Title: **PERSUADE: Modeling Framework for the Design of Modular Army Organizations**

Suggested Track: **C2 Concepts and Organizations, C2 Modeling and Simulation, C2 Analysis**

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PERSUADE: Modeling Framework for the Design of Modular Army Organizations[1]

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Abstract

In this paper, we present innovative approaches and algorithms for the design of Command and Control (C2) structures, mission planning, and course of action development. These models are integrated into the PERsonnel-based Unit of Action Design Environment (PERSUADE). PERSUADE converts a textual description of mission and a graphical representation of an organization into quantitative models, and through optimization algorithms (Levchuk et al., 2002, 2004) validated in several empirical studies (Kleinman et al., 2003; Levchuk et al., 2003; Entin et al., 2003; Diedrich et al., 2003) will help the commanders at various echelons to synthesize command and control organizations tailored for a specific mission set. Our studies show that organizations designed using the PERSUADE methodology outperform their traditionally designed counterparts.

1. Motivation: New Army Doctrine to Address Changing Missions and Environments

For much of the 20th century, the organization of the American military remained relatively constant. Faced with a well understood adversary, U.S. forces were structured and positioned in direct opposition to the capabilities and posture of recognized rivals. The location and composition of weapon systems and forces were established specifically to offset the set of threats considered most critical to national security. Likewise, command and control systems were maintained to support optimal asset employment in opposition to those threats, resulting in the preservation of layered, hierarchical organizational structures. Because the tactics of Cold War adversaries could be directly observed, and because threats changed slowly over time, the U.S. force composition could remain constant without a significant loss in military effectiveness.

This traditional approach depended on having relatively complete knowledge of the threat (e.g., composition of enemy forces, likely scenarios, geographic conditions). However, today's threats are significantly different. Environments are fast-paced and uncertain, with an increased range of potential events which are often difficult to assess a priori. New adversaries cannot be fully engaged using conventional approaches and organizations. They require more facile, dynamic organizational structures to enable agile and precise action.

[1] The research reported in this paper was performed in connection with contract/instrument W911QX-06-C-0045 with the U.S. Army Research Laboratory. The views and conclusions contained in this document/presentation are those of the authors and should not be interpreted as presenting the official policies or position, either expressed or implied, of the U.S. Army Research Laboratory or the U.S. Government unless so designated by other authorized documents. Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation hereon.

To address these new challenges, the U.S. Army is undertaking a gradual organizational redesign of its combat and associated support units to provide modular forces focused on joint and expeditionary capabilities. The Brigade Combat Team (BCT), an intermediate realization of the Unit of Action (UA) concept, typifies this change (FMI 3-90.6). These forces are characterized by modularity of force composition, which allows resources to be rapidly configured or 'packaged' for specific mission requirements. Modular forces enhance the ability to quickly respond to wide range of contingencies with proper force composition (neither too large nor too small).

While modularity has the potential to provide agile forces tailored for specific mission environments, there are some obstacles that need to be addressed to realize this concept. How should the composition of dynamic organizational structures be determined? Relying solely on doctrine ensures that the criteria for force composition will be constantly out of date as new enemy tactics outpace the speed at which doctrine can be updated. Despite significant experience, military commanders cannot create new organizational structures based on subjective assessment alone – there are too many factors to weigh effectively. The process of employing modular components to construct organizations must be based on solid principles. The Army needs tools and methodologies that help define and optimize command and control structures, processes, and performance of novel Army organizations such as the UA.

In this paper, we illustrate our methodology to design Army modular forces. In Section 2 we outline the problem of force tailoring. Section 3 presents the description of our concept approach, which forms the basis of PERSUADE decision aid tool (Section 4). In Section 5 we describe the quantitative modeling framework. We illustrate our models with a realistic example of PERSUADE use (Appendix). Section 6 presents conclusions and directions for future research and employment of our methods.

2. Domain: Forces Tailoring and Reorganization for Improved Mission Execution Effectiveness

To improve the likelihood of successful execution of the theater campaign plan, increase the lethality of the forces, and enable the Joint Force Commander (JFC) to seize the initiative, the commanders use the **force tailoring** principles. Army operations field manual FM3-0 describes the force tailoring as the process determining the right mix and sequence of units for a mission. Army commanders tailor forces to meet specific mission and anticipated deployment requirements determined by the JFC and passed through the Army Service Component Command (ASCC). Generally, commanders tailor subordinate forces. For example, a corps commander may tailor a division by augmenting its organic assets with an additional infantry brigade and two corps artillery brigades. During tailoring, commanders balance the combat power necessary to accomplish the mission with the speed of deployment to ensure the deploying force is operational and sustainable upon arrival. Oftentimes, commanders need to substitute one type of unit for another or add units that have never trained together, in which case the teamwork at the early stages of deployment is emphasized. Tailoring the force includes force allocation, force augmentation, and force refinement.

The **force allocation** is a first phase in force tailoring process (Army FM3-0). During this phase, the combatant commander allocates a basic force – a combat unit (a division, an armored cavalry regiment, a Special Forces group, a combined arms maneuver brigade, or, for stability and support operations, a combat support [CS] or combat service support [CSS] unit such as military police, medical, civil affairs, engineers, etc.). The second phase of force tailoring is **force augmentation** – selecting support units to augment the organic capabilities of the basic force. These support units can be placed under the operational control, in direct or in general support of the augmented unit. For example, the Army planners, using experience and planning guides, may augment the divisions with combat, CS, and CSS forces, which are later assigned to in-theater headquarters by ASCC commander. The final phase of force tailoring is **force refinement**, which includes adjusting the basic force and its augmentations to account for the multiple constraints of the projected operation. Force refinement involves Mission, Enemy, Terrain, Troops available, Time, and Civilian (METT-TC) adjustments, force sequencing, and staff tailoring, and task organizing. The METT-TC step is performed by commanders to adjust the current forces after analyzing the factors of METT-TC – mission, enemy, terrain and weather, troops and support available, time available, civil considerations. For example, planners may decide to add nuclear, biological, or chemical (NBC) group due to threat of weapons of mass destruction (WMD), water distribution unit may be added due to dry weather and terrain considerations, target acquisition and MLRS battery may be added because of field artillery threat, etc. Next, commanders consider force deployment sequencing using METT-TC factors. For example, commanders often balance early deployment of combat forces against the need to deploy tailored CSS capability to generate and sustain combat power. Both the criticality of units and their relationships with other units need to be considered when scheduling the deployment. Next, commanders tailor units and staffs, both in size and organization, to meet mission conditions. The standard peacetime staff may undergo significant changes in both size and organization to meet conditions. Finally, the commander and his staff conduct the task organizing – establishing an organization with certain command relationships to accomplish the tasks at hand.

Currently, force tailoring is a manual ad-hoc process, prone to errors due to the multitude of factors that need to be considered. New missions and environments change quickly, and previous experience and doctrine become less relevant in new surroundings. In addition, the introduction of new technologies (such as Future Combat Systems and C3I tools) permits the creation of novel efficient C2 designs. As the result of constant change, commanders cannot create the most optimal C2 structures based on subjective assessment and experience alone. A decision aid that supports organizational design decision making will improve force effectiveness, reduce the decision-making cycle, and speed-up deployment and response time.

3. Method: PERSonnel-based Unit of Action Design Environment

Our approach to addressing force tailoring challenges is the PERSonnel-based Unit of Action Design Environment (PERSUADE) methodology which will allow the Army to make optimal use of the modularity afforded by Future Combat Systems (FCS). PERSUADE will assist commanders in developing the mix of units (**force composition**) for executing the mission(s) at hand. It will identify the best ways to **organize** and **configure** units to create a single cohesive force. PERSUADE will also provide commanders with a decision support to develop efficient **mission execution plans**, and will present mechanisms and guidance that will enable a force to *adapt to mission changes*. Modeling and optimization capabilities of PERSUADE will be complemented by *simulation and assessment modules* to design and evaluate the likely effectiveness of novel organizational forms.

In our research, we have focused on addressing three problems critical to the design of Army organizations (Figure 1): (1) the force composition problem, (2) the C2 structure and roles problem, and (3) the mission execution planning problem.

Force composition optimization will assist a commander in deciding which *mix of units* should be employed to execute any particular mission. These units are selected from the set of modular units available to the commander. The main premise of modularity is to allow the deployment of only the portions of the global force that are required to accomplish the assigned mission, leaving the rest of the force available for later deployment or in support of other missions. Commanders need to address several challenges:

- Different systems and units often have some overlap in their capabilities but nevertheless vary in their ability to execute assigned missions;
- The resources (systems, soldiers) are finite and must be apportioned among multiple missions;
- The deployment of forces requires time and a high maintenance cost;

- A smaller-size force is easier to control and can respond to incidents faster than the larger-size force.

