Designing the information space for a command center based on team performance models

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ABSTRACT

Display design for command centers often focuses on the best methods to display information. An even more fundamental issue, however, is the design of the "information space" for the command center, defined as the set of information that is needed by each individual in order to perform their individual and team tasks. Instead of being systematically designed, the information infrastructure and physical layout of command centers often evolve over time as new technologies are added, new positions created, and new connections and communication links are established within and between command nodes. This paper presents a systematic, quantitative method for designing the information space for a command center to best support team performance, based on the communication and information structure of the team. Using information about the team's communication patterns and information needs, we apply model-based principles to generate candidate designs for the physical layout of the command center and to develop designs best suited to the team structure.

Keywords: Command Center Design, Team Modeling, Information Space, Optimized Team Structure

1. INTRODUCTION

The information infrastructure and physical layout of command centers often evolve in a somewhat ad hoc fashion as new technologies are added, new positions created, and new connections and communication links are established within and between command nodes. The problem is especially acute for shipboard command centers like the Combat Information Center (CIC) aboard the Navy's AEGIS ships. Equipment acquisition for the CIC often has been "stovepiped," with each new system or capability developed in isolation from all others, and with little consideration given to the existing CIC team organization or how the new capability will best fit into the existing structure. With each new technology, a new, dedicated team member must be added to operate the new system, and the new equipment and new watchstanders must be fitted into the limited space wherever possible.

Within the CIC, the physical layout of the spaces is often not optimized for the organizational structure that exists. For example, in an AEGIS Cruiser CIC, the space is organized into basic command, anti-air warfare (AAW), and anti-surface/anti-submarine warfare (ASUW/ASW) groupings. However, each of these sub-teams sits facing away from each other and the leaders of these teams are not convenient to the command personnel. This layout is forced by the design of the display equipment.

Systematic, reliable methods are needed for the design of command centers—both the information space and the physical space—to best support the command team's organizational structure. In an on-going research effort, the Office of Naval Research has sponsored the development of a comprehensive, systematic, quantitative methodology for *designing command teams* that are optimized for the accomplishment of military missions.[1] The Team Integrated Design Environment (TIDE) design approach, based on this methodology, produces a mission-driven specification of team roles and specifies in detail the interactions of the optimally structured team. The results of a TIDE team design can be used, in combination with practical design principles, to guide the design of shared information displays, communication networks, and physical lay-outs for command centers that best support future command teams.

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2. ISSUES IN DESIGNING INFORMATION AND PHYSICAL SPACE FOR A COMMAND TEAM

Military command teams, whether located aboard ships or elsewhere, exhibit a number of characteristics that make them a team, as defined by Salas, Dickinson, Converse, and Tannenbaum[2]:

- There is **dynamic, interdependent, and adaptive interaction** among team members.
- There is a **common goal**, mission, or objective.
- There is some **organizational structure** of the team members.
- Each individual team member has **specific tasks or functions**.
- Task completion requires the **dynamic interchange** of information, the **coordination of task activitie**s, and constant adjustment to task demands.

This definition of a team suggests the factors that must be considered in designing physical and information space for the team. The design should take into account the mission objectives for the team, the specialized roles and functions of each team member, the information exchange and coordination interactions that must take place among the team members based on those roles and functions, and the organizational structure for the team. In evaluating how to design a new command space for a team, or to how best to utilize existing physical space and hardware (consoles, watchstations, etc.) on board ship, the following issues must be considered:

