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Title: **Design of command and control organizational structures: from years of modeling to empirical validation**

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Design of command and control organizational structures: from years of modeling to empirical validation

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Abstract

Today's military command and control (C2) organizations are growing in both scale and complexity. It is becoming increasingly challenging for these organizations to adapt rapidly in dynamic environments and make the necessary changes to improve performance. In asymmetric conflicts, including maritime interdiction, urban security operations or disaster relief missions, the traditional hierarchical C2 organizational structures do not provide enough flexibility needed to enable agile functioning of the force. Instead of such centrally-controlled operations, researchers have focused on designing non-traditional C2 architectures that incorporate the benefits of centralized planning, hybrid resource allocation, distributed execution, and dynamic coordination (Alberts and Hayes, 2003).

In this paper, we take a look back at the history of model-driven C2 architecture design, and present the results of an empirical study that compared C2 organization designed using optimization model described in (Levchuk et al., 2006) versus one developed by a subject-matter expert. The domain of the study was the Brigade Combat Teams (BCT), which are primary fighting force formation of the Army. BCTs have been designed to enable rapid configuration or ‘packaging’ of multiple force elements for specific mission requirements (FMI 3-90.6). Since C2 redesign occurs constantly in BCTs, they provide a perfect test environment for optimization-based C2 solutions. In our empirical study, the model-based C2 organization outperformed the one designed by an expert across several key performance metrics. The results once again prove the efficacy of model-based C2 design solutions, shed the light on the reasons behind improvements in performance, and provide insight on how optimization models could be used to develop more efficient C2 architectures and processes.

Introduction

A short history of related research in C2 architectures

In recent years, various concepts of non-traditional military C2 organizations have been explored. Researchers approached the problem in several directions. First, they developed quantitative problem formulations for designing the C2 structure and processes and invented algorithms to find near-optimal C2 architecture solutions (Levchuk et al, 2002-4, 2006; Yu, Tu, and Pattipati, 2008). The optimization formulations usually make simplified assumptions about many C2 variables and their relationships. Accordingly, researchers developed detailed simulations that allowed comprehensive evaluation of potential performance improvements of alternative C2 architectures and processes (North et al., 2009; Taylor and Petryk, 2009; Ruan et al., 2007; Forsyth et al., 2006). Optimization models enable automated C2 solutions, while simulations support better manual C2 design through “what-if” analysis; however, neither

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guarantees that commanders and C2 team members will behave according to simulation rules and make optimal decisions in the real world. Therefore, researchers then empirically examined how model-derived non-traditional C2 structures compare to traditional C2 teams (Entin et al., 1999, 2004; Kleinman et al., 2003), and studied decisions made by experts and novices in situations that posed difficulties to traditional C2 structures (Jundt et al., 2004; Johnson et al., 2006; Diedrich et al., 2003; Entin et al., 2003, 2006). The goal of these empirical studies was to develop better approaches for eliciting correct adaptation actions from the team members using guidance and feedback strategies. However, most of the experiments examined local adaptation decisions, and never compared C2 architectures designed by modelers against those designed by experts in the domains where the C2 restructuring is an on-going process. In this paper, we present details of recently conducted empirical study that filled the gaps of previous experiments.

Typology of C2

Traditional planning, organizational design, and tactical mission execution processes of U.S. military depended on having relatively complete knowledge of the threat (e.g., composition of enemy forces, doctrine, likely operational and tactical situations and geographic conditions). However, both conventional adversaries and asymmetric threats confronted in the Current Operational Environment (COE) can no longer be fully engaged using conventional approaches and organizations. They require more facile, dynamic organizational structures that enable agile and precise operational and tactical actions. As a response to volatile environments, organizations struggle to balance stability against flexibility, specialization against generalization, and centralization against decentralization (Alstyne, 1997).

A traditional command and control (C2) *hierarchy* has a topology that largely restricts interactions among members of the organization to direct superior/subordinate interactions and whose number of levels is determined by the limits of span of command (Alberts and Hayes, 2003). Its approach to command and control is characterized by centralized planning, decomposition of tasks, and control processes that largely rely on deconfliction. A *heterarchy* is an emergent, self-organizing form that resembles a network or a fishnet (Alberts and Hayes, 2003; Levchuk et al., 2003, 2004; Yu, Tu, and Pattipati, 2008). It has lateral or distributed authority, has no fixed superior and has bi-directional relationships among team members.

An organization, which utilizes the beneficial characteristics of both hierarchy and heterarchy and can evolve over time, is termed a *hybrid* organization (Levchuk et al., 2003, 2004). Hybrid networked organizations uncouple command from control: command is involved in setting the initial conditions and providing the overall intent, while control is not a function of command, but an emergent property that is a function of the initial conditions, the environment, and the adversaries. Such organizations are designed to be agile while at the same time able to execute complex plans that require joint synchronized operations. Since agility requires not only the ability to respond to the changing environment, but also maintain a high level of performance in succeeding objectives (Alberts and Hayes, 2003), hybrid organizational structures bring both the ability to adapt the organization and stay organized and coordinated over the time of the mission.

In the research described in this paper, we selected the experimental domain of mission-based force-tailoring in the Army. Brigade Combat Teams frequently require hybrid C2 structures to achieve mission success. Currently, their C2 design is performed manually by mission planning experts, and many concepts of non-traditional C2 structures primarily in resource and role allocation have been used. This expands the space of potential C2 solutions, allowing direct comparison of automated model-based C2 designs and those developed by experts. This approach would allow us to find if the algorithms could come up with C2 architectures that would not be obvious to human expert planners but which could provide improved mission performance.