The methodology embedded in PERSUADE would allow the commander to develop multiple options for force mix by trading off the importance of deployment and maintenance cost and the efficiency of mission operations. PERSUADE uses as inputs the set of available units and their characteristics (firepower, speed, location, experience, etc), the set of parameterized mission tasks (e.g., what needs to get done, and in what order), expectations of enemy activities, parameters of efficiency of force components/units to execute tactical tasks/missions (which could be defined from the functional capabilities of the units, their training background, and experience in tactical tasks), thresholds of tactical task load of the units (how many tactical operations, and of what magnitude, can a single unit be tasked with during the span of the mission?), the difficulty of mission tasks (e.g., size of enemy forces, the size of area of operations, etc.), the cost associated with deployment and support of the friendly units, and other factors.

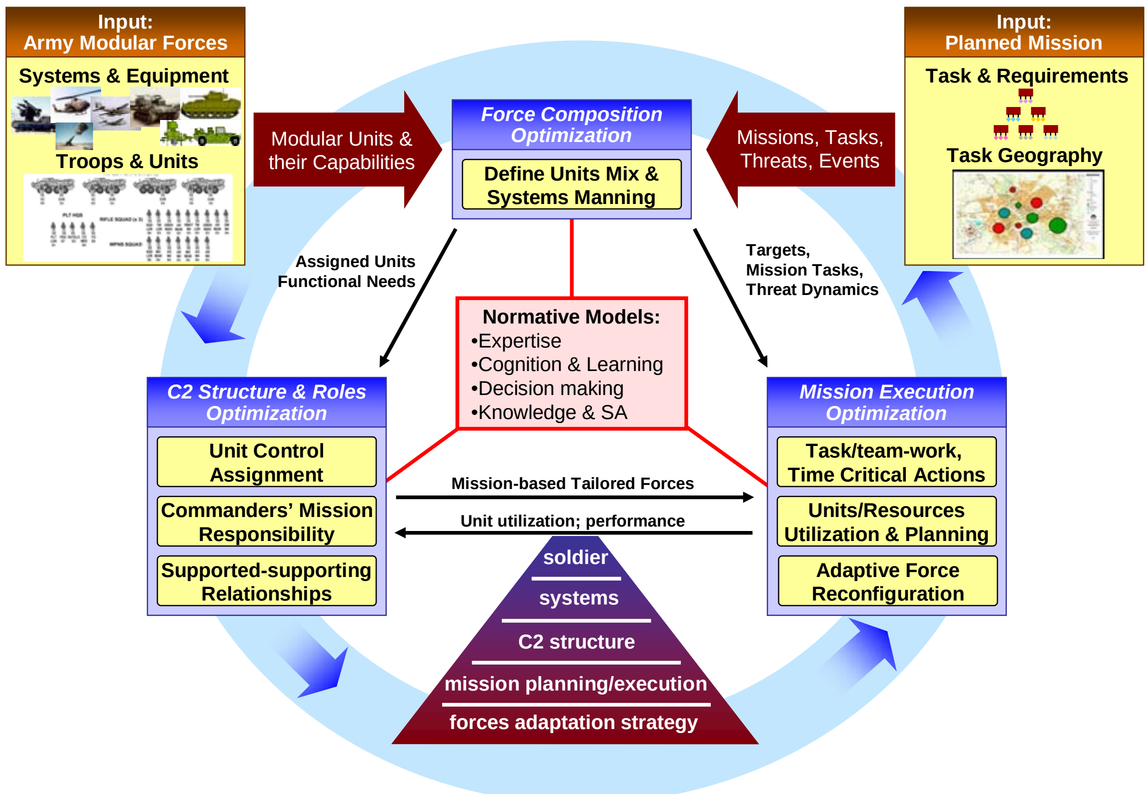


Figure 1: PERSUADE Optimization Components

Once units and resources are identified for a given mission, they must be structured into a cohesive organization that will be able to quickly exercise C2 processes to accomplish mission objectives. First, the units and resources must be assigned to commanders under Army control principles. Second, the supported/supporting relationships among commanders must be defined for a given mission. The latter signifies a departure from a fixed doctrinal force to a more agile and dynamic organizations, so that they could be tailored for a mission or even reconfigured to dynamically adapt to the environment. Despite significant experience, military commanders cannot create new organizational structures based on subjective assessment alone – there are too many factors to weigh effectively. **C2 structure and roles optimization** will allow a commander to *optimally organize* units into cohesive command and control organizations, define the roles of the commanders in the mission, and identify their supporting-supported relationships. The model will employ either algorithm-derived or commander-specified assignment of units to tactical tasks to first identify the dependencies among the units. These dependencies specify a need to coordinate units in order to achieve the mission successfully, where the coordination is related to synchronization of unit operations.

When the Army units are selected and the C2 organization and roles defined, the next step is to plan the mission execution. Since many units have similar capabilities (e.g., Infantry Company and Reconnaissance Company can perform similar search operations; Tanks and Attack Helicopters can provide direct fire; etc.), the problem of assigning the units to tasks becomes very complex. Commanders need to identify critical resource bottlenecks on which to focus the attention. Many variables must be considered during planning, for example:

- Maneuver capabilities of units;
- Quickness of deployment;
- Firepower and other resource capabilities;
- Experience and proficiency in executing specific operation/function;
- Experience of personnel and commanders;
- Size and cost of operations;
- Fatigue;
- Control/ownership of the unit(s) and associated command and control overhead delays.

Mission execution optimization will allow the commander to identify the most efficient *mission execution strategy*, as well as devising the *optimal organizational adaptation policy*. The execution strategy will provide the commander with the options for employment of units and resources during the mission, assignment of units to tactical tasks, synchronization requirements, and the processes to respond to time critical events (e.g. call for indirect fire support). The adaptation policy will present the commander with options to redeploy and/or reorganize (select additional units, change unit-to-commander assignment, change control processes) given the environment state (e.g., what threats occur) and/or state of the organization (e.g., status of units), especially during missions that span days and weeks.

In this paper, we are focused on how to compose the forces and organize them in cohesive C2 structure. The formal quantitative models to solve these problems are outlined in the next section. The details of mission execution optimization are beyond the scope of this paper. We refer the reader to (Levchuk, Weil, Levchuk, and Paley, 2005) for more details.

4. PERSUADE Design Tool

The PERSUADE tool has 5 main components (Figure 2).

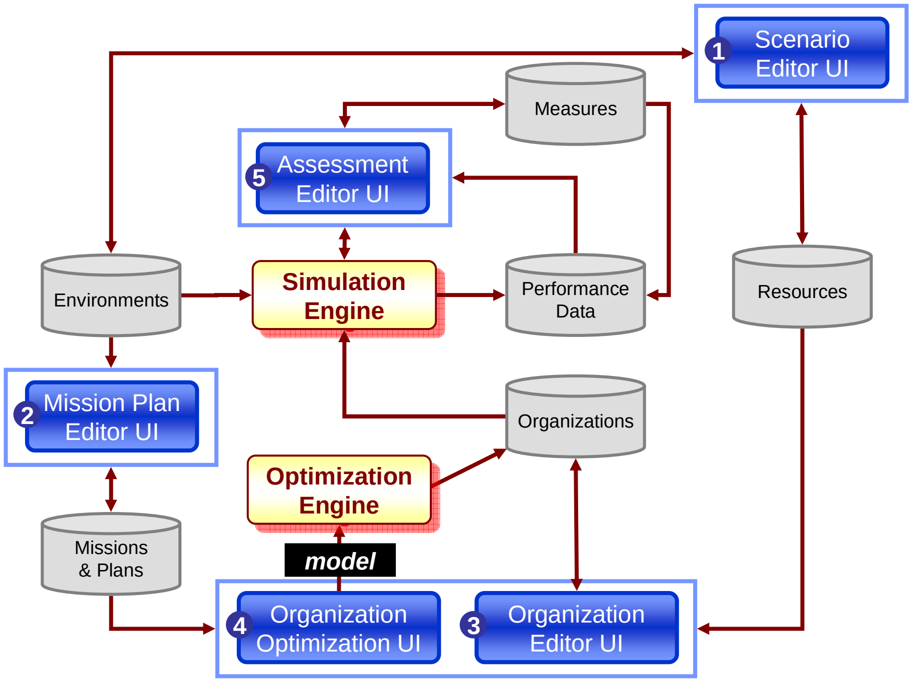


Figure 2: PERSUADE Software Components

Component 1: *Scenario Editor.* The mission scenario editor component provides the ability for the user to define the mission of the team. In PERSUADE we focus on diagram-defined missions, although parameters of the tasks depend on the geography in which the mission occurs. The map editing modules will facilitate connecting diagramed mission plan with real world. The data from scenario editor is kept in the "Resources" and "Environments" storage. The resources storage contains the data about the available units, assets, communication means, decision cells, and other constraints of the organization. The environments storage keeps the information about mission scenarios and physical environment characteristics.

Component 2: *Mission Plan Editor.* The mission plan editor takes the data from the environment and allows the user to develop that goal models, mission-event-task decomposition, and associate these tasks with the objects in the environment. The task precedence graph and information flow requirements are then specified. The data is stored in the missions and plans data container.

Component 3: *Organization Editor.* This component allows the users to manually edit/specify the organization – decision makers and commanders, resources, control allocation, command, communication network, etc. The organization editor creates the instances of organization or partial substructures which are kept in the "Organizations" storage.

