Analytic Model Driven Organizational Design and Experimentation in Adaptive Command and Control*

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Abstract

The purpose of this paper is to present a methodology for the design of experiments to examine organizational behavior of command and control teams operating in a complex mission environment. This methodology can be used to design an executable model for human-in-the-loop model-based experiments that provide the necessary empirical components for current and future research in adaptive C2 architectures.

1. Motivation

Today's revolution in information technology is changing the way people within military organizations interact and deal with conflicts. Indeed, the changing patterns of potential threats and conflicts in today's world require a strong military capability that is sufficiently versatile to execute a national strategy across a full range of operations - to include war and operations other than war. Advanced information systems and capabilities must be tailored to support new military Command and Control (C2) roles and requirements. In view of such demands on modern C2 decision-making systems, experimentation is put forth as a way to examine human decision-making and coordination processes and to identify organizational structures that lead to superior performance.

While drawing inferences from empirical data is an important element in gaining scientific knowledge, in many cases the large cost associated with experimentation makes it impractical to rely on inductive reasoning only. This is especially true when dealing with organizational behavior of human teams designed to operate in a complex multi-task mission environment. The high cost of experimentation demands a skillful experiment design. Furthermore, in order to formulate the hypotheses to be tested empirically, one needs to identify (as well as understand) the key variables of the underlying system structure. Thus, to design an experiment, a normative model of the process is needed to formulate the hypotheses, to devise organizational structures, and to develop a set of measures to characterize various dimensions of organizational performance. The challenge facing the scientific community is to develop and empirically validate theories and models of human decision-making in distributed systems - models that could ultimately contribute to design modifications that enhance the overall human-machine system performance.

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2. Organizational Design Problem

Over the years, research in organizational performance has demonstrated that a strong relationship exists between the specific structure of a task environment (i.e., mission) and the concomitant organizational design. Subsequently, the *optimality* of an organizational design depends on the actual mission parameters (and organizational constraints) – i.e., there is no universally "best" organization. This premise has led to the application of systems engineering techniques to the design of human organizations.

The systems engineering approach to organizational design is as follows. First, a quantitative model describing the mission and the organizational constraints is built. Then, one or more objective functions for the design are specified, and an organization is designed to optimize the objective function(s). When the objective function includes several non-commensurate criteria, the organizational design problem is treated as a multi-objective optimization problem.

3. Modeling Paradigm

The power of quantitative modeling lies in its ability to describe the structure of a mission and of an organization by a relatively limited set of fundamental elements (or entities), parameters, variables, laws, and principles. The last two specify the functional interdependencies among the structural elements and the dynamics of system parameters and variables.

It is easier to establish functional reciprocity between the structures of a mission and of an organization if both are modeled in a unified manner. The *sine qua non* duality in modeling a mission and an organization can be achieved, for example, by employing graph formalism to describe both structures. The graph formalism has the advantage of representing the internal system dependencies in a concise, illustrative, and numerically efficient way. In addition, use of color-coding allows the graphical model to reveal more than just quantitative aspects of a system.

When modeling a mission or an organization, the designer must take into account the complexity of the underlying problem, as well as the computational resources available to "solve" the mathematical models. The degree of granularity of a model must be adjusted to allow for real-time solution of the resulting design problem. In addition, different modeling techniques (e.g., different ways of decomposing a mission into its constituent tasks) will generally result in different mission models, and ultimately may lead to different organizational designs. Thus, adopting the "right" models of a mission and an organization is the first essential step toward designing truly optimal organizational structures.

3.1 Representing Mission and Organization

3.1.1 Modeling a Mission

Over the years, research in team decision-making has demonstrated that an organization operates best when its command and control architecture - its organizational structure and processes - fits, or matches, the mission task environment. Consequently, it has been concluded that the optimality of an organizational design ultimately depends on the actual mission structure. Hence, devising an analytical model of the mission is the first step toward designing an optimal C2 organization.

Devising an analytical model of the mission implies the identification of a set of fundamental mission elements (*entities*), the functional *interdependencies* of their *attributes*, and *principles* governing the evolution of the attributes over time. A fundamental question underlying a distributed organizational design - '*who should do which part of the mission*?' - implies that the mission must be decomposable into a set of tasks. Although a task constitutes an essential mission entity, elements that determine the structure of the mission are, in general, not limited exclusively to tasks. Mission entities can stipulate the natural domain, as well as the external objects, conditions, and processes that influence the dynamics of the mission (e.g., terrain, weather, road network, population areas, enemy platforms, neutral objects, and so on).