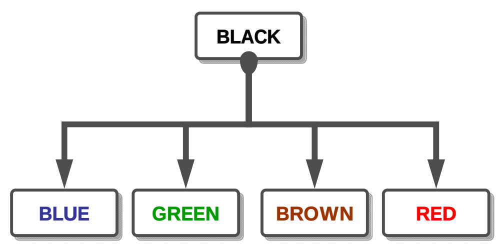
Elements of C2

In our research, we defined four basic architectural elements of military C2 organization (Levchuk et al., 2002, 2005, 2006):

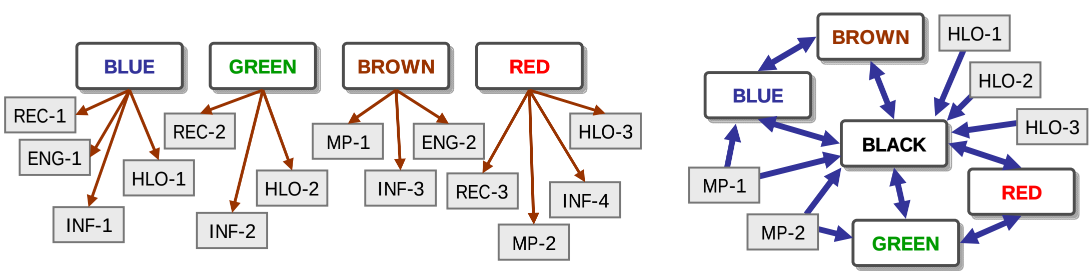
- **Resource composition** refers to the mix of units and personnel, called *organizational resources*, from which the C2 organization is constructed. The resources are often selected from an existing larger pool of resources.
- **Control network** defines the assignment of operational control from resources of the organization to command nodes. The control allows commanders to make decisions about allocating their units to execute assigned tasks, and also places responsibility on commanders to monitor the unit operations and coordinate joint task execution.
- **Command network** specifies role allocation, superior-subordinate, and supported-supporting relationships among command nodes. It allows commanders to allocate tasks among each other and make prioritization decisions.
- **Communication and information flow network** specifies what information can be shared among commanders and how it can be passed.

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 composition



(c) Command Nodes & Structure



(b) Control Structure **(d) Communication Structure**

Figure 1: Example of Elements of C2 Organization

In Figure 1 we present an example of the U.S. Joint Task Force command and control military team consisting of 5 command nodes and 14 resources. The commanders of this organization make decisions to manage assigned resources in cooperative manner to achieve team objectives, execute mission tasks and prosecute the targets using their controlled resources, and coordinate task execution and target engagements. Figure 1.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., 2002) of the units and resources in terms of direct fire, intelligence and surveillance, engineering, and interrogation capabilities. The command structure among 5 command nodes in this example is a flat hierarchy (Figure 1.b) with a single commander (“BLACK”) being a main commander of the forces with other commanders being his subordinates. In general, the command structure can be any directed network, where a single commander could potentially have multiple superiors, and support relationships could be defined separately for various mission phases, tasks, geographic areas, etc.

The assignment of assets and units to commanders (Figure 1.c) determines the control structure of the C2 organization. Note that in the example of Figure 1 the main commander (“BLACK”) does not control any resources directly. A communication structure of the organization is depicted in Figure 1.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).

In our research, the C2 design consists of 4 abovementioned elements. These elements are general to any military or civilian organization that consists of more than one entity (people, resources) and must execute a mission or a set of missions. These elements can be defined manually as well as in automated way using optimization algorithms (Levchuk et al., 2002, 2006).

Domain of empirical study

C2 organization redesign in the Army

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 current Brigade Combat Team (BCT), the outcome of the Unit of Action (UA) concept, typifies this change (FMI 3-90.6). These new tactical formations are characterized by modularity of force composition (including joint, allied or coalition units), which allows resources to be rapidly ‘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 threats and enemy tactics traditionally 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. Since C2 organization of BCT needs to be tailored for each mission, this provides a rich domain for testing novel C2 architectures.

C2 design for Army forces: force tailoring process and the opportunity for model-based solutions

To improve the likelihood of successful execution of the theater campaign plan, increase force lethality and enable the Joint Force Commander (JFC) to seize the initiative, the commanders use **force tailoring** process. Army operations field manual FM3-0 describes the force tailoring as the process determining the right mix and sequence of deployment 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).

During “tactical 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 (and employment as well once in Area of Operation) is emphasized. Tailoring the force includes three phases: force allocation, force augmentation, and force refinement.

During **force allocation** phase, the combatant commander selects a basic force – a combat unit to perform the mission (a division, an armored cavalry regiment, a special forces group, a BCT, 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, army planners, using experience and planning guides, may augment divisions with combat and sustainment 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, staff tailoring, and task organizing. The METT-TC steps are performed by staffs under the commander’s guidance 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) units due to threat of weapons of mass destruction (WMD); water distribution units may be added due to dry weather and terrain considerations; target acquisition and additional fire support may be added for increased counter-fire and/or enemy defense suppression capabilities, 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 a tailored sustainment capability to generate, support and maintain combat power. Both the criticality of units and their relationships with other units need to be considered when scheduling a 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 and requirements. Finally, the commander and his staff conduct task organizing – establishing a C2 organization with certain command relationships to accomplish the tasks at hand.

Currently, force tailoring is a time consuming manual ad-hoc process, based in large part on planner experience, intuition and other largely subjective criteria. Tailoring is often delayed by “planners writing cramp” because of there being no truly objective baseline or start point. The process is prone to errors due to the sheer multitude of factors that need to be considered. New missions and environments change quickly, and previous experience and doctrine become less relevant under these fast moving 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.

Design of empirical study

The C2 design decisions during force tailoring process require short turn-around time. The designed organizations are small (at most tens of command elements) and short-lived (mission execution times spanning hours to days or weeks). This allows easier empirical testing, where human-in-the-loop (HIL) experiments can be designed to include all participating command elements played by a single participant in the virtual gaming environment.

Objectives

In our study, we compared C2 designs for BCT developed using o*ptimization models* (Levchuk et al., 2006) versus ones developed by the *expert planner*. Consequently, designed organizations were called OPTIMAL and SME. The C2 architecture solution had four elements as specified in previous sections: (i) resource composition; (ii) control network; (iii) command network; and (iv) communication and information flow network. To simplify the experimental setup, both C2 organizations had the same resource composition, command (flat hierarchy) and communication (fully connected) networks; as the result, the main *comparison variable* was the design of control network (allocation of resources to commanders).

The C2 organizations to be designed were division-size forces operating in urban environment. The scenarios were of two phases: an attack mission to remove the opposing forces from the area of interest (Phase I), and stability/support mission to aid local government and establish security in the area (Phase II). As the result, the two independent variables – an organization and a mission for the virtual game – allowed us to form a *condition* for each human-in-loop experiment and a pair of organization and mission. For example, a condition can be labeled “OPTIMAL-I”, which means an OPTIMAL (algorithm-defined) C2 organization playing an attack mission (Phase I). Our validation thus became a classical 2x2 experiment.