Component 4: *Organization Optimization Engine and UI.* This component allows the user to develop a set of alternative sub-optimal organizational structures using specified algorithms and defined parameters (allowing for hybrid manual-automatic optimization – optimize a set of variables while fixing others), as well as find optimized alternative courses of action. The UI component allows guiding and controlling the optimization process, and the optimization engine contains the algorithms that perform the optimization. The organization optimization UI populates the model and enters this model into optimization engine which then finds the optimized structure alternatives and stores them in the "Organizations" data storage.

Component 5: *Assessment Module and Simulations Engine.* The simulation engine conducts simulation of organizational performance via Monte-Carlo runs and provides data for assessment of the organization and the mission. The assessment module allows full assessment of the organization and the mission via defining the measures, developing simulation analyses reports, and visualizing the mission execution outcomes and performance simulation.

In the next section, we describe the models and algorithms used in the optimization engine of the PERSUADE tool.

5. Optimizing the Tailored Forces

5.1. Quantitative Representation of Command and Control Team

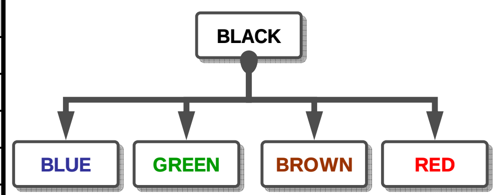
Our force tailoring optimization methodology is based on understanding and quantitatively modeling the command and control structures and decision-making processes in the military organization. Given specific functions and principles of individuals together with the structural form in which they are organized, myriads of the different potential organizations can be constructed. All of them are based on the underlying C2 principles. Since one of the most important findings from the organization theories research is that there is no single "best" approach to (or philosophy of) C2, many organizational constructs are possible.

Command and control refers to procedures used in effectively organizing and directing armed forces to accomplish a mission. The *command* function is oftentimes referred to as an art of an individual to set the initial conditions and providing the overall intent for mission execution. The *control* is referred to as those structures and processes devised by command to enable it and to manage risk and other entities in the organization. The commander in a C2 organization issues instructions to subordinates, suggestions to commanders of adjacent units, and requests and reports to supporting units and superiors. He develops and maintains situational awareness of the area of his operations through reports presented by other people or by electronic systems (Coakley, 1991). The basic purpose of a C2 organization is distribution of responsibilities among its elements and coordination of seemingly independent entities for operations to achieve the objectives. The fundamental need for communications significantly constrains the options for both command and control, making communications infrastructure a critical feature of a C2 system. However, describing the communications links and nodes of a fighting force does not suffice to explain, understand, or predict successes and failures in command and control. We need to be able to represent, model, and identify the functions and objectives of the individual elements of the C2 organization.

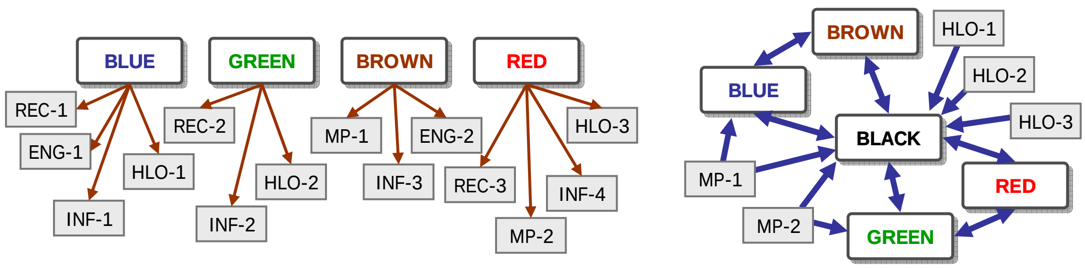
In our modeling, we describe the *command and control organization* as a collection of C2 nodes and resources connected via command, control, communication, and task structures (Figure 3). The roles, responsibilities, and relationships among C2 nodes and resources constrain how the organization is able to operate. **C2 nodes** are entities with information–processing, decision–making, and operational capabilities that can control the necessary units and resources to execute mission tasks, provided that such an execution does not violate the concomitant capability thresholds. C2 node can represent a single commander, liaison officer, system operator, or a command cell with its staff. A set of physical platforms and assets, C2 nodes, and/or personnel can be aggregated to a **resource** (e.g., squad, platoon, weapons system, etc.). A resource is considered a physical asset of an organization that provides resource capabilities and is used to execute tasks. The level of aggregation depends on the problem at hand. For example, in cordon and search missions executed by the company–size forces, we can consider resources being the single squads. The roles and responsibilities of the C2 nodes and resources identify possible operational and tactical policies: decisions they can make and actions they can perform.

Name	#	Description	FIRE	REC	ENR	MP
REC	3	Reconnaissance Team	0	2	0	0
ENG	2	Engineering Team	0	0	1	0
INF	4	Mechanized Infantry	1	0	0	0
MP	2	Military Police Team	0	1	0	1
HLO	3	Helicopter Section	2	0	0	0

(a) Resources of C2 Organization

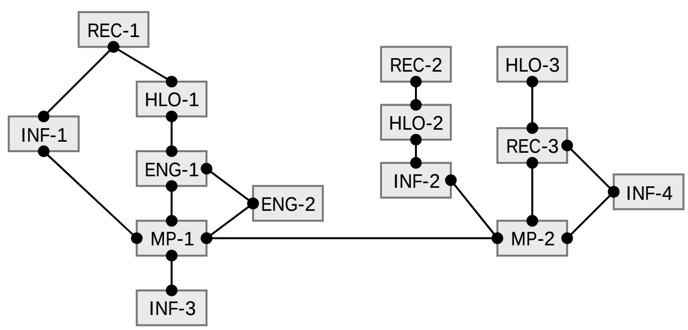


(b) C2 Nodes & Command Structure



(c) Control Structure

(d) Communication Structure (with resource reporting beyond control structure)



(e) Task Structure (example)

Figure 3: Example of C2 Organization

Command structure, represented as a network with directed links, defines superior–subordinate relationships among C2 nodes of the organization, thus specifying who can send commands to whom. **Communication structure** is a network between the decision makers of the organization, that defines "who can talk to whom," the information flow in the C2 organization, the communication resources that decision-makers can use (communication channels), as well as the security of the communication channels. A **control structure** is an assignment of resources to C2 nodes, and specifies which commanders can send tasking orders to what assets. A **task structure** is a network among resources, where each link corresponds to operations jointly executed by these resources.

In Figure 3 we present an example of the U.S. Joint Task Force command and control military team consisting of 5 command elements and 14 units/resources. The commanders of this organization make decisions to manage assigned resources in cooperative manner to achieve team objectives. Commanders are executing mission tasks and prosecuting the desired targets via allocating their resources (military assets and weapons) and synchronizing their mission task execution and target engagements. Figure 3.a describes the set of resources – military units and assets controlled by commanders. The assets include reconnaissance teams, engineering teams, mechanized infantry, military police teams, and helicopter sections. This chart also shows the *functional* or *resource capabilities* (Levchuk et al., 2001) of the units and resources in terms of direct fire, intelligence and surveillance, engineering, and interrogation capabilities. The authority structure among 5 commanders is a flat hierarchy (Figure 3.b) with a single commander ("BLACK") being a main commanders of enemy forces. The assignment of assets and units to commanders (Figure 3.c) determines the control structure of the C2 organization. Note that in hypothetical example of Figure 3 the main commander ("BLACK") does not control any resources directly. A communication structure (who can talk to whom) of the organization is depicted in Figure 3.d along with the direction of where the units report the detected/observed events (information flow) beyond the control structure (we assume that units controlled by commanders also report their observations to these commanders). A partial task structure – a network between resources – is shown in Figure 3.e. The task structure is due to the joint task execution by resources; therefore, it evolves throughout mission execution and depends on how the commanders manage their resources to assign and execute tasks.

The meaning of the force tailoring is the ability to **design** the command, control, communication, and task structures of the organization to achieve the highest performance possible for a specific mission or a range of missions. The first step in this process is to select the units (resources) in this organization. We outline our approach for unit selection in the next section.

5.2. Force Composition Optimization

Forces composition optimization will assist a commander in selecting the most efficient the *mix of units* to be employed in the organization to execute a mission at hand. The outcome of this module is the set of units and their generic impact on mission execution. The impact is calculated at a high level given what is expected during the mission and what the units will be tasked to do to accomplish the commander's objectives. These units are selected from the modular set of units available to the commander.

The force composition model uses as inputs the set of available units and their characteristics, and the set of parameterized mission tasks, expectations of enemy activities, etc. We propose to address this problem by using the parameters of efficiency of force components/units to execute tactical tasks/missions (which could be defined from the functional capabilities of the units, their training background, and experience in tactical tasks), thresholds of tactical task load of the units (how many tactical operations, and of what magnitude, can a single unit be tasked with during the span of the mission), the difficulty of mission tasks (e.g., size of enemy forces, the size of area of operations, etc.), and the cost associated with deployment and support of the friendly units. The methodology would allow the commander to develop multiple options for force mix by trading off the importance of deployment/maintenance cost and the efficiency of mission operations.