- **Common Information and Reference.** Based on the shared objectives of the team and on the roles and functions of the team members, certain information will be needed by all team members, while other information is needed by only a subset of team members or by only one team member.
- **Data Distribution Among Decision Makers.** The data that should be made available to each team member will depend on the task and responsibilities of that team member. Even in a situation where it is technically possible to distribute available data to all team members, it is desirable to filter information by relevance to avoid overloading individuals with information.
- **Efficiency and Effectiveness of Interfaces.** Information should be presented to team members in the most readily understandable and useable form, depending on the nature of their tasks. The mechanisms for the control of resources (information, sensors, weapons, etc.) should be designed to be as easy to use as possible.
- **Communication Efficiency.** Teamwork almost always requires communication among team members, and that communication requires time and attention. To the extent that necessary communication can be made more efficient, the workload of the team members can be reduced.
- **Coordination Efficiency.** It is the nature of a team to work together to coordinate task activities in pursuit of a shared goal. To the extent that the need for coordination can be reduced or the process of coordination can be made more efficient, however, the performance of the team may be improved.
- **Private Versus Public Workspaces.** Team members typically perform a range of tasks, some of which are completed by an individual acting alone and others of which are completed through close coordination among multiple individuals. The workspace available to team members should support both types of activities, both private and public.

To address these issues, we suggest the application of a series of command center design principles, based on team theory and on an understanding of the design and functions of the command team:

- Physical **proximity among team members** should, to the extent possible, be based on information flow and the need for coordination. The team members who work most closely together should be co-located, if possible given other constraints.
- Physical **proximity of individuals to equipment** should, to the extent possible, be based on the functions of those individuals.
- The design of **public and private decision domains** should be based on the distribution of individual and shared responsibilities for tasks. The use of private workspace for individual functions allows the filtering out of information that is not relevant to other decision makers. Display and control of information should be considered separately—for example, information may appear in a shared display, but that display may be controlled by only one individual.

- Team members should have the **ability to transfer both information and control**, depending on the nature of the tasks being performed and the need for shared information or shared control.
- Command center design must support the **integration of automation** into decision and control processes. As automated capabilities become more advanced, the benefit of integrating such capabilities into the command center increases. Automation must be integrated into the team's decision making processes, however—not added as an independent afterthought.
- The design must support **monitoring by upper levels of the command hierarchy**. Team commanders must gain insight into changing events and the decisions and actions that are in process in the command center. Monitoring ability can be provided by both physical proximity and by information supplied to team leaders. For example, the team leader may need to monitor the workload of each of the team members in order to identify and assist overloaded individuals. This can be facilitated by physical line-of-sight monitoring, monitoring of communication links, or monitoring of task load via shared displays.

The application of these design principles to a command center design requires a detailed understanding of how the command team functions, including the tasks performed by each individual on the team, the information needed to perform these tasks, the demands for communication and coordination that are generated by these tasks, and the command hierarchy. For an existing team, this detailed understanding can be gained through observation and systematic interview techniques such as Cognitive Task Analysis.[3] For a new team, or a team that is being reorganized or modified, the specification of a mathematical model of the team's mission and the development of an optimized team structure based on that model can provide extensive information about how the team *should* function to perform effectively. This optimized team design process yields a wealth of information that can then be used to design the command space that best supports the team.

3. OPTIMIZING THE TEAM STRUCTURE FOR A MISSION

The Team Integrated Design Environment (TIDE) approach to team design is *model-based* in the sense that it represents the mission, tasks, and functions to be accomplished by the team, the demands of those tasks and the resources required to accomplish them, the constraints on the team structure, and the performance goals for the team in a mathematical structure. This mathematical structure can then be manipulated to create a team design that is optimized for specified criteria.

3.1. Three-part allocation for team design

Team design requires, in essence, the specification of "who does what when." The central thesis of our team-design method is that a set of interdependent, interrelated tasks that must be completed under time constraints has an underlying quantitative structure that can be exploited to design the "best" team for accomplishing those tasks.

At the core of the TIDE method is a systems engineering approach that describes organizational performance criteria as a multi-variable objective function to be optimized. This approach is based on a three part allocation model, presented in Figure 1, that considers: 1) the tasks that must be accomplished and their interrelationships (the "mission"); 2) the external resources needed to accomplish those tasks (e.g., information, raw materials, or equipment), and 3) the human decision makers who will constitute the team. The team design process is, in simplest terms, an algorithm-based allocation between these three parts.