Experiment design

Human-in-loop experiments were conducted Michigan State University (MSU) Psychology Department in the winter of 2008 and included 21 teams, each consisting of 5 undergraduate students (a total of 105 students) playing a role of a command node in the C2 organization in the virtual game. All teams have played 4 conditions. The sequences of plays for different teams have been counterbalanced to minimize impact of learning on experimental performance. As there were four possible conditions, there could be 24 different sequences of 4 plays. Our objective was to have a team for each such sequence. However, the availability of students prevented to have all situations. Still, there were no teams that played in the same sequence. In Figure 2, we show the teams and their sequence of four plays. The label for each configuration indicates an organization and a mission setup for a given play.

The platform for virtual game

Aptima’s Distributed Dynamic Decision-making (DDD) simulation system (Serfaty & Kleinman, 1985) is currently used in more than 30 government and academic laboratories to test a variety of factors in missions rife with uncertainty such as joint command and control (Entin & Serfaty, 1999; Diedrich, Carley, MacMillan, Baker, Schlabach, & Fink, 2003) and Airborne Warning and Control (Hess, MacMillan, Serfaty, Entin, 1999). The result of a 15-year research program on human behavioral modeling, DDD’s development has been funded in part by several government agencies, including the Air Force Research Laboratory (AFRL), the Army Research Institute

(ARI), the Office of Naval Research (ONR), and the National Aeronautics and Space Administration (NASA). The DDD is unique in its flexibility, allowing researchers to select and rapidly reconfigure scenarios that create challenging situations for command and control operators and leaders.

Team #	***Play 1***	***Play 2***	***Play 3***	***Play 4***
1	OPTIMAL-II	SME-II	OPTIMAL-I	SME-I
2	OPTIMAL-II	OPTIMAL-I	SME-II	SME-I
3	OPTIMAL-II	OPTIMAL-I	SME-I	SME-II
4	SME-I	OPTIMAL-II	OPTIMAL-I	SME-II
5	OPTIMAL-I	SME-I	SME-II	OPTIMAL-II
6	OPTIMAL-I	OPTIMAL-II	SME-II	SME-I
7	SME-II	OPTIMAL-I	OPTIMAL-II	SME-I
8	OPTIMAL-I	SME-II	SME-I	OPTIMAL-II
9	OPTIMAL-II	SME-I	OPTIMAL-I	SME-II
10	SME-II	OPTIMAL-I	SME-I	OPTIMAL-II
11	OPTIMAL-II	SME-I	SME-II	OPTIMAL-I
12	SME-I	SME-II	OPTIMAL-I	OPTIMAL-II
13	OPTIMAL-I	SME-I	OPTIMAL-II	SME-II
14	SME-II	SME-I	OPTIMAL-II	OPTIMAL-I
15	OPTIMAL-I	SME-II	OPTIMAL-II	SME-I
16	SME-I	SME-II	OPTIMAL-II	OPTIMAL-I
17	OPTIMAL-II	SME-II	SME-I	OPTIMAL-I
18	SME-I	OPTIMAL-I	OPTIMAL-II	SME-II
19	SME-II	SME-I	OPTIMAL-I	OPTIMAL-II
20	SME-I	OPTIMAL-I	SME-II	OPTIMAL-II
21	SME-I	OPTIMAL-II	SME-II	OPTIMAL-I

Figure 2: The sequencing of plays for MSU human-in-loop virtual experiment

The DDD simulation environment (Figure 3) implements a complex synthetic team C2 task that includes many of the behaviors at the core of almost any team task: assessing the situation, planning response actions, gathering information, sharing/transferring information, allocating resources to accomplish tasks, coordinating actions, and sharing or transferring resources. Successive DDD generations have demonstrated the paradigm’s flexibility in reflecting different domains and scenarios to study realistic and complex team decision-making. DDD has already proven to be an effective testbed for conducting experiments in a number of different tactical environments including the Air Force AWACS, JTF, Naval Battle Group, Army Ground Maneuvers, Army Urban Warfare/Special Ops, NASA Search and Rescue, and Joint Peacekeeping Operations. Embedded within DDD 4.0 are tools that capture and quantify team performance to help team members improve their skills and help planners increase mission effectiveness.

Unlike simulators that are limited to a fixed application, DDD gives its users (which includes military customers and researchers) the ability to create and modify their own virtual environments and operating scenarios. Mission planners, trainers, and researchers can modify operational roles, mission resources (weapons, fuel, troop strength, and other assets allocated to commanders who are played by game participants) and objectives to simulate realistic and challenging team activities.

A game in DDD is orchestrated as follows. The players perform the roles of commanders (in the reported experiment they played roles of BLUE organization). They “own” assets (platforms, units) that represent the subordinate forces and resources of the C2 organization. The players move assets around the game area and engage other game entities – including the assets of opposing forces (opposing RED organization in our experiment) and various mission tasks. The engagement can be represented as one asset attacking another, as information or material exchange, as data extraction, engineering work, etc. The players during the game need to coordinate with other players which tasks to execute and entities to engage, when to do this, and which assets to use.