Our integrated cost-efficiency optimization approach to find the optimal mix (quantities) of units to be deployed utilizes an abstract mission/task modeling, and can be used at various levels of abstraction – from the manning requirements for planning cells to the specification of composition of division-size forces for specific mission (task-organizing).

We start by defining the tasks that the organization must perform (together with task operational load), the available execution node (unit/resource/asset) classes (and their parameters, including the maximum operational workload/taskload, cost of utilization or deployment, and number of available units), and the efficiency of executing the task with each node. As the result, we obtain the quantity of each node class to compose the organization, and determine the assignment of the tasks to those nodes. For illustration of force composition problem, see Appendix section D.1.

Mathematically speaking, the force composition optimization problem based on cost-efficiency paradigm is formulated as follows. Let number of nodes classes (combat units, operators, assets, resources, etc.) be M, with number of available nodes of each class $N_i; i = 1,...,M$. Let $c_i; i = 1,...,M$ be a cost of unit of class i, and its workload threshold, corresponding to the maximum tactical load of the node, be $W_i^A; i = 1,...,M$. Let K be a number of tactical tasks, and task load for task j be equal to $w_j^T;\ j = 1,...,K$. We define the efficiency of executing task *j* with the node of class i as $a_{i,j}; i = 1,...,M;\ j = 1,...,K$ (these variables could be obtained by matching the operator expertise and experience, or unit capability, against requirements for the task). The force composition model allows computing the number of units/nodes of each class: $n_i; i = 1,...,M$, where $0 \le n_i \le N_i$, and obtain an assignment of tasks to node classes: $x_{i,j}; i = 1,...,M; \; j = 1,...,K$

The solution is found to minimize the cost of deployment while maximizing the efficiency of mission execution. If we define α as the weight for execution efficiency (this efficiency needs to be maximized) and β as the weight for the unit utilization cost (this cost needs to be minimized), then the objective is achieved by optimized a weighted difference between mission execution efficiency score $\sum_{i=1}^{M}\sum_{j=1}^{K} x_{i,j} e_{i,j}$ and unit cost $\sum_{i=1}^{M} n_i c_i$. The problem becomes a variation of the multiple-knapsack programming problem that could be solved in pseudo-polynomial time:

$$\max \alpha \sum_{i=1}^{M}\sum_{j=1}^{K} x_{i,j} e_{i,j} - \beta \sum_{i=1}^{M} n_i c_i$$

$$s.t. \begin{cases} \sum_{j=1}^{K} w_j^T x_{i,j} \le W_i^A n_i \\ \sum_{i=1}^{M} x_{i,j} = 1 \end{cases}$$

5.3. C2 Structure and Roles Optimization

C2 structure and roles optimization will assist a commander to *optimally organize* units into cohesive command and control organization, define the roles of the commanders in the mission, and identify their supported-supporting relationships. The outcomes of this module is the set of alternative sub-optimal organizational structures, which can be used by commanders to focus on only most critical options for force tailoring and task organizing.

The model will employ either algorithm-defined or commander-specified assignment of units to tactical tasks to first identify the dependencies between the units. These dependencies specify a need to coordinate units in order to achieve the mission successfully, where the coordination is related to synchronization of unit operations.

When the mix and quantities of the forces are established, we need to define a C2 process and structure to support such a tailored organization. This is needed because the classes of modular force elements available for designing a contingency-based forces range from C2 cells and company-size units to brigade-level teams, with their capabilities overlapping. Current joint operations often require non-symmetric operations – distributed in space (non-contiguous) and simultaneous in time. Therefore, a rigorous process to identify the roles and responsibilities of units in the mission is essential to maintain effective joint operations.

The force composition methodology described in the previous section is only a first step in the force design and mission planning, and lacks a definition of the interdependencies between different missions and tasks. These interdependencies play a significant role in developing the procedures to distribute the responsibilities in the mission to commanders and units, because the units that execute tasks become dependent on each other (e.g., to synchronize sequential operations, to execute tactical tasks in parallel, etc.). Such a distribution is essential in defining the authority structure, command and control relationships, operational roles and supported-supporting relationships among commanders at different levels in the organization, and is required for successful operations in asymmetric environments.

We approach the problem of defining a C2 organization from the standpoint of finding the allocation of assets to C2 nodes driven by the roles of assets in the mission. The model is executed in several phases (see Figure 4). The first phase defines the assignment of units to tasks. This phase uses inputs from three components of PERSUADE model. The Mission Development component provides the tactical mission tasks and their parameters – locations, resource requirements, interdependencies, etc. The force composition component specifies the resources (modular force units, systems, etc.) that the organization will have to execute the mission. The mission execution component specifies the algorithm to assign the resources. Given these inputs, Phase 1 obtains the tentative mission execution schedule, assuming that it is possible to operate all of the resources/units by a single C2 node that has unlimited capacity to maintain the coordination of the units. This phase produces the assignment of resources to the tasks and task execution times in the mission. For illustration of this phase, see Appendix sections D.2.

Phase 2 of our design model finds the dependencies between units in terms of the coordination that is required to operate them. This coordination comes from the unit-task assignment obtained in Phase 1 (multiple units assigned to the same task require coordination for successful task execution) and natural dependencies between mission tasks (tasks that depend on each other; e.g., close in geography, are time-critical predecessors of other tasks, or require the same function impose the coordination requirements on the units that execute them). Defining the dependency function is more of an art than a science, and requires subjective judgment of what relationships between tasks and units are essential and impose coordination. Phase 2 defines a dependency network between units (for illustration, see Appendix section D.3).

The unit dependency network is used in Phase 3 to generate a tree network which minimizes the total coordination cost between the units. This *coordination cost* of a unit is found as the direct coordination with units connected to it in the tree plus the coordination overhead. The latter is equal to the flow of information through the node under flow conservation constraints from the coordination links among units that has not been included into the tree. The algorithm for minimum coordination tree construction has been used in (Levchuk, et al. 2002) to generate the command hierarchy. Here, we apply similar approach to generate the coordination tree between assets/units, which is used to cluster the units and determine C2 Structure in Phase 4. Phase 4 could be done either manually with the support of the information obtained in Phase 2 (dependencies between assets/units) and in Phase 3 (organization of dependencies into hierarchical network), or automatically given the clustering algorithm that accounts for the capacities of C2 nodes. The clustering algorithm merges the sub-trees of the asset coordination tree and assign them to the C2 nodes of the organization. Thus, Phase 4 defines (i) C2 node hierarchy; and (ii) allocation of assets/units to C2 nodes. The assignment of units/assets to C2 nodes constrains the capabilities of commanders and their roles. For illustration of command hierarchy and unit assignment designs, see Appendix section D.4.