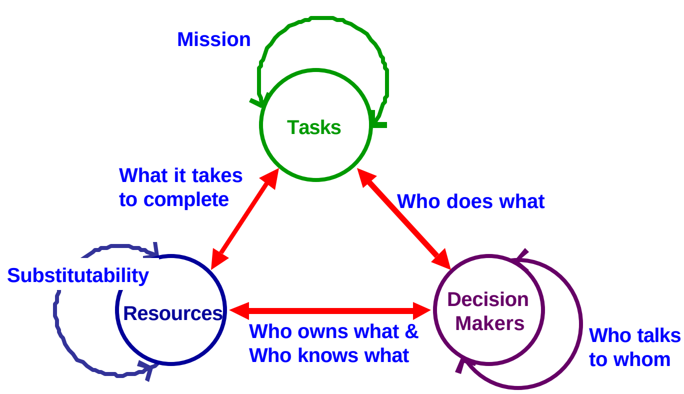

Figure 1. Three Part Allocation Model for Team Design

First, a quantitative model describing the mission and the existing organizational constraints is built. Then, one or more objective functions for the design are specified. Finally, 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. The power of quantitative modeling lies in describing a great variety of phenomena underlying the structure of a mission and of an organization by a relatively limited set of fundamental elements, parameters, variables, laws, and principles. These laws and principles, especially, specify the functional interdependencies among the structural elements and the dynamics of system parameters and variables. The algorithms that are fundamental to this team design method[4] were originally developed under the sponsorship of the Office of Naval Research for the Adaptive Architectures for Command and Control (A2C2) program.[5]

3.2. Inputs from Subject Matter Experts

Our team design method is algorithm-based, but it relies on heuristics and on the judgment of subject matter experts to frame the design problem in a meaningful way, including decomposing an overall mission (or goal) into specific tasks, specifying the relationships between tasks, specifying the resources needed to complete the tasks, and specifying the criteria to be optimized for the team. Subject matter experts in the area of application are also needed to review and revise the organization and structures suggested by the model. The design method is iterative. Typically, review of the team designs suggested by the algorithms reveals adjustments and corrections to be made in the task structure, the organizational constraints, or the optimization criteria.

The team-design methodology is goal- or mission-driven. That is, the model uses a detailed scenario that specifies the tasks required to accomplish a goal and the resources available to accomplish those tasks, and uses algorithms to optimally allocate these tasks and resources to team members to create an organizational structure for best accomplishing the goal. To capture the operational elements in a scenario, we rely on expert insight from subject-matter experts who develop scenarios. The interaction between operational experts and modeling specialists at this stage is essential for the design process.

In addition to the selection or development of a scenario (or multiple scenarios), it is necessary to create a detailed model of the mission that serves as the input for the method. An essential question that underlies all organizational design processes is “Who does what?” This requires that a mission be described in terms of its tasks (the “what” independent of the “who”). There are multiple ways to decompose a mission, and this process relies on interaction between the designer and domain experts. Mission analysis, functional decomposition, and subsequent function allocation must be driven by design goals.

After multi-dimensional task decomposition is used to identify mission elements, specific modeling techniques are applied to capture the internal structure of the mission. The mission decompositions are used to define parallelism, sequence, and structure for the mission tasks. These task interdependencies are used to create a hierarchical structure among mission tasks which is represented by a mission task dependency graph.

There are two major inputs for the team design method, the quantitative mission structure just described, and a set of organizational constraints. Organizational constraints include the specific resources and technologies available for accomplishing the tasks as well as any restrictions on how tasks are assigned to team members, based on specifications by subject matter experts who understand the domain of application. Team size may be set as an organizational constraint, or allowed to vary as part of the optimization.

3.3. Steps in the design process

Figure 2 shows the steps followed in a typical team design process. The first stage is mission representation, which depends heavily on inputs from subject matter experts. At this stage, we define the tasks that must be completed in order to accomplish the mission and specify their interdependencies. Tasks may be triggered by events (e.g., the appearance of a new air track triggers the task of identifying that track) or they may be triggered by other tasks (e.g., once a track is identified, its intent must be evaluated). Still other tasks are on-going, independent of events or other tasks (e.g., the need to continually monitor for new tracks). Typically we work with one or many mission scenarios in designing the team. If possible, we develop a stochastic mission model, which specifies the scenario in terms of the probabilities of various events occurring, rather working from a single deterministic scenario.