Every task in itself represents a "small mission", and can oftentimes be further decomposed into more elementary tasks, thus increasing the number of mission entities and, consequently, the complexity of the model. The number of mission entities determines the granularity of the model; it must be adjusted to allow for an efficient computational solution of the resulting design problem.

The identification of mission entities and their attributes can be derived from a verbal description of a mission. In addition, a variety of modeling techniques (e.g., Object Oriented Modeling (OOM); Entity Relationship (ER) [Elmasri *et al*., 1994]; Integrated Definition (IDEF) Modeling [NIST, 1993a and 1993b]; Relational Database Design (RDD)) can be applied to capture the internal structure of a mission. One of the most popular modeling methodologies employs a graph formalism to describe the mission structure. The graph formalism may be used to construct various *dependency diagrams* to specify different dimensions of the mission structure and its evolution over time (e.g., an entity relationship diagram, a task precedence diagram, a data-flow diagram, and so on).

We conclude that devising an analytic model of a mission requires the identification of: (i) *entity types*; (ii) *attribute types*; and (iii) *relationship types*. To identify the entity types, different *mission decomposition techniques* can be applied. After distinguishing a set of tasks and objects that represent mission entities, a modeler specifies their attribute values, and formulates quantitative interrelationships among the attributes via *equations*. To complete the analytic model of a mission, various *dependency diagrams* are constructed to delineate the principles governing the joint evolution of attributes over time.

While many different models of the mission can be constructed, it is important to select the "right" model that highlights those dimensions of the mission structure that are the most relevant to the prospective organizational design process. Thus, a comprehensive mission modeling process consists of the following steps:

- choosing an appropriate mission task decomposition(s) and identifying the mission tasks;
- specifying the task attributes;

- representing functional dependencies among the task attributes via equations;
- constructing the task dependency diagrams.

3.1.2 Defining Organization

One of the goals in studying C2 team decision-making is the development and subsequent validation of theories and models that could ultimately suggest organizational design modifications to enhance the overall human-machine system performance. The application of systems engineering techniques to modeling and design of organizations allows one to establish a mathematical framework for optimizing *predicted* human team performance.

The problem scope and complexity faced by large-scale C2 systems that involve humans, machines, computers, networks, and databases interacting within an organization often require that the decision-making and operational functions be *distributed* over several human subjects. Thus, a characteristic feature of such systems is the presence of *teams* of human decision-makers (DMs), who, while geographically separated, must coordinate their information, resources, and activities in order to achieve their common goal in what is generally a complex, dynamic, and uncertain mission environment.

Since the decision-making and operational capabilities of a human are limited, the distribution of *information*, *resources*, and *activities* among DMs must be set up accordingly, with the decision-making and operational load of each DM remaining below the corresponding thresholds. For example, when the overall information available to a team during the mission overwhelms the information processing capabilities of an individual DM, the team's information acquisition and decision-making must be decentralized so that operators can focus on their local/relevant information.

As a consequence of decentralization in large-scale systems, each DM only has access to a portion of the information available to the team. Moreover, in realistic situations, the total information set may be incomplete and inaccurate due to lax updating, missed detection of events, information whose quality changes with time, and errors in data taking. Hence, team information processing is characterized by a high level of uncertainty with partial overlap of information among DMs. The critical issues in team *information processing* are: *who* should know *what*, *who* should communicate *what* and with *whom*, and *when* people should and should not communicate?

The total decision-making and operational load is generally partitioned among DMs by decomposing a mission into tasks and assigning these tasks to individual decision-makers who are responsible for their planning and execution. Moreover, an overlap in task processing (wherein two or more DMs share responsibility for a given function/task while each possesses the capability to process the task) gives the team a degree of freedom to adapt to uneven demand by redistributing load. The critical issues in team *task processing* are: *what* should be done, *who* should do what, and *when*?

In general, decision-makers are provided with limited resources with which to accomplish their objectives either in information processing or in task processing. The distribution of these resources among DMs and the assignment of these resources to seek information and to process tasks are key elements in an organization's design. Team members must dynamically coordinate their resources to process their individual tasks while assuring that team performance goals are met. The critical issues in team *resource allocation* are: *who* should own or transfer a specific resource, *when*, and *for how long*?