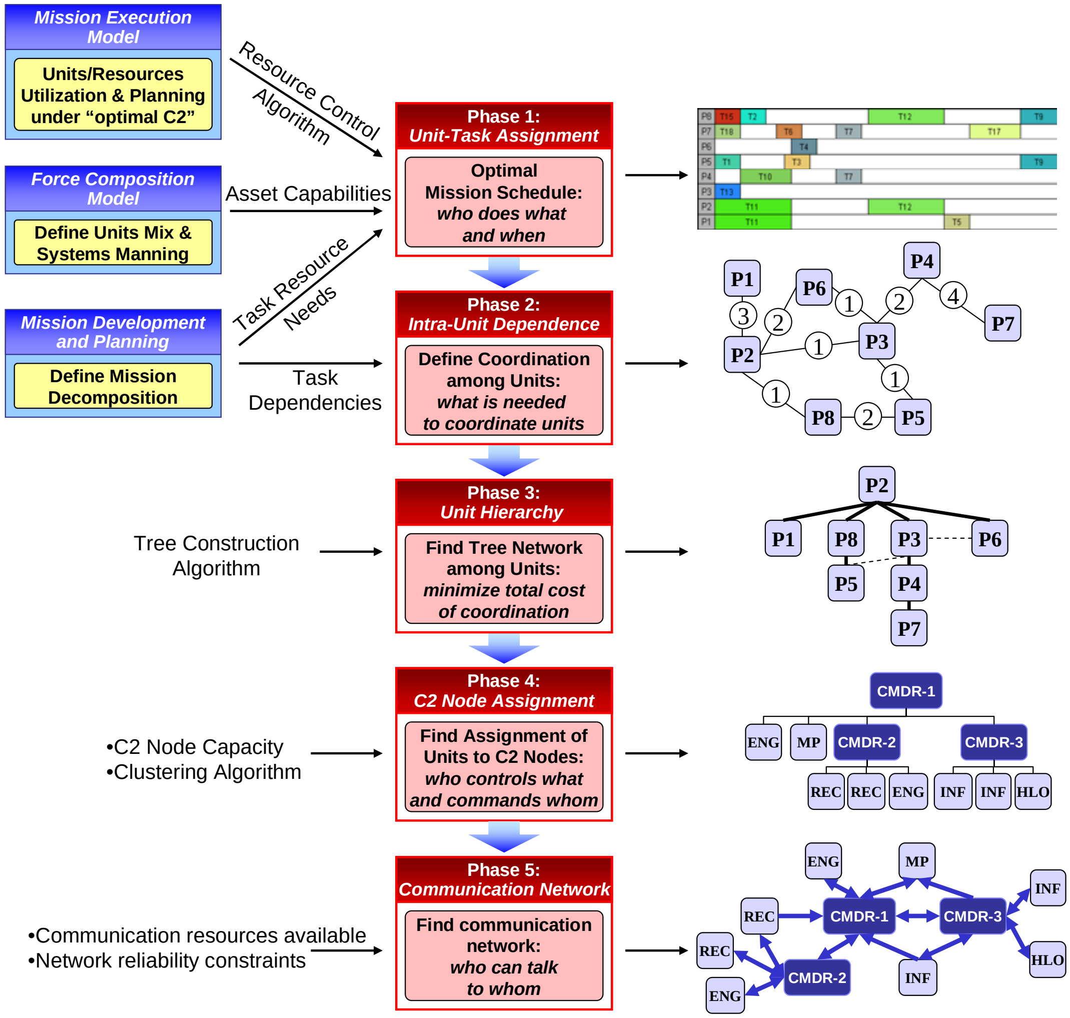


Figure 4: C2 Structure Identification Model

Phase 5 finalizes the C2 structure generation process by defining (i) a communication structure between the C2 nodes and assets; and (ii) allocation of tasks to assets, and therefore to C2 nodes that are assigned the corresponding assets. The asset-to-C2 node links correspond to the information broadcast flow from sensor assets/units, and links among C2 nodes correspond to who can talk to whom. The communication structure topology and communication resources allocation is solved using network optimization and heterarchy design algorithms (Levchuk *et al*., 2003, 2005). Allocation of tasks to C2 nodes explicitly defines the responsibilities of C2 nodes for tactical mission tasks. Together with asset assignment (control structure) defined in Phase 4, this phase reduces the overlap in the capabilities and responsibilities of commanders, but it does not remove this overlap altogether. When events occur that have not been preplanned before the mission, we are faced with the need to programmatically identify what commander or C2 node(s) will be responsible for this event. We address this challenge by developing a classification algorithm that will associate incoming events with commanders, thus providing a control schema to distribute the responsibilities between commanders and C2 nodes. For illustration of communication network designs, see Appendix section D.5.

6. Conclusions

In this paper, we have presented new PERSUADE framework for the design of C2 structures, mission planning, and course of action development. PERSUADE is envisioned to be used by military commanders and their staff, not just organizational researchers. The use-case presented in the Appendix describes how PERSUADE could be employed in realistic military operations. PERSUADE converts a textual description of mission and a graphical representation of an organization into quantitative models, and through optimization algorithms (Levchuk et al., 2002, 2004) validated in several empirical studies (Kleinman et al., 2003; Levchuk et al., 2003; Entin et al., 2003; Diedrich et al., 2003) will help the commanders at various echelons to synthesize superior C2 organizations tailored for a specific mission or a set of missions. Our studies show that alternative organizations designed using the PERSUADE methodology outperform their traditional counterparts (Levchuk et al., 2005).

In addition, PERSUADE will allow one to:

- Predict how overall performance is affected by changes in the mission environment, organizational structure, resources and dynamics (e.g., higher mission tempo/complexity, additional team members or automated agents, addition of novel multi-functional assets, changes in command hierarchy, information structure, communication structure, asset allocation, and so on);
- Predict how environmental uncertainty and time stress affect the rate and quality of decision making;
- Rank-order alternative organizational architectures and strategies with respect to performance and scenario expectations to rapidly analyze trade-offs in achieving the mission objectives and adapt to unforeseen mission dynamics.

The performance simulation engine component of PERSUADE decision aid tool allows visualizing the effects of reorganization on mission execution efficiency and conducting "what-if" analyses. The discussion of the simulation settings and models is beyond the scope of this paper. We refer the reader to a companion paper (Lovell and Levchuk, 2006) for more information about the model-based simulation approach.

PERSUADE is intended to complement existing modeling environments, and to provide additional capabilities for the Army. For example, the IMPRINT modeling environment was developed by ARL to aid in the evaluation of different organizational structures and information technologies on mission performance. Within IMPRINT, a user can configure the organization, the people within the organization, and the tasks and functions they perform. The goal of this system was to provide a "what-if?" capability to see the impact of the incremental changes to the organization (i.e., people, structures, technology). While PERSUADE can be used to perform similar analyses, the unique capability of the proposed system is the ability to *prescribe novel, optimal organizations* for a set of missions, people, and technologies. In this sense, PERSUADE provides the means to transition organizational design from an evolutionary (e.g., "what-if," Monte Carlo) to a revolutionary (e.g., design optimization) process. This optimization-based approach has the benefit of providing the means for the organizational design process to "step off the curve" and generate novel structures that can yield exponential changes in mission effectiveness.

Appendix: Illustration of PERSUADE Process

To illustrate the workflow of PERSUADE tool, we have constructed a use-case scenario in coordination with subject-matter experts from MPRI (http://www.mpri.com/). In this section, we will explain how PERSUADE tool can be utilized by the users to construct the organization best suited to perform the mission.

A. Receipt of the Mission

A commander (CMDR) of the division-size ground forces has received a request from headquarters to conduct a stability operation in which the division must protect a section of the oil production infrastructure from insurgent activity. This oil infrastructure is critical for stability and vulnerable to a variety of possible insurgent actions. Although the assets can be recovered and repaired following disruption, the cumulative effect of constant disruption has a negative impact on generating long term economic stability, and increases environmental hazards. The intelligence reports indicate the presence of foreign insurgent forces in the vicinity of two oil pumping facilities in the eastern boarder of the division's area of operations (AO), and a significant section of pipeline between the oil fields to the north of the AO and an oil refinery south of the AO. At least one of the oil pumping stations has sustained damage that has made the facility inoperable. Repair will require the expertise of civilian petroleum engineers. The CMDR has determined that each of these pumping facilities must be secured, and the operation for accomplishing this objective must be planned and conducted with the forces available for the division currently congregated in a Forward Operating Base (FOB) located at the western border of the AO. The CMDR and his staff now need to designate the forces capable of performing the operation. The first step in this process is to visualize the environment in which the operation will occur, understand the locations of main targets and infrastructure, designate the predicted enemy activities, and determine the forces which can be used in the operation.

B. Environment Visualization and Resources Definition for Scenario Development

The **scenario editor** component allows the commander to create a virtual battlefield environment that could be then used to plan the operation. First, the CMDR and his staff identify the critical geographical elements in the environment and enter them in the map editor component of the PERSUADE scenario editor tool (Figure 5). These include forward operating base (FOB), major routs and highways, villages, mountains and geo-formations, and infrastructure. Three passable roads lead from the FOB towards the critical targets. The North Access Road is located at the northern edge of the AO. The South Access Road is located at the southern edge of the AO. A third passable route lies to the west of the FOB, and leads directly to the village. En route to the village are several locations that could be used as staging grounds for support activities (e.g., fires positioning area [PA], insurgent holding area [HA]). Jabal or Mount Zulu is located to the north of the AO. The geographic features of the mountain include areas that are not visible from the air, and are therefore possible insurgent locations. The village of Foxtrot is located due east of the FOB. It is composed of 8-12 buildings, and is home to ~100 people. It is unclear if the local villagers are supporting the insurgents who have been undermining stability efforts to the east. However, the proximity of the village to the suspected insurgent launching point in Jabal Zulu suggests that insurgents may be using the village to re-supply food and equipment stores. Villagers may be detained for questioning, requiring that a holding area (HA) be set-up outside the village boundaries. A two lane highway lies east of Foxtrot, parallel to the oil assets to the east of the area of operations. It is in disrepair, but passable. A large wadi, or gully, transects the area of operations from north to south between the major highway and the oil pipeline and pumping station. Although individuals on foot can traverse the gully at a number of locations, the dimensions of the wadi are such that motor vehicles must use bridges to cross. Two bridges have been constructed to reach the pumping stations from the North and South Access Roads. The North Bridge provides access to Pumping Station 1 from the North Access Road. This bridge has been the location of insurgent activity in the past, and HUMINT indicates that this bridge most probably is partially destroyed. The South Bridge provides access to Pumping Station 2 from the South Access Road. This bridge has been the location of insurgent activity in the past, although not as heavily as the North Bridge. To the north of the area of operations is a large oil field, which supplies energy products for much of the region. The crude oil is transported to a southern port in the Persian Gulf via a major oil pipe line. The section of oil pipeline within the area of operations includes two pumping stations. The stations within the area of operations are of high criticality, as other oil assets in this part of the country are non-functional. To improve the economic health of the country and sustain its current leadership, these facilities must be protected from insurgents and would-be saboteurs.