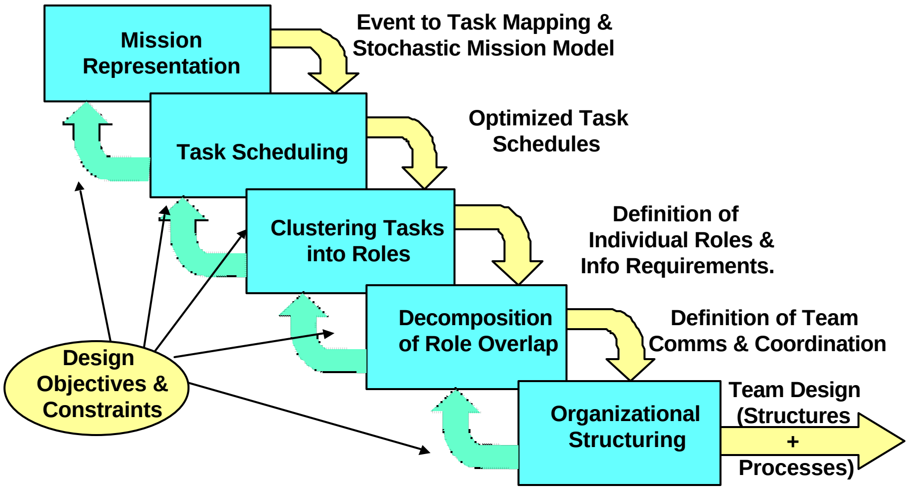

Figure 2. Steps in Designing a Team

At the mission representation stage we define "attributes" for the tasks to be accomplished. The task attributes of greatest interest will vary depending on the nature of the team design problem, but typical attributes that are considered include the workload associated with the task, the time needed to complete the task, the information needed to accomplish the task, and the communication/coordination links that exist among tasks due to the nature of the work being performed (e.g., the planning of air-to-ground strikes requires coordination with the planning of ground troop movements).

At the mission representation stage, we also specify the resources that *could* be used to accomplish the task, if the problem is resource constrained. Resources include, for some types of teams, assets such as sensor or weapons systems. Some types of assets can only be used at one place at one time (e.g., an artillery unit) while other types of assets can be used simultaneously by many people in many locations (e.g., information). Depending on the domain of application, there may be multiple ways to accomplish the same task with different combinations of assets (e.g., ships, amphibious units, and aircraft may all be involved in a mission task such as "take the beach"). If there are multiple ways to accomplish a task, we specify (based on subject matter expert input) the relative effectiveness of each of the possible combinations of assets for accomplishing the task.

The nest step in team design is task scheduling. This step is accomplished by algorithms that determine the optimal way to use the available assets to accomplish the tasks given an overall objective, e.g., to minimize the time needed to accomplish the mission or to maximize mission effectiveness. The importance of the task scheduling step in team design depends on the nature of the mission domain. If there are a number of assets that can only be used in one place at one time, and a number of different ways that assets can be combined to accomplish tasks, this step may be extremely important in team design. In contrast, if there is relatively little competition for assets, or only one way to accomplish a task with those assets, then task scheduling is not a major factor in the design of the team. The output of this step in the design process is an optimized task schedule for using the available assets to accomplish the mission. At this stage, human roles have not yet been considered.

The next step, and the central one for team design, is to create roles for individuals by clustering tasks (and the resources needed to accomplish them) in such a way as to optimize an objective function. Task clustering is often done on the basis of two (potentially competing) criteria: the goal of equalizing workload across the team members, and the goal of minimizing the amount of communication/coordination required between team members. The tension between these two criteria can been seen from a simplified example: the best way to minimize the need for coordination is to assign all of the tasks to one individual, but this obviously directly contradicts the goal of equalizing the workload across the team.