The tentative classification of a DM's mission processing activities *into decision-making* and *operations* can be further expanded, and the corresponding thresholds can be estimated. For example, activities such as communication, target detection, external information release, platform maneuvering, firing weapons, and so on, - all represent various dimensions of a DM's load. The interdependencies among the levels of the thresholds corresponding to these dimensions of a DM's workload delineates one of the key *principles* describing the behavior of a human DM. When a modeler needs to emphasize the individual differences among DMs, he can do so by specifying an *expertise* level of each DM with respect to a particular DM activity. For example, the expertise can be specified by stating the likelihood(s) that a DM can solve "model" problem(s) using the necessary resources and maintain the required speed of task processing.

The *sine qua non* duality in modeling a mission and an organization can be observed by recognizing that it is impossible to classify all DM activities without the knowledge of the type of mission that the organization will be facing. In turn, to decompose a mission into tasks requires the knowledge of resources available to an organization. Hence, it is important that the modeling of both the mission and organization be carried out simultaneously to elucidate the functional reciprocity between the two structures.

While organizational design specifies the distributed nature of mission processing by assigning each DM his share of information, resources, and activities, a command *hierarchy* among DMs designates their *control responsibilities* (through command authority) and regulates the inter-DM *coordination* (by assigning the responsibility of resolving decision ambiguities among coordinating DMs). In addition, organizational design can specify a *communication structure* among DMs (e.g., a communication net) to facilitate distributed information processing required to complete the mission.

In summary, when modeling an organization, we differentiate two classes of *entities*: (i) *decision-makers* (DMs) and (ii) *resources*. The key *attributes* in modeling a DM are the individual DM *thresholds* with respect to particular DM activities (e.g., information processing and operational activities). The interdependencies among the thresholds corresponding to different dimensions of a DM's workload explicates the *principles* governing the joint evolution of DM's attributes. In the model of an organization, the classification of *resource entities* can be further expanded (e.g., platforms, machines, computers, networks, databases, etc.), with their attributes specified accordingly. Hence, a comprehensive model of an organization includes:

- a specified (maximal) number of available decision-makers (DMs);
- a classification of a DM's activities, with a specification of the corresponding thresholds and their inter-relationships;
- a classification of resources, together with their numerical attributes.

For a given mission structure, including mission decomposition into constituent tasks, and organizational constraints, a distributed organizational design must delineate:

- a coordination structure among DMs;
- a DM-resource allocation;
- a DM-task processing assignment/schedule.

3. 2 Functionality of Organization as Hierarchical Network

The advanced information systems and resource capabilities available to modern C2 structures will determine new versatile doctrine for organizations in their respective missions. One needs to thoroughly understand the functionality of different components in a C2 structure to predict the performance of a particular organizational design. While the functions that are carried out by an organization may vary based on the makeup of a specific mission, the general classification of the basic processes inherent to a C2 organization is critical to the evolution of the organizational design process. The facilitation of the fundamental processes (such as coordination, communication, management of weapons, operational planning, situation awareness, dynamic distributed decision-making, etc.), common to a large variety of C2 organizations, is the key to superior organizational performance.

We seek the optimal design of adaptive C2 organizations to establish a proper balance among the following general intrinsic processes:

- segmented information acquisition and processing;
- distributed decision-making;
- managing operational resources;
- inter-DM action coordination;
- mission monitoring;
- failure and anomaly detection;
- strategy adaptation / reconfiguration enforcement.

The classification of the processes that define the functionality of an organization provides a modeler with a basis for choosing the design parameters and performance measures.

4. Optimization Criteria

When speaking of design optimality, one should realize that different people may value different criteria when judging the optimality of an organization, i.e., the notion of optimality is subjective. In addition, in an organizational design process, different objective functions often lead to different "optimal" organizational structures. Hence, the correct choice of optimization criteria is critical to generating an optimal organizational design. Relative weights of optimization parameters in the objective function are also important because they impact the outcome of the design process. Therefore, one of the designer's goals is to appropriately select the optimization criteria to adequately reflect the principles stated in the original hypotheses.

5. Adaptability Requirements

When designing organizations to operate in an uncertain environment, the specific information about many mission parameters may be inaccessible a priori, with only estimates (e.g., the forms of probability density functions, expected values and standard deviations, etc.) available to the designer. Once the mission commences, the actual values of its parameters may require the implementation of a *particular strategy* to achieve desired performance. Furthermore, throughout the course of a mission, various events (e.g., an erroneous initial mission parameter estimation, operational resource failures, malfunctioning of a decision node, etc.) may trigger unexpected changes in either the mission environment or in the organizational constraints. As a result of such changes, it may no longer be possible for an organization to successfully complete the mission while maintaining the same strategy it was using initially. Moreover, none of the strategies, feasible for the current organizational design, may allow the organization to successfully complete the mission.

