimate of the processing rate range of the data flow structure. In order to compute these quantities, the algorithms that perform the data processing must be developed and be implemented in software.

The computation of total activity of the functions is based on the Information theoretic model [Boettcher and Levis, 1982]. The entropy H(w) of the discrete random variable w is defined as:

$$H(w) = - \sum_i [pr(w=w_i) \log pr(w=w_i)] \qquad [7]$$

If the base of the logarithm is 2, then the entropy is measured in bits. The total activity G of a function implemented by one algorithm is:

$$G = \sum_i H(w_i) + H(x) + H(y) \qquad [8]$$

where x is the input, y is the output, and $\{w_i\}$ are the internal variables of the algorithm.

If two algorithms can be used alternatively to implement the function, then the total activity of the function is:

$$G = p_1 G_1 + p_2 G_2 + a_1 H(p_1) + a_2 H(p_2) + H(x) + H(y)$$

where p_1 and p_2 are the probabilities of use of algorithms 1 and 2, $p_1+p_2=1$, G_1 and G_2 are the total activities of algorithms 1 and 2, a_1 and a_2 are the number of internal variables of algorithms 1 and 2, and H is the entropy of a binary variable.

In order to compute these entropies, the probability mass functions of these variables must be obtained. This computation is performed by simulating the decision-making process and keeping track of the values obtained by the variables and their respective frequency. At the same time, the accuracy of the response is computed. Then a representative value F_0 of the processing rate of the human decisionmaker is selected and the processing time T_i of function i is computed.

$$T_i = G_i/F_0 \qquad [9]$$

The processing times thus obtained are subsequently used in the computation of the response time of the organization, the timeliness measure(s), and the processing rate. Therefore, the workload constraints will be satisfied because the C^2 organizations that will be developed from these data flow structures have been designed so that enough time is allowed for the decisionmakers to execute their assigned tasks.

Next, an estimate of the processing rate range is computed as follows: The processing rate r_i of transition (function) i is :

$$r_i = F_0/G_i \qquad [10]$$

Assuming that each transition is assigned to a different decisionmaker, the maximum processing rate of the data flow structure is equal to the minimum of the processing rates of the individual transitions. Information flow paths are the paths on the Petri Net that emanate from the input and terminates at the output. The processing time along each information flow path is the sum of the processing times of the transitions that belong to the path. The inverse of the maximum processing time is the minimum processing rate of the data flow structure. The processing rate range thus obtained is only an estimate of the range of the Decision-making organization, since it does not take into account the delays along the communication links that will be introduced in Phase 3.

If the task arrival rate is less than the minimum processing rate, the C^2 organization that will be designed from the data flow structure is likely to satisfy the processing rate requirement. If the task arrival rate is greater than the maximum processing rate, multiple processing channels, which are copies of the basic data flow structure must be introduced, so that the arriving tasks can be assigned to alternate channels of the C organization.

Phase 3: Transformation of data flow structures into C^2 organizations.

In Phase 3, each candidate data flow structure is augmented and is transformed into a decisionmaking organization. During this phase, functions are allocated to the decisionmakers, the required communication processes are introduced and represented by transitions on the Petri Net, and finally the protocols for information exchange among decisionmakers are selected (synchronous vs asynchronous).

Function allocation: Functions allocated to a decisionmaker must observe 3 requirements: (1) They must be related through an input-output relationship, i.e. the output of one function must be the input to the next function perfomed by the decisionmaker so that each decisionmaker processes information relevant to the same subtask; (2) They must belong to different slices on the Petri Net so that they observe concurrency; and (3) They must conform to the specialization of the respective decisionmaker.

Requirements 1 and 2 are satisfied by functions that are on the same information flow path; thus only functions that belong to the same information flow path are considered for allocation to a particular decisionmaker. When such a set of functions is allocated to a decisionmaker, a resource place [Hillion , 1987] is introduced that is an output place of the last and an input place to the first transition allocated to the decisionmaker.

Phase 4: MOPs and MOE evaluation for the C^2 organizations.

In Phase 4 the computation of the measures of performance of the candidate desisionmaking organization designs is performed. Specifically the Accuracy J, Timeliness T and Processing Rate R are computed. Then the Measure of Effectiveness of each design, defined in the decision strategy space as the ratio of the number of decision strategies that satisfy the requirements to the total number of decision strategies, is computed. If the MOE is not satisfactory,iterations are performed to modify the design so that the MOE value is increased. The modifications may include alternative function allocation, introduction of decision aids and databases and revision of the communication protocols. Finally the design having the highest MOE value is selected.

IV. EXAMPLE: NAVAL ANTI AIR WARFARE

The objective in this case is to design the Command and Control organization for naval anti air warfare.

The inputs to this organization are: data from airborne radar, from friend-foe-neutral identification, and from radar on the platform. The outputs of the organization are: commands for aircraft deployment and commands for missile deployment. The computations of the MOPs of the data flow structure in phase 2 and the MOPs of the decision-making organization in phase 4 follow the procedure presented in Andreadakis and Levis [1987]. To illustrate the design methodology, the data flow structures of phase 1 and the operations of phase 3 that transform the data flow structure into a decisionmaking organization are shown in Fig. 5 through 8. In Figure 5, a class 1 data flow structure is depicted, in which all information flow paths are of flow type 1, whereas in Figure 6, a class 2 data flow structure is shown, in which all information flow paths are of flow type 2. These are two representative flow structures that have been selected at the end of Phase 1.