While the goal of equalizing workload (or keeping workload below a tolerable threshold) is a relatively intuitive one, the goal of minimizing the need for coordination requires further explanation. It is not that coordination is, in itself, "bad." However, if communication is required in order to achieve that coordination, then that communication takes up the time and attention of team members. Therefore, the need to coordinate through communication can have a negative effect on performance in conditions where there is a high task load (i.e., workload imposed from outside the team). While it is always good to have information about what other members of the team are doing, there may be a cost to acquiring that information. Communication can be good or bad for team performance, depending on when it occurs and what else is going on at that time.

Team theory suggests that if individuals on a team have a good "mental model" of what each of the other team members is doing and a good shared mental model of the situation, then this mental model allows them to anticipate the needs of the other team members.[6 7 8 9] This mental model can be acquired through communication and planning during periods of low workload ("here's how we are going to handle it when…")[10] or through cross training (each team member receives training in the other's job) [11 12]or simply through experience.

In periods of high workload, these mental models allow members of the team to anticipate the needs of other team members so that they can coordinate "implicitly" (with less need for communication) rather than coordinating explicitly (requiring communication of the form "send me this" or "do this now"). Implicit coordination reduces the need for communication under high task load, freeing team members up to do other things, and causing the team to perform better[13 14]. So, it is not that either coordination or communication is bad, it is just that, especially under stress, teams often perform better if they can coordinate without the need for frequent communication.

For team design, assigning tasks to minimize the *need* for coordination (to the extent possible, without overloading any of the team members) reduces the amount of knowledge the team members need to have about each other's roles, and the amount they need to communicate. This is most critical, and probably will have the most effect on performance, when the team is in high stress conditions.

The product of the clustering step in team design is to define roles for individuals in terms of the tasks for which they will be responsible. Associated with those roles, based on the attributes of the tasks, is a specification of the information that will be used by each team member, the resources that each individual will control in order to accomplish the tasks, and the need for coordination among team members (based on the interdependencies of tasks). Another product of the clustering is a prediction of each individual's workload over time, based on the tasks assigned to that individual and the timing of the tasks in the mission scenario. Note that if workload is a major concern for the team design, we als o include an estimate of the "overhead" workload associated with managing multiple tasks simultaneously.

The results of the clustering step must be fed back into the optimized task schedule to determine if that schedule is feasible given the assignment of tasks to individuals. We might discover, for example, that the "optimal" schedule requires an individual to accomplish too many tasks simultaneously, and will therefore need to delay tasks or to change the task assignments as a result.

For some team designs, it will be possible to assign tasks to individual team members in such a way that no one team member is overloaded. For other teams, such an assignment may not be possible, and it may be necessary to assign the same task to multiple individuals, creating an overlap in task responsibilities. If so, this creates a need for communication and coordination among the individuals with overlapping responsibilities, which must then be factored back into calculations of the workload for each of the affected team members.

For overlapping tasks, it is often necessary to analyze in more depth the subprocesses required for the task. For this analysis we use an Information-Decision-Action-Outcome (IDAO) decomposition, as illustrated in Figure 3. Within a task, information may be used to make a decision, which leads to an action, which lead to an outcome (the diagonal arrows in Figure 3.). The process is more complex than this, however. One type of decision is a decision to seek information, and the one outcome of actions may be information that leads to other decisions.