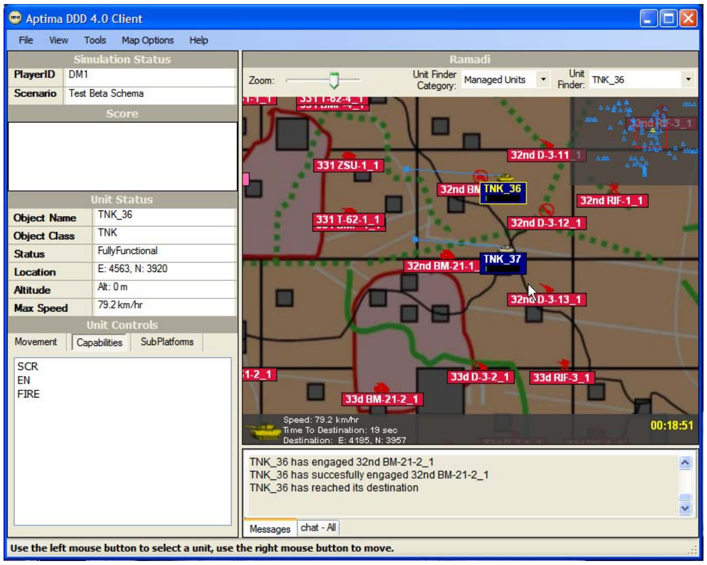
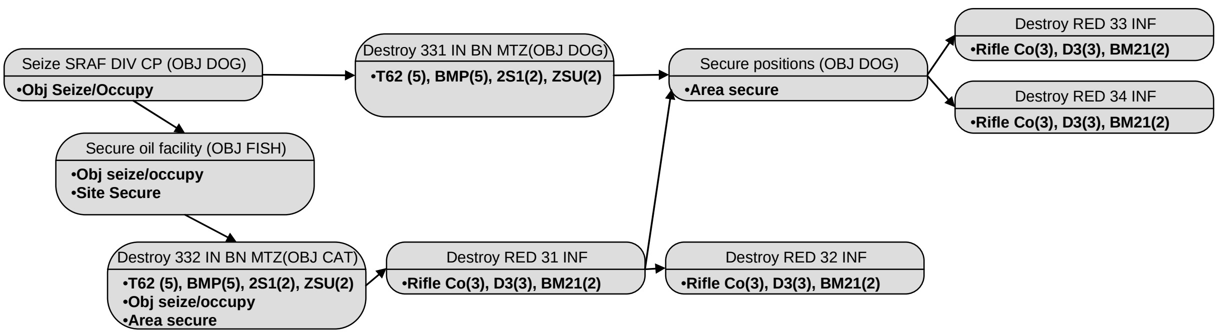
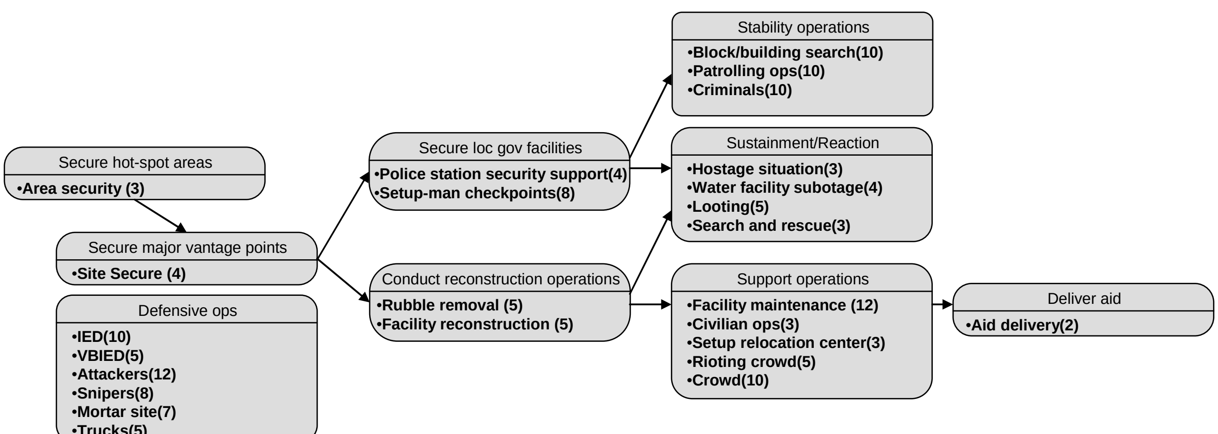


Figure 3: Sample Screenshot of DDD 4.0 used for PERSUADE Experiments



(a) Mission Plan for Phase I



(b) Mission Plan for Phase II

Figure 4: Experiment Plans

The situation and mission vignettes

As mentioned above, the experiment was setup with two scenarios to mimic a complex two-phased operation with the phases having significant differences between them.

Phase I consisted of primarily urban combat operations intended to defeat enemy regular forces; the civilian population during this period is assumed to either have fled the area or hiding. This phase’s objectives included seizure of the RED positions, destruction of their forces, and security of high-value facilities. Typical operations (mission tasks) in phase I included site and area security, enemy forces engagement, seize/occupy an objective, etc. Typical RED events that must be dealt with in Phase I included destroying infantry, armored, fighting vehicles (tanks and armored personnel carriers), howitzers (both towed and self-propelled), and mortars and air defense systems.

During Phase II, primary enemy units have been driven away or otherwise combat ineffective as the civilian populace returns to normal activities. This phase requires extensive civilian support operations, humanitarian relief aid delivery, rubble removal, reconstruction and security of key facilities and areas with isolated counter-insurgency operations against low-level sporadic enemy attacks. Typical operations (mission tasks) in phase II included site and area security, facility reconstruction, crowd control, patrolling, searches, support of civil security operations, hostage situations, aid delivery, police station support, checkpoints, etc. Typical RED events that must be dealt with in Phase II included responding to Improved Explosive Device (IED) and Vehicle-borne IED attacks, Small-arms attacks, mortar attacks, snipers, riots and criminal activities.

For each of the missions, we defined their plans. Plans specify the sequence of engagements and sub-missions, allow tracking mission success over time, and determine critical tasks and engagements. Figure 4 shows the temporal order structure of the goals and their corresponding subtasks.

Quantitative definition of resources and tasks

In order to define the interactions among assets and entities in DDD, the notion of “capabilities” and “vulnerabilities” is used. *Capabilities* define what the units can do – and can be interpreted as their resource capabilities. The capability types describe specific resources capabilities of units, for example ability to conduct ground surveillance, ability to deliver close-air fire support, availability of engineering resources and capabilities to conduct infrastructure repairs, ability to establish and maintain checkpoints, etc. Similarly, the *vulnerabilities* define what can affect the units, or more precisely, what other units’ capabilities are needed to affect the unit or accomplish a task. Vulnerabilities thus define specific resource requirements for successful engagements, for example the amount of ground surveillance capabilities needed to detect a target, the amount of engineering resources required to repair an oil facility or the amount of air support needed to successfully destroy a tank, a level of enemy troop concentration or fighting position that could result in achieving the goal, etc.

Capabilities and vulnerabilities allow defining the transition states for all objects in the scenario. For example, to kill a target a certain amount of precision fire might be needed (vulnerability), and this might be obtained by using several missiles (and accounting for their combined capabilities). However, the lower amount of fire might only damage the target reducing collateral damage so it later could be repaired and brought to the same level of previous level functionality. It is natural that types of capabilities and vulnerabilities are defined using the same names. As the result, we then need to define vectors of capabilities and vulnerabilities for each object in the simulation.