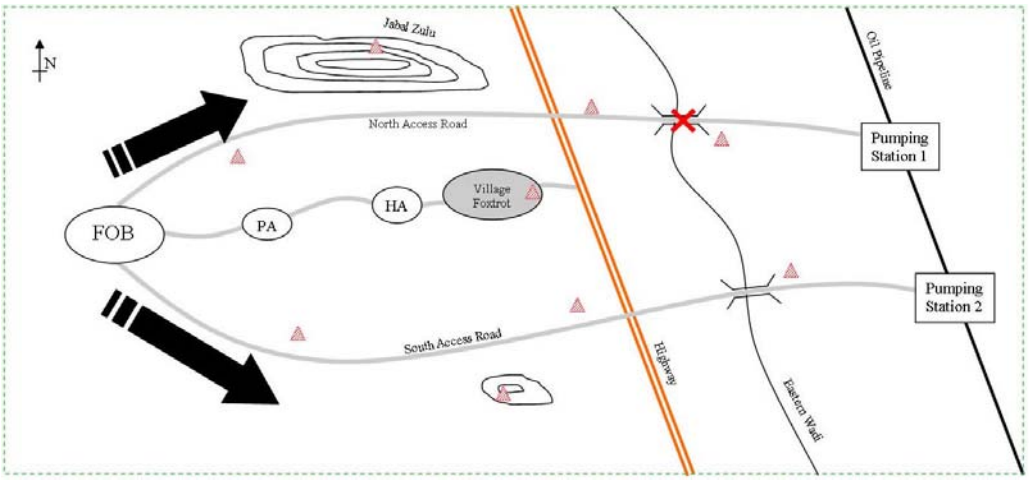


Figure 5: Map of PERSUADE Scenario Area of Operations

As the CMDR and his staff develop the visual understanding of the environment, they also need to identify the forces and resources that could be used to conduct the operation. The **scenario editor** allows listing all resource classes available to the CMDR and defining their capabilities. The division contains several brigade-, battalion-, and company-size modular units that could be task-organized into a mission-tailored brigade force with added service and combat support units using various control (operational, tactical) options. In our illustrative example, the forces available to commander include military police teams, human collection teams, reconnaissance team, mechanized infantry companies, engineering sections, tactical UAVs, and attack helicopter sections.

The analysts using PERSUADE scenario editor define the ***assets*** and ***decision makers***. The resources are comprised of physical controllable and/or movable *units*, e.g. individual weapons or weapon systems, sensors (TUAVs, radars), fire support elements (mortars, batteries, attack helicopters), transportation assets, teams of any granularity level (squad, platoon, company), etc. Attributes defining the units include: velocity, maneuver constraints, functional capabilities, attack range, identification range, kill range, etc. The decision makers are comprised of the *individuals* and their *expertise*. The single individual is a human commander, operator, staff member, etc. The decision-making expertise refers to the capabilities of humans to perform various tasks such as observations, information fusion, analyses, tracking, intelligence assessment, plans preparation, etc.

Each defined asset is considered unbreakable – that is, a single cohesive force element, which can be a part of a larger organization. Assets are used to *process* (execute) mission tasks – activities/events that require resources for successful execution and are generated from a mission plan or event list (e.g., attack, kill, observe, apply, negotiate, etc.). The staff decision-makers are used to execute planning and information processing tasks, and commanders are general resources performing command and control duties.

Assets oftentimes have embedded structure, with some units being physical sub-units of larger force (e.g., sniper squad being a part of infantry platoon), other units being physically located on carrying platforms (for example, the infantry teams are transported on HMMWVs) or munitions being a part of warfighting systems. Thus, the hierarchy of the units needs to be constructed. In our simplified example, there is no unit hierarchy – that is, all units are treated as equal.

The functions or ***function categories*** are defined to model the (*functional*) capabilities of a unit or a decision-making expertise. These categories are used to match the assets and decision-makers to tasks, and thus the requirements for task processing (*task-function requirements*) need to be modeled as well. Thus, in order to process a task, the organization needs to match the functional capabilities to the task requirements. The functions are specified based on the following attributes:

- Volume/strength (e.g., Infantry Company has *direct fire* capability from mortars; to secure the city, Recon Co need to operate together with Engineer Co);
- Range (TUAV can identify vehicles at a range of five miles);
- Context (MP cannot execute direct fire operations);
- Skills (forward observer is trained as accurately assessing the enemy target priorities and calculate the distance to the target); etc.

For our illustration (Table 1), we selected the following set of function categories:

$$[\mathrm{REC}, \mathrm{SCR}, \mathrm{ENG}, \mathrm{FIRE}, \mathrm{MP}, \mathrm{FP}, \mathrm{OPS}]$$, where:

- REC = area reconnaissance
- SCR = assault, search and secure operations
- ENG = engineering operations (construction and remove of obstacles, breaching, repairs, explosive clearing)
- FIRE = (in)direct fire
- MP = military policing
- FP = future plans
- OPS = current operations, COAs planning and resource management

Table 1: Example of assets and decision makers available

Resource Classes	# Available	Velocity (mph)	Functional Capabilities						
			REC	SCR	ENG	FIRE	MP	FP	OPS
Assets									
Reconnaissance Team	4	5	2	1	0	0	0	0	0
Military Police	4	40	0	0	0	0	1	0	0
Mechanized Infantry	4	40	0	2	0	1	0	0	0
Engineering Section	4	40	0	0	1	0	0	0	0
TUAV	3	90	1	0	0	0	0	0	0
Attack Helicopter	5	170	0	0	0	2	0	0	0
Decision Makers									
Future Plans Officer	3	-	0	0	0	0	0	1	0
Current Plans Officer	4	-	0	0	0	0	0	0	1
Commanders	5	-	0	0	0	0	0	0	0

C. Building the Mission Plan

The **mission plan editor** allows commanders and their staff to develop the plan to execute the mission: set objectives, define the mission tasks, visualize the threats in the environment, and decide on the milestones and essential decision points. This plan, termed ***mission scenario***, will quantify the environment and the actions that need to be performed, and will allow finding the tailored forces most suitable for conducting this mission.

First, after analyzing the scenario description, geography and critical targets, the staff members with help of PERSUADE's mission plan editor conduct mission-task decomposition. This stage of the design is an art rather than a science, and is conducted by the forces commander or his staff who define the mission plan. There are several approaches to conduct mission decomposition, including geography-based decomposition, goal decomposition, functional decomposition, or a hybrid of those. An example of mission-task decomposition for our illustrative example is shown in Figure 6.

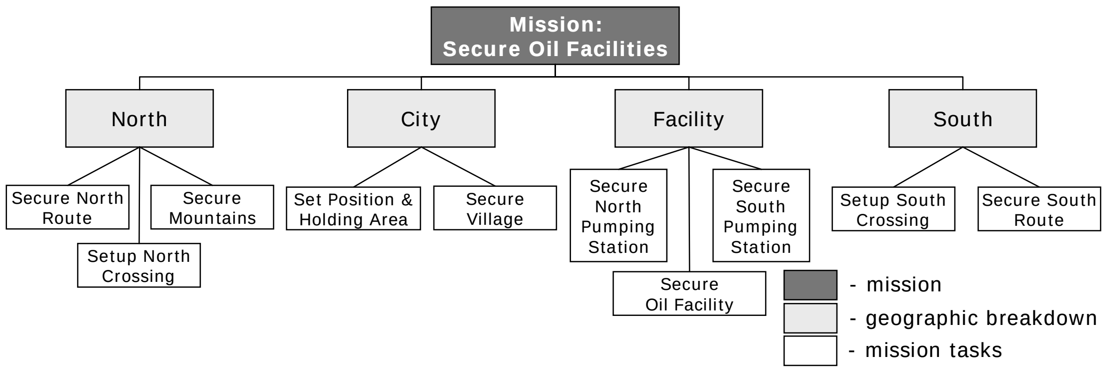


Figure 6: PERSUADE Mission Task Decomposition

Table 2: Example of task attributes and functional requirements

ID	Mission Tasks	Location (x,y)	Duration (hrs)	Value	Functional Requirements						
					REC	SCR	ENG	FIRE	MP	FP	OPS
T1	*Secure North Route*	(12,17)	1	5	1	1	0	1	0	1	1
T2	*Setup North Crossing*	(37,20)	0.5	5	0	1	1	0	0	1	1
T3	*Set Position & Holding Area*	(12,12)	0.5	10	1	1	1	0	0	0	1
T4	*Secure Village*	(25,12)	2	15	1	1	0	1	1	0	1
T5	*Secure North Pump Station*	(50,17)	1.5	25	1	1	1	0	0	0	1
T6	*Secure Oil Facility*	(50,12)	1.5	30	0	1	2	0	0	0	0
T7	*Secure South Pump Station*	(50,7)	1.5	25	1	1	1	0	0	0	1
T8	*Setup South Crossing*	(37,5)	0.5	5	0	1	1	0	0	1	1
T9	*Secure South Rout*	(12,7)	1	5	1	1	0	1	0	1	1
T10	*Secure Mountains*	(12,25)	2	15	1	1	1	1	0	0	0

Next, the analysts need to quantify mission tactical tasks – specify duration, value in terms of quantitative reward or loss to the team when a task is executed, functional requirements, precedence constraints, information flow and coordination requirements, events and threats, and the decision points. The task *functional requirements* (Table 2) help match the set of resources (forces units, munitions, weapons and sensor systems) with the tasks for most efficient task execution; therefore, as alternative, the analysts may want to directly define the asset packages to execute the tasks. The *precedence constraints* (Figure 7 shows example of precedence and information flow network for our illustrative example) between tactical tasks constrain the sequence of the mission execution. *Information flow requirements* are specified when the information obtained during execution of one task is needed for successful execution of another task (e.g., finding the location of potential enemy hideouts and disposition of buildings found during reconnaissance operation is needed to successfully execute subsequent search and security operation). The example in Figure 7 shows the information flow quantified according to number of information messages provided from one task to another. In our example, we use two types of messages: (a) intelligence of the area; and (b) enemy and civilian disposition. For example, both these types of information will be provided from executing "secure South rout" to "setup South crossing", while only area information can be provided from "reconnaissance of North rout" task to the "mountain security".