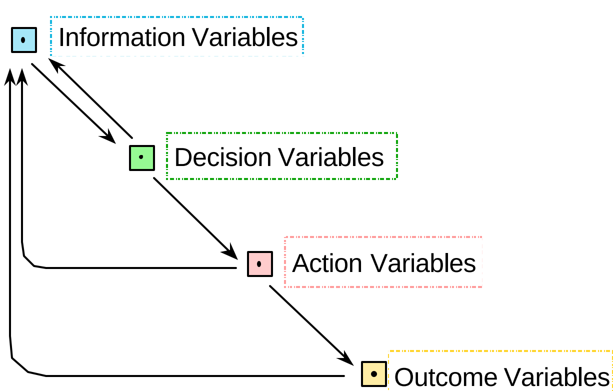

Figure 3. Information-Decision-Action-Outcome Decomposition of Tasks

Figure 4 provides an example of how the IDAO decomposition is applied to understand the subprocesses within tasks and the links among tasks. The example shown decomposes four tasks for an Anti Air Warfare (AAW) scenario, showing the information, decision, actions, and outcomes involved in those tasks. Note that the same information may used in several tasks (e.g., system status information is used in the Initiate/Confirm Engage Order task and in the Review Engagement Status task. Note also how many separate pieces of information and decisions come together in the Initiate Engage Orders decision. This pattern suggests that if the Initiate/Confirm Engage Order task is not assigned solely to one individual, then separating this task into multiple decisions made by multiple individuals would require a great deal of communication and coordination among those individuals.

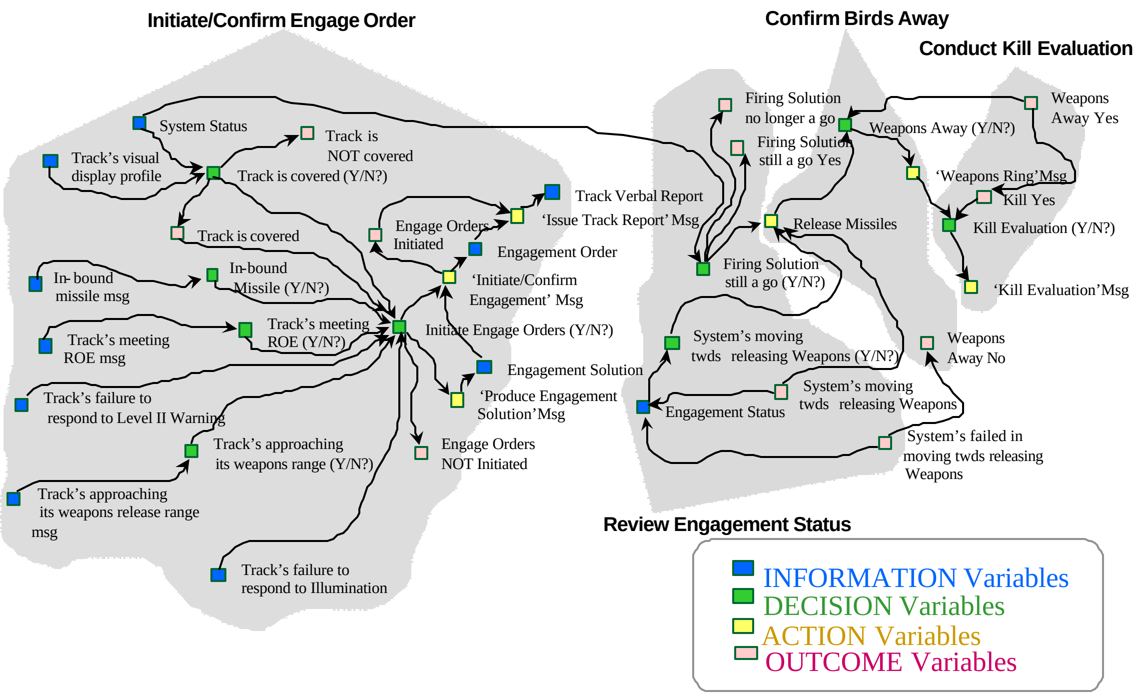

Figure 4. Example of IDAO Decomposition for Mission Tasks

The final step in the design process, once individual roles have been defined, is the specification of an organizational structure (e.g., a command hierarchy) for the team. For military teams, this is usually straightforward, driven primarily by the need to designate a team commander. The workload associated with being the team commander must also be fed back into the workload calculations, however, to ensure that command responsibility has not been placed on an individual who is already at a maximum workload ceiling.

The final output of the team design process is a specification of both a team structure and a team process associated with that structure. The team design specifies which team member (or members) accomplish each task, what resources are controlled by each team member, what information is used by each team member, and who needs to coordinate with whom (and about what). Depending on the criteria used to optimize the team and the attributes defined for the tasks, the final design can also produce predictions about the team's performance and the workload that will be experienced by each of the individuals on the team.