In our HIL scenarios, the types which defined capabilities and vulnerabilities are shown in Figure 5. The capabilities of the BLUE assets are shown in Figure 6, and vulnerabilities (resource requirements) of RED assets and mission tasks are shown in Figure 7. These parameters allowed players to decide what resources to use and where.

Type	Description
SCR	Secure (areas, sites);
SZ	Seize & Occupy (areas, sites)
EN	Envelope-Isolate-engage (of the enemy forces)
TRSP	Transport/MED Evac (of forces, soldiers, civilians, etc.)
CENGR	Combat engineering & counter-IED ops – to conduct repairs of equipment and IED disarmament and road blocks removal
MENGR	Engineering and Reconstruction (mechanized) – to conduct facility reconstruction and complex repairs
MAN	Manage-Maintain-Setup (checkpoints, facilities, buildings)
GREC	Ground Recon-Search – to search buildings, routs, collect intelligence on the ground
AREC	Air Recon – to collect intelligence from the air (e.g. by UAVs) – mostly imagery and radar
INT	Interrogate civilians, criminals, enemy combatants
STOP	VBIED attacker engagement – be able to stop the vehicles without harming the occupants (w/o destroying the vehicle)
SNIP	Sniper fire against enemy – this refers to precision small-arm fire that is provided by sniper teams
FIRE	Non-precision Fire against enemy – including direct and indirect fire capability, such as missiles, bombs, artillery, etc.
CRIOT	Riot/Protest Control ops – this refers to security operations that need to be conducted to reduce hostilities and prevent rioting
DTN	Detain enemy combatants, civilians, etc.
PTRL	Patrol/Force presence ops – patrolling operations, which very often are conducted to enforce the curfews, show presence and discourage criminals from illegal actions, and militia from attacks
IED	Attack by IED – will most probably create casualties; a very common piece of attacks by RED on BLUE
RIOT	Civil disturbance, protests, rioting; these are capabilities of RED and vulnerabilities of
CRIME	Criminal activity of looting, robbing, sabotage
CA	Civil affairs, Public works

Figure 5: Types of capabilities and vulnerabilities used in PERSUADE scenario

For example, a rifle company unit of RED forces requires the following resources to be engaged successfully:

SCR	SZ	EN	TRSP	CENGR	MENGR	MAN	GREC	AREC	INT	STOP	SNIP	FIRE	CRIOT	DTN	PTRL	IED	RIOT	CRIME	CA
0	0	1	1	0	0	0	1	0	0	0	2	0	0	0	0	0	0	0	0

Looking at capabilities of BLUE assets, we see that in order to successfully engage a RED rifle company, BLUE must attack it with 5 assets: 2 Rifle Companies, 1 Recon Troop, 1 tank company (or equivalent heavy force), and 1 UH60 (or CH47) helicopter platoon.

Arcronym	SCR	EN	TRSP	CENGR	MENGR	MAN	GREC	AREC	INT	STOP	SNIP	FIRE	CRIOT	DTN	PTRL	IED	RIOT	CRIME	CA
Name	Secure	Envelope-Isolate-engage	Transport/MED Evac	Combat engineering & counter-IED ops	Engineering and Reconstruction (mechanized)	Manage-Maintain-Setup	Ground Recon-Search	Air Recon	Interrogate	VBIED attacker engagement	Sniper fire against enemy	Fire against enemy	Riot/Protest Control ops	Detain	Patrol/Force presence ops	Attack by IED	disturbance, protests, rioting	of looting, robbing, sabotage	Civil affairs, Public works
RFL CO	1	0	0	0	0	1	0	0	0	0	1	0	1	0	1	0	0	0	0
WPN CO	1	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
MTD TRP	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
DSM TRP	1	0	0	0	0	1	0	0	0	0	0	0	1	1	1	0	0	0	0
REC TRP	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
BTTR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TNK CO	0	1	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
MECH ENGR CO	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CMBT ENGR CO	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
FA BTR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MP CO	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0
MI CO	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
OH58D (4)	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
AH64 (4)	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0
UH60 (4)	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
CH47 (4)	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
HELLFIRE Msl	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0
HOW 105 Msl	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0
HOW 155 Msl	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0

Figure 6: Capabilities of BLUE assets

	Arcronym	SCR	SZ	EN	TRSP	CENGR	MENGR	MAN	GREC	AREC	INT	STOP	SNIP	FIRE	CRIOT	DTN	PTRL	IED	RIOT	CRIME	CA
	Name	Secure	Seize & Occupy	Envelope-Isolate-engage	Transport/MED Evac	Combat engineering & counter-IED ops	Engineering and Reconstruction (mechanized)	Manage-Maintain-Setup	Ground Recon-Search	Air Recon	Interrogate	VBIED attacker engagement	Sniper fire against enemy	Non-precision Fire against enemy	Riot/Protest Control ops	Detain	Patrol/Force presence ops	Attack by IED	Civil disturbance, protests, rioting	Criminal activity of looting, robbing, sabotage	Civil affairs, Public works
RED (Phase II)	VBIED Truck	0	0	0	0	0	0	0	0	1	0	**1**	0	**0**	0	0	0	0	0	0	0
RED (Phase II)	IED	0	0	0	0	**1**	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
RED (Phase II)	Attackers	0	0	**1**	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0
RED (Phase II)	Snipers	0	0	0	0	0	0	0	1	0	0	0	**2**	0	0	0	0	0	0	0	0
RED (Phase II)	Rioting crowd	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1
RED (Phase II)	Mortar site	0	0	0	0	0	0	0	0	**1**	0	0	0	**4**	0	0	0	0	0	0	0
RED (Phase II)	Criminals	0	0	0	**1**	0	0	0	0	0	**1**	0	0	0	0	**1**	0	0	0	0	0
RED (Phase I)	Rifle Co	0	0	1	1	0	0	0	1	0	0	0	**2**	0	0	0	0	0	0	0	0
RED (Phase I)	T-62	0	0	0	0	0	0	0	0	**1**	0	0	0	**4**	0	0	0	0	0	0	0
RED (Phase I)	BMP	0	0	0	0	0	0	0	0	**1**	0	0	0	**2**	0	0	0	0	0	0	0
RED (Phase I)	122mm D-3	0	0	0	0	0	0	0	**1**	**0**	0	0	0	**2**	0	0	0	0	0	0	0
RED (Phase I)	122mm SP 2S1	0	0	0	0	0	0	0	**1**	**0**	0	0	0	**2**	0	0	0	0	0	0	0
RED (Phase I)	BM-21	0	0	0	0	0	0	0	0	**1**	0	0	0	**2**	0	0	0	0	0	0	0
RED (Phase I)	ZSU-23-4	0	0	0	0	0	0	0	1	1	0	0	0	4	0	0	0	0	0	0	0
Mission & Civilians	Crowd	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0	**1**
Mission & Civilians	Truck	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0
Mission & Civilians	Block/Building Search	0	0	0	0	0	0	0	**2**	0	0	0	0	0	0	0	0	0	0	0	0
Mission & Civilians	Site Secure	**1**	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mission & Civilians	Area Secure	**2**	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
Mission & Civilians	Facility Reconstruction	**1**	0	0	1	0	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mission & Civilians	Setup-Man Checkpoint	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Mission & Civilians	Rubble Removal	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mission & Civilians	Facility maintenance	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Mission & Civilians	Relocation Center	1	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0
Mission & Civilians	Objective Seize/Ocpy	**2**	**0**	**2**	0	0	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mission & Civilians	Hostage Situation	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1
Mission & Civilians	Aid Delivery	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Mission & Civilians	Water facility sabotage	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mission & Civilians	Police station security support	**2**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
Mission & Civilians	Civilians ops	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2
Mission & Civilians	Looting	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
Mission & Civilians	Search & Rescue	1	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mission & Civilians	Patrolling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0