Consequently, an *on-line* decision *strategy adaptation* and/or *structural reconfiguration* could become a prerequisite to the successful completion of the mission. Thus, the challenge is to construct organizational architectures that can:

- *maintain* the mission *schedule*, while operating in a time-pressured and uncertain environment;
- *capture* the necessary *information* about organizational node failures and/or unforeseen dynamic changes in the mission environment;
- *determine if* an adaptation is required;
- *analyze* the available adaptation options;
- *recommend/adopt* appropriate forms of adaptation (*or abort* the mission in the case where no adaptation is available or its cost is unacceptably high);
- *implement* the required on-line adaptation of structure and/or strategy.

For an organization to be able to adapt and still maintain its mission schedule, the adaptation phase must be compatible in time with the processing of mission tasks (in some cases, the adaptation time must be significantly smaller than the time to process the corresponding mission tasks to allow for successful completion of the mission). Thus, in order to determine if adaptation is required, the appropriate mission/organization *monitoring* data should be analyzed, and the *failure diagnostics* should be performed in a timely fashion. For large missions, such an analysis is usually beyond the information processing capabilities of human organizations. To transcend the limitations of human DMs, appropriate software tools are required.

Oftentimes, it is not efficient to analyze all available adaptation options, as such an analysis can be time consuming and computationally expensive. When this is the case, the number of examined options will be restricted by the timeliness requirements and the processing speed of the supporting algorithms. Thus, *it may be beneficial to look for design solutions that*, in the event of adaptation triggers (e.g., unexpected changes in the mission environment, resource failures, DM node malfunctions, etc.), *would allow for the rapid search of adaptation options among preprocessed data.*

Since the reliability and accuracy of the organizational data, and hence the ability of an organization to detect the need to adapt, are strongly dependent on the accuracy of the observed measurements, the resources that accommodate the information acquisition function play a special role in the adaptive organizational design. The allocation of these resources to a DM will impose the additional monitoring function/responsibility/workload on such a DM.

After the proper adaptation option (e.g., strategy shift, resource reallocation, hierarchy reconfiguration) is selected, the organization needs to coordinate among its members to implement the selected change. In hierarchical networks, the *authority* to declare and enforce on-line reconfiguration belongs to the superior DM (known as a root DM). Hence, it is natural (although not necessary) that a decision to adapt be taken at this highest level of the command hierarchy.

6. Model Predictions and Hypothesis Testing Phase

The hypotheses underlying an organizational design provide a *terminus a quo* for aggregating the key model variables into a set of measures to characterize the organizational performance. When designing an experiment, the collected data (both quantitative and qualitative) must be sufficiently rich to advance the inductive inferences of the experiment. In the hypotheses testing phase, a numerical comparison of model predictions versus experimental data serves as a basis for either validating or rejecting the hypotheses. In addition, the model-data comparison helps to identify human limitations and biases, and to formulate new hypotheses to be tested in a Model-Test-Model cycle. Thus, the model based quantification of hypotheses and the development of quantitative model predictions constitute critical steps in the scientific investigation of organizational decision-making.

7. Setting Parameters for the Experiment

In general, different parameters (e.g., coordination, workload, resource allocation) have dominant effect on organizational performance under different experimental conditions. In order to validate a hypothesis stipulating the nature of interaction among particular model variables, the experimental data may prove ineffective when the variables of interest are dominated by other variables or measurement noise. Therefore, in addition to quantifying the hypotheses and providing quantitative performance measures, the experimenter must establish the relevant settings of external parameters for the experiment. The search for better parameter settings should be based on a fundamental, model-specified, understanding of the process being studied, the limitations of measuring equipment, and the relationships the experimenter is explicitly seeking to determine or to validate.

8. Key Steps in Designing Experiments

We conclude that, in order to carry out a comprehensive design of experiments to examine organizational behavior of C2 structures in a complex mission environment, one needs:

- a modeling paradigm;
- a method to represent a mission and an organization;
- an algorithm to synthesize an organization;
- a procedure for measuring organizational performance;
- a way to evaluate hypotheses prior to experiment;
- a process to establish relevant parameter settings for the experiment.