4. SPACE DESIGN BASED ON OPTIMIZED TEAM STRUCTURES

The process of designing a team using a mathematical model of the team's mission and optimization techniques to develop the best structure for that mission, as described above, produces extensive information relevant to the design of the physical and information space needed by that team. Figure 5 summarizes the information produced by the team design process that can be used to design the command center.

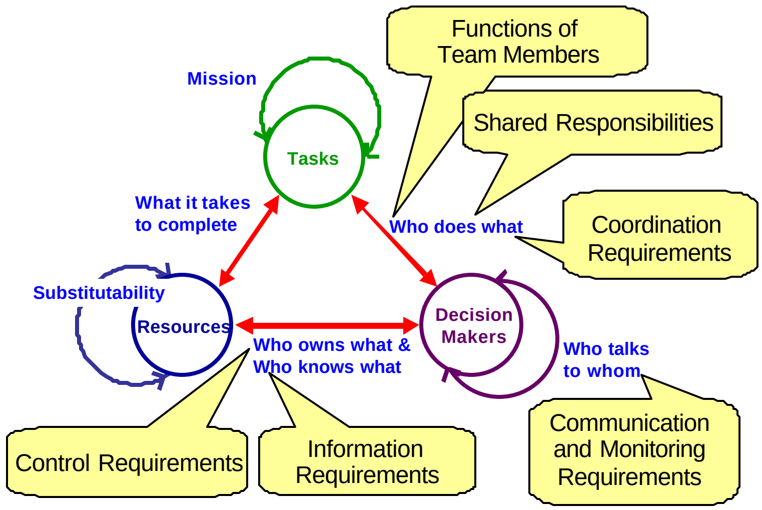

Figure 5. The Team Design Process Supports Command Center Design

The mapping of tasks and resources to decision makers on the team supports the definition of both control requirements and information requirements for team members. This mapping helps to specify what information is needed by each team member in order to perform his or her tasks and functions. It also identifies the information that is shared across decision makers and should therefore be available through shared or common displays. The control requirements associated with the tasks assigned to each team member are used to specify the degree of individual or shared control of resources such as sensors or weapons.

Depending on the flexibility of the systems that support the command center, the need for information and for the control of resources may also provide input into the physical design of the command center. If, for example, there is only one console from which a weapon system can be controlled, then any team members that control that system must be in close proximity to it. In more flexible systems, where all of the information display and control functions may be accessed from any location, the need for information and control will not drive the physical location of team members. Specialized functions of team members may drive the design of displays, however, to ensure that each individual has rapid access to the information needed for his/her responsibilities without being overwhelmed with irrelevant information.

Because the optimized team design takes into consideration the communication and coordination needs associated with the tasks to be performed, the process of assigning tasks and subtasks to individual team members provides information on the extent of the communication that will be required between those team members. This information can be used in the design of communication networks for the command center as well as in the physical layout of the command center. If possible, it is desirable for those individuals who have the greatest need for communication and coordination to be in physical proximity to one another.

The structure of the team will also provide information on the monitoring functions that must be supported by the design of the information space and the physical space. Team members who have been assigned to monitor other team members must have access, either directly or through communication links or displays, to information about the actions, decisions, and workload of the team members whom they are monitoring. If the physical layout of the command space does not support this monitoring through line of sight, then communication links or displays must be provided to supply the team leader with insight into the team's state.

5. CONCLUSIONS

We suggest that both the information space and the physical layout of a command center should be engineered to support the structure and functions of the command team that will use that space. Designing a command space that best "fits" a command team requires detailed knowledge of that team's structure and functions, including the tasks and functions performed by individuals, the information needed to complete those tasks, the communication and coordination requirements associated with tasks, and, therefore, the need for individuals to communicate, and the command structure of the team. The systematic TIDE team design process is based on a detailed analysis of the mission tasks to be performed and the requirements of those tasks, and produces a team structure that specifies information usage, control of resources, coordination requirements, and communication patterns for the team in a way that is easily accessible for developing a command center design that is tailored to support that team.

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