Figure 7: Vulnerabilities (resource requirements) of RED assets and mission tasks

<u>Assets of BLUE forces:</u>

- **Rifle Company (RC):Under this scenario, the** primary mission of the rifle company is to conduct various security operations
- **Weapons Company (WC):** primarily used for combat engagements with crew served weapons and mortars
- **Motorized Troops (MT):** primarily used for maneuver combat missions and for patrol operations
- **Dismounted Troops (DT):** primarily used for maneuver combat missions and for patrol operations
- **Reconnaissance Troops (RT):** used for ground recon operations
- **Battery (BT)** unit consisting of 4-6 howitzers, rockets or heavy mortars: used for indirect fire missions; does not have resident capabilities - has ten 81-120 mm rounds or rocket equivalents with a 1000 km/hr velocity
- **Tank Company (TC):** mostly used for offensive engagements with enemy ground forces
- **Mechanized Engineer Company (ME):**used for mobility and counter mobility operation and field fortification and fighting position preparation

- **Combat Engineer Company (CE):** used for the equipment repair missions and facility maintenance and route repair and maintenance
- **Field Artillery Battery (FA):** used for indirect fire missions; contains self propelled howitzers or towed artillery; does not have capabilities – medium artillery is modeled to carry ten 155mm howitzer rounds or rocket equivalents with , 300 km/hr velocity
- **Military Police (MP) company:** used for policing, traffic control, checkpoint manning, facility/site security, interrogation and, detention of enemy combatants, POW control and routine patrolling
- **Military Intelligence (MI) company:** used for intelligence gathering (ELINT, SIGINT and HUMINT) and analysis, for interrogation of detained enemy combatants or other sources of intelligence, as well as targeted patrolling to gather specific information
- **OH58D helicopter (OH58D):** Kiowa helicopter platoon (of 4 helos) used for air recon and target designation
- **AH64 helicopter (AH64):** Apache helicopter platoon (of 4 helos) does not have capabilities; instead it is modeled to carry eight HELLFIRE missiles
- **UH60 helicopter (UH60):** Black Hawk helicopter platoon (of 4 helos), used for medical evacuation and general medium lift transportation and air assault operations
- **CH47 helicopter (CH47):** Chinook helicopter platoon (of 4 helos) used for heavy lift of personnel, supplies or equipment through conduct of routine transportation operations
- **Civil Affairs (CA):** used for civil affairs operations in support of local or host nation officials and entities.
- **Munitions and Missiles:** there are three types of munitions in the current scenario; all have capabilities of type "fire", and are distinguished by either the fire capability amount (essentially, an impact of the weapon) or by the weapon's velocity and range; these systems are:
  - **Howitzer 105mm round:** *FIRE = 6*, velocity = 300 km/hr, range = 11 km
  - **Howitzer 155mm round:** *FIRE = 6*, velocity = 500 km/hr, range = 22 km
  - **HELLFIRE (AGM-114) missile round:** *FIRE = 6*, velocity = 1000 km/hr, range = ½ km

<u>Assets of RED forces:</u>

- **RED Rifle Co (RR):** this models RED infantry company-size unit that can engage BLUE in ground combat using small-arms area and precision fire
- **T-62 (RT):** this models RED 2-Tank formation, which will engage BLUE in ground combat providing direct fire against BLUE units
- **BMP (RBMP):** this models a group of 2 RED mechanized infantry fighting vehicles involved in maneuver combat operations against BLUE forces utilizing direct weapons systems (small arms, machine guns and light automatic cannon)
- RED artillery **–122mm D-3 (RD) weapons system** which is a towed howitzer, **122mm SP 2S1 (RSP) weapons system** which is a self-propelled howitzer (Gvozdika), and **BM-21 (RBM)**, a mobile mortar system (Grad) modeled to represent RED indirect fire artillery. These units differ by their maneuverability, but are the same in terms of their resource capabilities:
- **ZSU-23-4 (RZS):** this is an anti-aircraft air defense gun system (Shilka), specifically used for targeting BLUE helicopter aviation
- **VBIED Truck (RT):** this models vehicle-borne explosives that are carried on a truck; that explodes on impact or is command detonated; the capabilities are modeled as "IED"

- **Improvised explosives device (IED):** Hidden bomb that is remotely detonated
- **Attackers (ATK):S**mall fighting formations that attack with small-arms fire
- **Snipers (SN):** Enemy teams that attack and harass BLUE forces; attack by precision fires
- **Rioting crowd (RIO):** Crowd that riots and can become blue force attackers
- **Mortar site (MS):** Launcher of usually short range projectiles onto BLUE forces; we model it as an asset with strong FIRE capability
- **Criminals (CR):** Criminal gangs that can damage facilities, interfere or impair SASO operations

Tasks of the Mission and Civilian entities

- **Conduct Block/Building Search**
- **Site Security**
- **Area Security**
- **Facility Reconstruction**
- **Establish Manned Checkpoints**
- **Rubble Removal**
- **Facility Maintenance**
- **Relocation Center**
- **Secure an Objective**
- **Hostage Situation Support**
- **Humanitarian Aid Delivery**
- **Water facility sabotage and mitigation**
- **Police station security support**
- **Civilians Operations**
- **Protect against Looting**
- **Search & Rescue**
- **Patrolling**
- **Crowd: crowd of civilians that may become unruly**
- **Truck: normal vehicle; but can become VBIED**

Results

C2 organizational structures designed by expert and by algorithms

In our HIL experiment, we have used the same assets for each phase. The assets that were not needed in one of the phases did not interfere with another phase, because they were positioned on other platforms and hidden from view of the players. This prevented excessive cluttering of the battlefield (a playfield for human-in-loop game participants). However, the allocation of units to commanders in each phase was different.