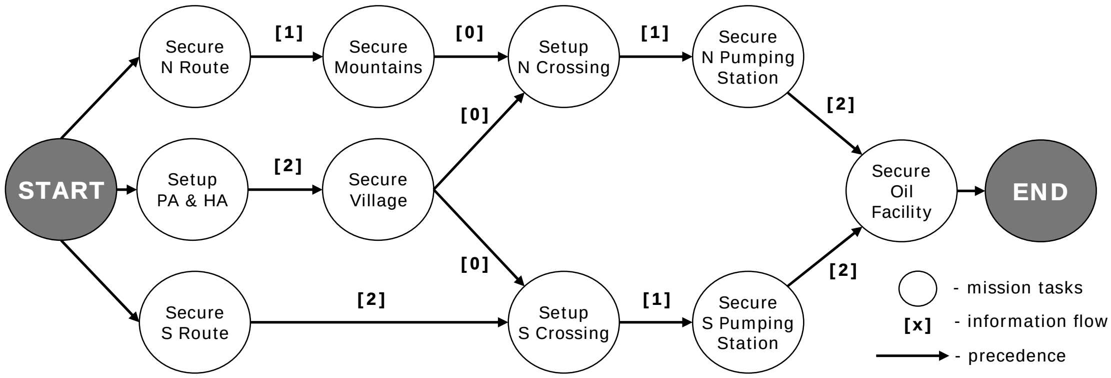


Figure 7: PERSUADE Mission Plan via Task Precedence Graph

The *coordination requirements* correspond to the need to coordinate task execution – e.g., jointly plan the tasks, synchronize their execution, and monitor performance and outcomes of those tasks. In the example of coordination network of Figure 8, the analysts add 1 "coordination point" for each of (a) joint planning; (b) synchronization; and (c) joint monitoring of execution and performance outcome. For example, all of these coordination activities are needed for crossing setup tasks and for pumping station security, while only execution monitoring is needed for crossing and pumping station setup (the decision maker responsible for the "secure pump station" task needs to wait for and monitor the execution of setup crossing task).

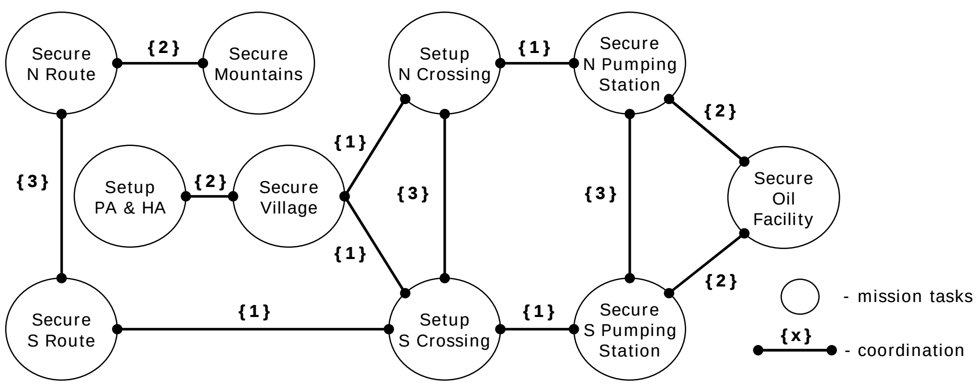


Figure 8: Task Coordination Network

Events are generated by decomposing the mission tasks into individual actions and threats, and *decision points* are decision tasks needed to be performed for successful mission execution, including planning, information processing, and resource management. Figure 9 shows a possible decomposition of the mission task "secure village" into events, and example of event structure. Without loss of generality and for simplicity of illustration, we continue our example assuming that there are no events associated with mission tasks.

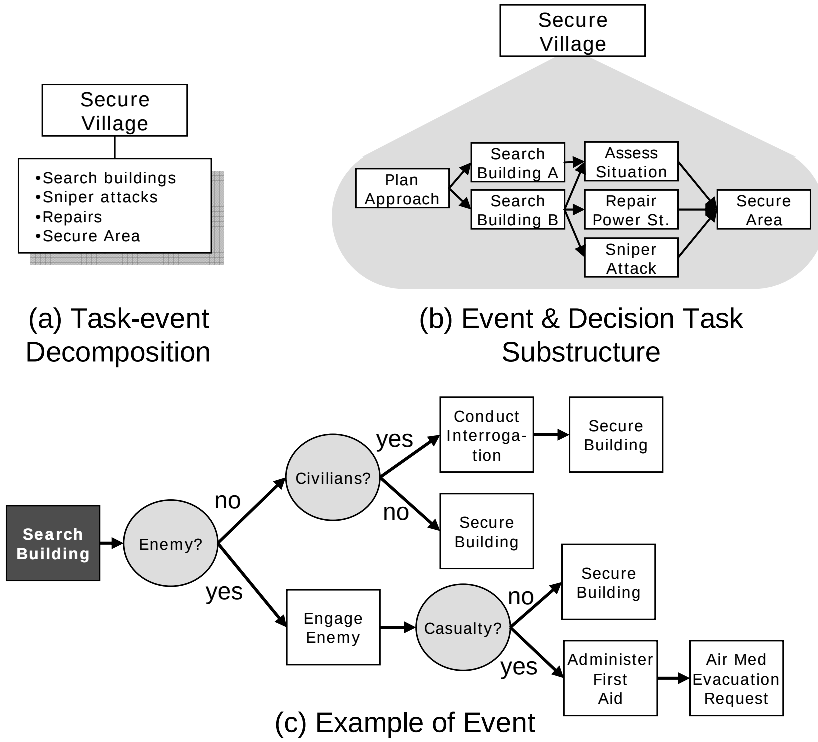


Figure 9: PERSUADE Mission Task Decomposition

D. Design the Organization

The PERSUADE tool allows tailoring and organizing the forces through several design stages with the help of the optimization algorithms.

Table 3: Functions and Resource Efficiency

Resource Classes	Workload Capacity	# Available	Cost	Functions (efficiency,load)						
				REC	SCR	ENG	FIRE	MP	FP	OPS
Total # of				7	10	7	4	1	4	8
Assets										
Reconnaissance Team	5	4	5	(2,2)	(1,2)	-	-	-	-	-
Military Police	1	4	2	-	-	-	-	(1,1)	-	-
Mechanized Infantry	4	4	10	-	(2,1)	-	(1,1)	-	-	-
Engineering Section	4	4	2	-	-	(1,1)	-	-	-	-
TUAV	2	3	1	(1,1)	-	-	-	-	-	-
Attack Helicopter	2	5	5	-	-	-	(2,1)	-	-	-
Decision makers										
Future Plans Officer	4	3	1	-	-	-	-	-	(1,1)	-
Current Plans Officer	4	4	1	-	-	-	-	-	-	(1,1)

D.1. Select Forces

To select the forces mix, the analyst can either create the list of units that will be involved in the mission and the staff required based on their experience and perceived mission requirements, or use the inputs from the optimization algorithms. The PERSUADE forces composition model collects functions from all defined tasks (according to task functional requirements) and uses values of resource cost, workload capacity, function-resource efficiency and load (Table 3) to determine the most efficient set of assets and decision makers. The *cost* of assets or decision-makers may refer to how difficult it is for commanders to request them from headquarters, or correspond to the deployment, maintenance, and service support cost (the latter is used as an abstract cost quantity in our illustrative example). The *workload capacity* of the assets or decision-makers help control how many elementary operations (functions and/or tasks) can they perform during the mission (this may be constrained due to limit on resources or to minimize the fatigue of the personnel). The overall workload for the resource from executing the functions cannot be above the workload threshold, and is calculated counting all functions that the resource is assigned to. The *function-resource load* and *efficiency* are variables quantifying respectively the difficulty and efficiency of executing the function by a resource – and might vary between different resources (e.g., both reconnaissance team and tactical UAV can conduct ground surveillance, but while reconnaissance team is more efficient in providing the intelligence information about the area, it is also more difficult for them to execute this task due to security concerns). Given the values in Table 3, the algorithmic example of the solution is the forces mix of Table 4, which produces the total resource cost equal to 56 and execution efficiency score equal to 66.