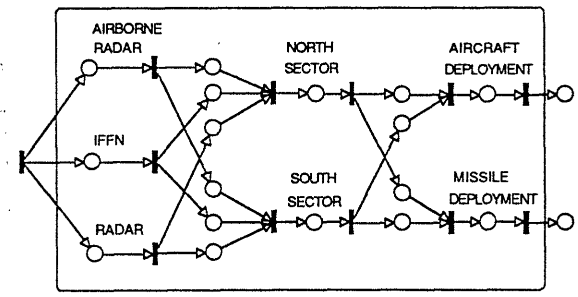

Figure 5. Class 1 Structure for AAW

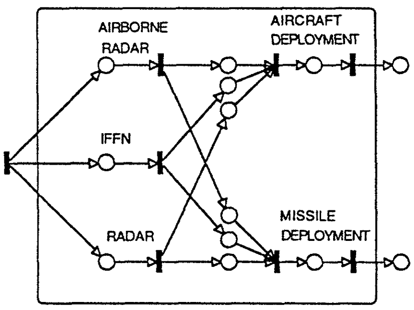

Figure 6. Class 2 Structure for AAW

In Figure 5, data from the three inputs are fused in two DF nodes.The fact that there exist data from three inputs that can be fused, leads to the selection of a degree of complexity, c, for the data fusion stage equal to 3.

The degree of redundancy for the data fusion stage depends on the requirements on survivability of the C^2 organization as well as the number of assets that are available for the task (in this case the number of platforms). If the degree of redundancy r is set to r_0, then the data will be fused in r_0 fusion stages that can be interpreted to correspond to r_0 sectors of the air-space. In this example the redundancy r for the DF stage is 2 corresponding to a north and a south sector.

The results of the middle processing stage are the determination of the assets to be deployed to each sector to respond to the situation. Thus, if the assets are common to all sectors, the results fusion has a degree of complexity c equal to the number of sectors. If it is desirable to allocate dedicated assets to groups of sectors, then the degree of complexity of the results fusion stage for such a group will be equal to the number of sectors in each group. In the example depicted in Fig. 5 the degree of complexity c of the RF stage is 2.

The degree redundancy of the RF stage depends again on the nature of the assets and their capabilities. Since there are two kinds of assets, aircraft and missiles, the results fusion stage may have a degree of redundancy of 2. In the example depicted in Figure 5, the degree of redundancy of the RF stage is 2; and reflects the fusion of the results in two RF stages corresponding to two asset allocation functions, namely aircraft deployment and misile deployment.

Finally, in Figure 6 a class 2 structure is depicted. Data from the three sources are fused in two DF nodes. One FP node processes the information to deploy aircraft, whereas the other FP node processes the information to deploy missiles. In this example, c = 3 and r = 2.

The difference between the two structures is the existence of the middle processing nodes, which represents the task subdivision into north and south sectors, and the results fusion nodes in the class 1 structure.

Figures 7 and 8 illustrate the operations required for the transformation of the data flow structure into a decisionmaking organization. In Fig. 7, one possible function allocation is depicted. The introduction of the availability place for each decisionmaker represents the fact that a decisionmaker is limited in the number of tasks that he can perform at any time. The maximum number is denoted by the initial number of tokens in the availability place. In Fig. 8, the communication processes are represented by the introduction of one transition for each process and the appropriate places that represent the protocols (in this case digital links and asynchronous protocols).

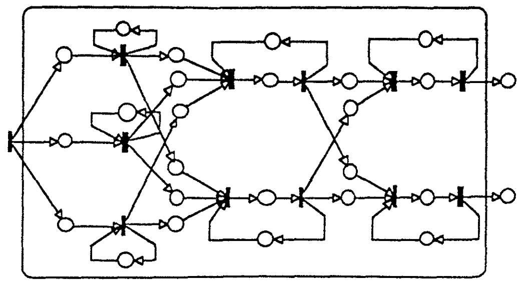

Figure 7. Function Allocation to Decisionmakers

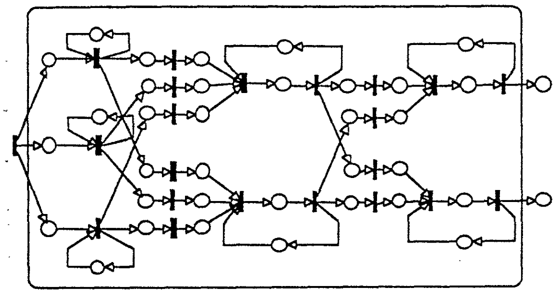

Figure 8. Inroduction of Communication Links

V. CONCLUSIONS

A methodology has been developed which provides a structured procedure for the design of Command and Control organizations, and for the specification of the hardware and software (decision aids, databases and communications links) that are required for its support.

The methodology tackles the design problem at two levels: the data flow structure level and the organization level. The importance of this differentiation is the ability to generate and classify structures parameterized by the complexity and redundancy of the information processing. After the generation of the candidate data flow structures, the methodology addresses the allocation of functions to organization members and the selection of the supporting system.

In this respect the methodology is a flexible top-down approach to the design problem, that results in the expansion of the set of candidate architectures. Another benefit from the top-down approach is that the requirements and specifications for decision aids, databases and communications equipment are derived through the objective evaluation of the effectiveness of the C^2 organization.

Finally the distinction between the data flow structure and the decision-making organization design, introduces two opportunities for the fine-tuning of the C^2 organization: one at the data flow level and one at the decisionmaker and system level.

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