The expert planner designed a single C2 structure for each phase of mission execution. Our model-based solution included two different C2 structures – one for each phase. Figure 8 shows the allocation of assets to the players (indicated in the columns as DM1[2] through DM5). We intentionally kept the quantities of resources the same for all organizations for a "cleaner" experiment. Original SME organization was specified with fewer resources of some types while larger number of resources of other types. We have evened the numbers according to the events and tasks within the scenarios – so that no redundant resources were present.

Comparison measures

In our study, we have used a set of measures to compare performance and processes of SME-designed and algorithm-based C2 organizations. The limited set of measures we used was based on our hypotheses about mission performance and some of the constraints of the experimental design. The latter include, for example, the fact that the experiment was designed with a binary deterministic variable describing the target/task execution (either as "completed successfully" or as

[2] DM stands for "Decision Maker", which corresponded to a single player in the DDD game

“not completed”); due to this, the “partial credit” assignment (i.e., “task completed with 80% success”) was not possible. The following list describes the measures of performance and process used in the experiment:

Performance measures:

- Number of Operations Completed Successfully
- Average Response Time per Operation

Process measures:

- Workload Balance of Commanders
- Team Coordination Load as average number of Commanders per Operation/Task

In the following sections, we provide a description of the comparisons for average measures together with statistical significance results. For the latter we used a P-value, which is the probability that an effect at least as extreme as the current observation has occurred by chance. f The P-value of 0.05 means that there is a 1 in 20 chance of obtaining a result as extreme as that observed solely due to chance. Thus, the P-value of 0.05 or low for the difference between two variables is considered statistically significant indication that the variables are not the same.

		SME						OPTIMAL-I						OPTIMAL-II					
	Assets	DM1	DM2	DM3	DM4	DM5	Tot	DM1	DM2	DM3	DM4	DM5	Tot	DM1	DM2	DM3	DM4	DM5	Tot
Troops	RFL CO	11	11	7	6		35	8	7	7	7	6	35	7	7	7	8	6	35
	WPN CO	2	2				4				2	2	4	2	1		1		4
	MTD TRP	2	2				4			1		3	4		1	1		2	4
	DSM TRP	1	1				2	1	1				2	1		1			2
	REC TRP			9	9		18	4	6	3	3	2	18	2	3	2	5	6	18
Fires	BTTR	2	2				4	1	1	2			4			1	1	2	4
	TNK CO	2	2	4			8	1	3	1	1	2	8	2	2	2		2	8
	AH64 (4)				6		6	1		1	2	2	6	1	2	1	1	1	6
	FA BTR					3	3		1	1		1	3				2	1	3
Support	MP CO					5	5	2			2	1	5		1		2	2	5
	MI CO			5			5	1	1	1	1	1	5	2		2		1	5
	MECH ENGR CO					3	3	1		1	1		3	2	1				3
	CMBT ENGR CO	2	2	2			6	1	1	1	1	2	6	1	1	1	1	2	6
	CA					6	6	2	1	2	1		6	2	2		1	1	6
	OH58D (4)				7		7	1	2	2	1	1	7	1		2	3	1	7
	UH60 (4)				12		12	2	3	2	1	4	12	1	1	3	4	3	12
	CH47 (4)				3		3	2	1				3				2	1	3

Figure 8: Control Structure (Resource Allocation) in Organizations in HIL Experiment

Comparing performance of model-based versus SME-defined C2 structures

One of the most important metrics of performance is the number of successfully completed operations (tasks) during the mission. These include number of targets killed (e.g., RED force elements destroyed) and number of tasks executed (e.g., number of planned engineering support provided and security operations completed). Figure 9 shows a comparison of designed organizations (OPTIMAL and SME) for each of two missions (Phase I and II). We can see that in both scenarios the OPTIMAL organization outperformed the SME-based organization: on average OPTIMAL organization achieved 33% improvement in the amount of successfully executed operations; P-value < 0.03 indicated a statistically significant difference in the obtained results. The improvement in amount of successful operations for OPTIMAL organization versus SME-defined C2 structure was lower in Phase II (17% improvement) than in Phase I (49%). After computing the total number of attempted operations and more detailed analysis (not presented in this paper), we found that the reason for this was in the type of tasks that were present in Phase II and the time window set up in the DDD scenario during which the attack must be completed. This time window affected the ability of a single player to engage the targets and complete tasks alone using only its controlled units.

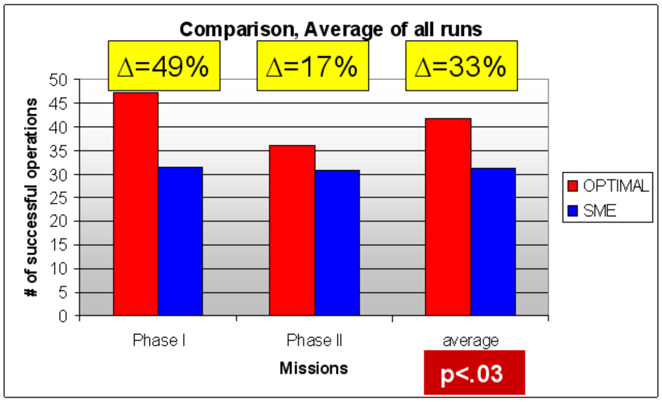


Figure 9: C2 performance comparison --- success of operations

While the total number of operations completed successfully during the mission might be the same, the actual speed with which the organizations can respond to the events, attack targets, and execute mission tasks might be different. This comparison can be conducted by calculating the average response time from the appearance of the event/operation (e.g., appearance of the enemy target) to its final completion (e.g., target kill). The more responsive the organization is (that is, the quicker the organization can find resources and bring them to the area of interest and start the operations), the smaller this measure will be.