Table 4: Example of the Forces Mix and Function Assignment

Resource Classes	# Available	# Selected	Functions Assignment (# of functions)						
			REC	SCR	ENG	FIRE	MP	FP	OPS
Total # of			7	10	7	4	1	4	8
Assets									
Reconnaissance Team	4	2	3	2	-	-	-	-	-
Military Police	4	1	-	-	-	-	1	-	-
Mechanized Infantry	4	2	-	8	-	0	-	-	-
Engineering Section	4	2	-	-	7	-	-	-	-
TUAV	3	2	4	-	-	-	-	-	-
Attack Helicopter	5	2	-	-	-	4	-	-	-
Decision makers									
Future Plans Officer	3	1	-	-	-	-	-	4	-
Current Plans Officer	4	2	-	-	-	-	-	-	8

D.2. Find Tentative Mission Schedule

Next, the commander and staff need to determine how the mission will be executed – find the tentative assignment of resources (assets, decision makers) to mission tasks and the schedule (start time when tasks need to be executed). The schedule need to account for geographic task distribution and the maneuverability of the assets. This can be achieved either manually using the user interface modules of PERSUADE, or using the scheduling algorithms of PERSUADE. The outcome of this step (see Figure 10 for our illustrative example) is not a final mission execution schedule, and will be later adjusted for the command, control, and communication tasks performed by the commanders and staff.

D.3. Find Resource Dependencies

In the next step, the analysts need to determine the coordination that must be performed to successfully execute the mission. The coordination is needed to synchronize resources to execute tasks, to send information obtained by one resource to other commanders, to plan resource employment, etc. The users of PERSUADE tool can define the resource coordination network manually, or use the algorithm-based coordination network identification method. The latter is using the task information flow, task coordination requirements, and simultaneous task execution from the tentative schedule to construct the network. In Figure 11(a) we illustrate the matrix of coordination requirements among the resources and decision-makers computed by adding “1” for each task coordination requirement, and task information flow requirement, and 30 min of simultaneous task execution based on schedule of Figure 10. We also depict the largest coordination dependencies (with coordination value $\geq$ 10) between resources in Figure 11(b).

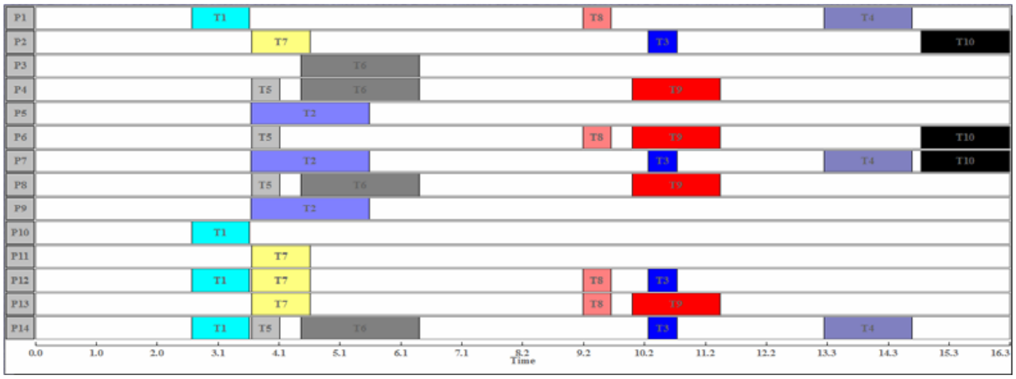
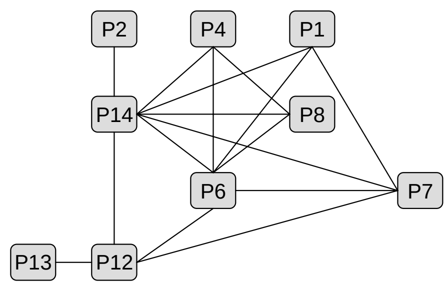


Figure 10: Example of Execution Schedule (P1-P2: Reconnaissance Team; P3: Military Police; P4-P5: Mechanized Infantry; P6-P7: Engineers Team; P8-P9: TUAV; P10-P11: Helicopter Section; P12: Future Operations Officer; P13-P14: Current Operations Officer)

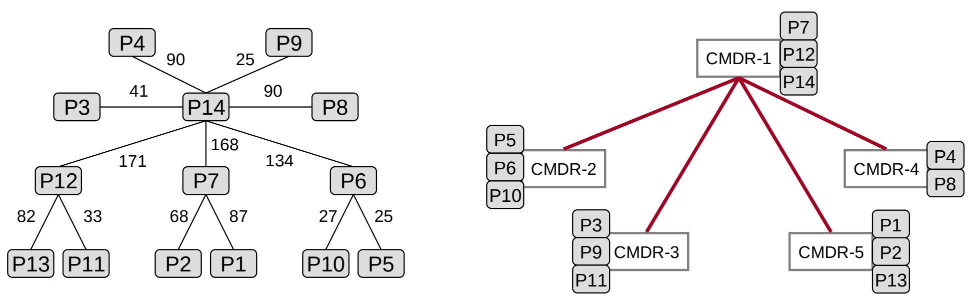
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14
P1	0	9	0	5	4	10	16	5	4	2	2	10	9	11
P2	9	0	4	4	0	6	9	4	0	3	3	9	5	12
P3	0	4	0	7	0	4	0	7	0	0	4	4	4	7
P4	5	4	7	0	2	11	2	16	2	3	4	9	8	17
P5	4	0	0	2	0	5	2	2	1	0	0	3	3	3
P6	10	6	4	11	5	0	10	11	5	6	2	11	9	14
P7	16	9	0	2	2	10	0	2	2	3	0	12	4	19
P8	5	4	7	16	2	11	2	0	2	3	4	9	8	17
P9	4	0	0	2	1	5	2	2	0	0	0	3	3	3
P10	2	3	0	3	0	6	3	3	0	0	0	2	3	2
P11	2	3	4	4	0	2	0	4	0	0	0	5	5	4
P12	10	9	4	9	3	11	12	9	3	2	5	0	13	12
P13	9	5	4	8	3	9	4	8	3	3	5	13	0	8
P14	11	12	7	17	3	14	19	17	3	2	4	12	8	0

(a) Coordination Requirements Matrix



(b) Most Critical Dependencies

Figure 11: Example of Resource Coordination Requirements



(a) Coordination Tree

(b) Command and Control Structure

Figure 12: Example of C2 Structure Design

D.4. Find Resource Hierarchy and Command and Control Structure

The analysts need to organize the units into a hierarchy and assign their control to the component commanders of the forces. This can either be done manually using organization user interfaces, or with the help of optimization algorithms that create the control assignment of the resources to commanders based on the coordination requirements among resources. The optimization is based on minimizing the total coordination overhead in the network of resources controlled by commanders organized in a hierarchical command formation. For our illustrative example, the algorithm first finds a coordination tree network

(Figure 12(a)). The overhead-minimizing hierarchical clustering of resources is obtained from non-crossing cuts along the edges in the coordination tree. The clustering is used to produce the assignment of commanders to resources and hierarchy between commanders (Figure 12(b)).

D.5. Find Communication Network

Given coordination requirements between resources (Figure 11(a)) and available communication channels, analysts complete the force organization design by defining who can talk to whom and about what. This is achieved by constructing the communication network (Figure 13) – determine topology and allocate communication resources to the links among resources and commanders. Both manual network specification and algorithm-based network design model is available to the users of PERSUADE tool. The optimization model uses information about the available communication bandwidth and the requirements for the reliability of the network (Levchuk *et al*., 2003), or can account for the efficiency of information processing and decision making at the command nodes (Levchuk *et al*., 2004).

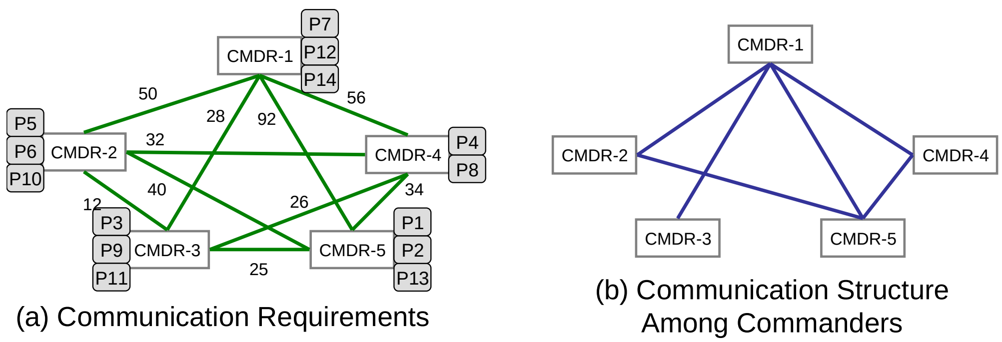


Figure 13: Example of Communication Structure Design

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