The basic steps in developing an executable model of an experiment to test hypotheses about a C2 design are outlined in Fig.1.

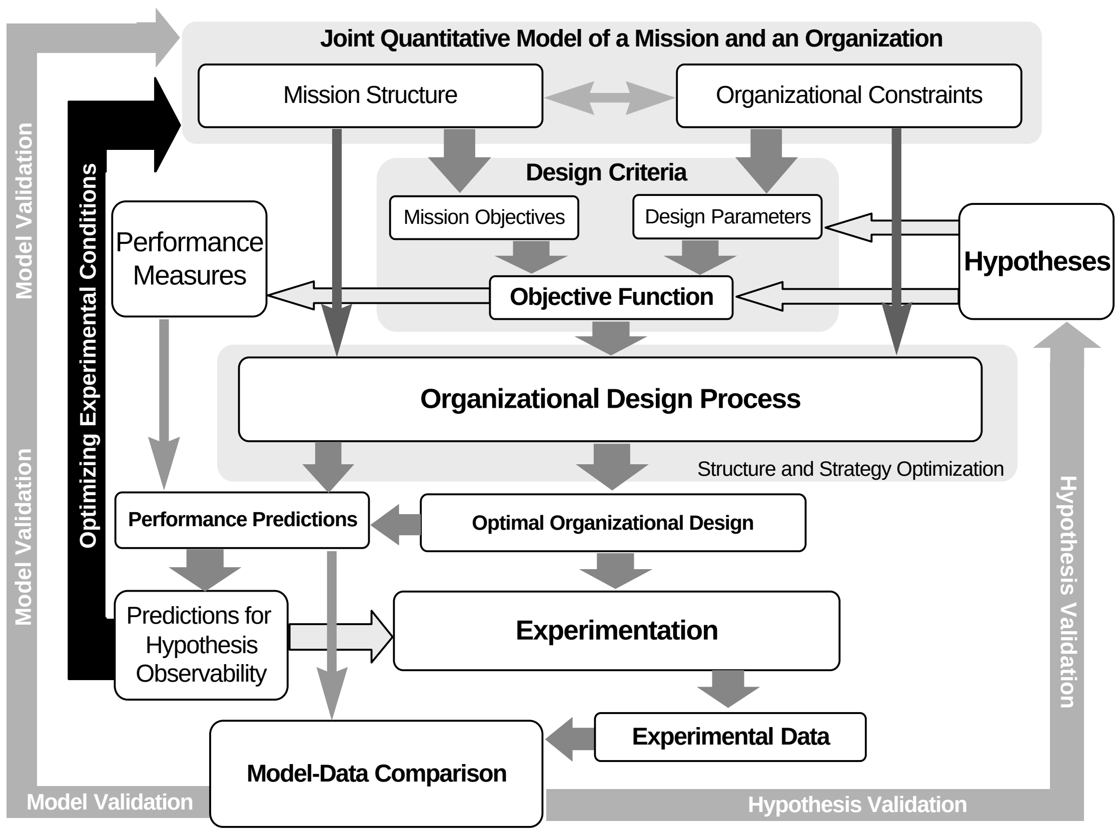

Figure 1. Outline for analytic design of experiments in a model-test-model cycle.

9. Summary and Research Prospective

In this paper, we presented guidelines for *designing experiments* to examine organizational behavior of command and control teams operating in a complex mission environment. We discussed a joint model of a mission and an organization to specify the structure of the mission, organizational constrains and processes, and the requirements for an organizational design. Our methodology illustrates the underlying principles that guide the design of organizations.

This paper provides an analytical starting point for model-based experimental research on adaptive architectures. In coordination with companion empirical efforts (see [Serfaty, 1996] and [Kemple et al., 1997]), it seeks to integrate optimization, modeling, and simulation-based research efforts with psychology-based and experimental activities to conduct humans-in-the-loop model-driven experiments studying adaptive C2 architectures. The proposed models drive the formulation of hypotheses, the determination of key variables and their values, and prediction of organizational performance and the processes of adaptation. The generated measures of organizational performance provide a basis for post-experimental model-data comparison. In addition, the implementation of the design procedure in software allows one to estimate the optimal experimental conditions to test a specific hypothesis. The empirical findings will assist a modeler in identifying new design parameters affecting organizational performance to further study the dependency of organizational performance on the mission structure and on organizational design.

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