Figure 10 shows average response time results for our organizations. We can see that there is a significant improvement in the execution/timeliness achieved by OPTIMAL organization versus SME-based organization in Phase I (over 31% improvement), while in Phase II the improvement was less pronounced (14%). To explain this data, we also looked at the average response time per operation (Figure 10). The results are statistically significant, with P-value < 0.001.

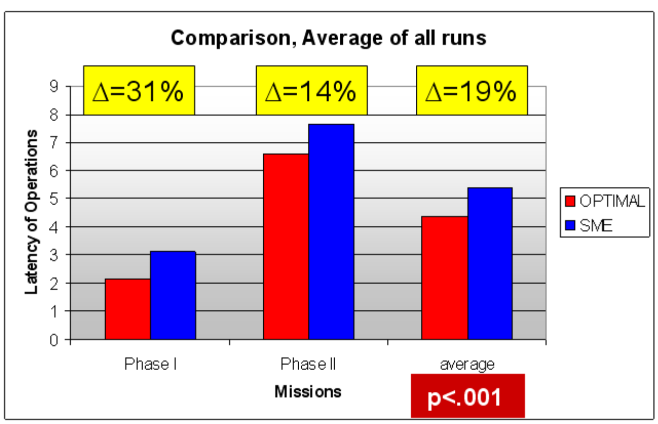
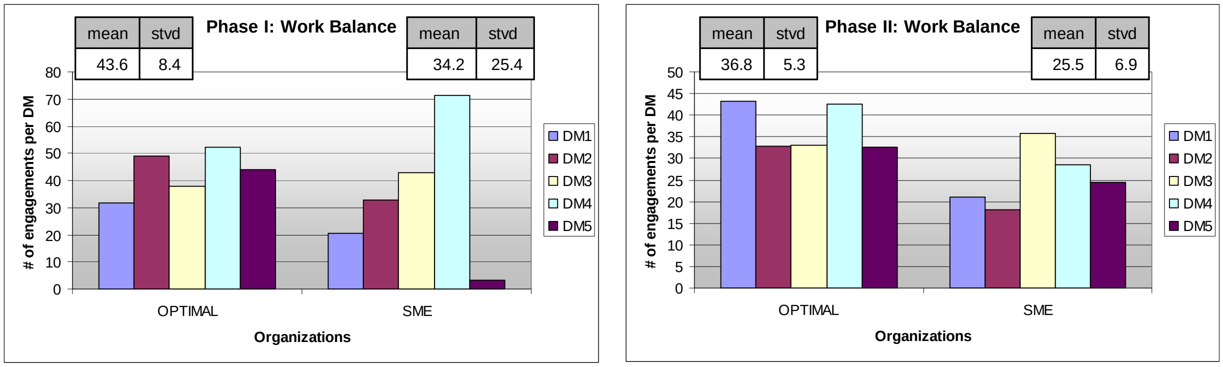


Figure 10: C2 performance comparison --- average response time

Comparing processes of model-based versus SME-defined C2 structures

Performance of the different C2 architectures is affected by their internal processes. The process measures allow us to understand why and how the structural differences influence performance values.



(a) Mission Scenario Phase I

(b) Mission Scenario Phase II

Figure 11: C2 process comparison --- workload balance

First, optimal algorithms attempt to distribute the load of engagements equally among different commanders (players in the game). The operations oftentimes involve using multiple BLUE assets to engage RED assets and complete mission tasks. Balancing the amount of these engagements, measured by “internal workload” of decision makers, prevents the situations in which some players are overloaded while others are not doing any tasks, and is critical to avoiding bottlenecks during mission execution. Figure 11 shows the average distribution of number of engagements per each DM for both missions. We can see that OPTIMAL organization achieves a better balance of such engagements than SME-defined organization. This was more pronounced in Phase I mission, which explains why we have seen a larger improvement in performance of OPTIMAL organization compared to SME organization in Phase I than improvement achieved in Phase II. For example, the SME-based C2 architecture assigned DM4 the control of all helicopter units, which were heavily used in Phase I of the scenario; this resulted in significant overload of the corresponding player during the game. On the other hand, the SME-based asset distribution resulted in number of engagements distributed evenly among players in Phase II. This indicates why in Phase II there was a smaller improvement in performance of OPTIMAL organization compared to SME-based.

Second, optimal algorithms attempt to reduce the coordination requirements among commanders, which is critical to the ability of the organization to operate successfully without overstraining its elements in unnecessary coordination. Coordination is required when a commander does not possess enough resources to execute the operation, or when its resources are overloaded. The coordination can be calculated by analyzing how many players on average participated in executing the same operation. In the ideal case, the tasks are executed by single commanders without reliance on the support from others; however, due to lack of overall resources, this condition can rarely be achieved.

Figure 12 shows the measure of the average number of commanders per operation. We can clearly see that the OPTIMAL organization allows a smaller number of commanders per operation (10% improvement on average), which results in decreased external coordination workload and in turn frees DMs to manage their assets and conduct engagements. We can see that the improvement is more pronounced in Phase I than in Phase II, which follows the same trends described earlier in the performance of two organizations.

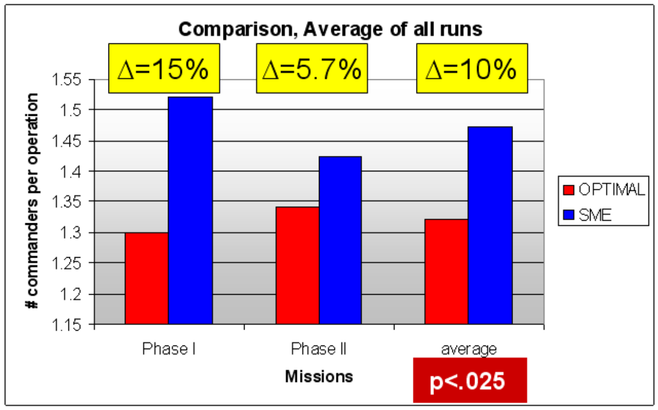


Figure 12: C2 process comparison --- coordination load

Conclusions

The result of human-in-loop experiments presented in this paper provided a final validation of the mission-based optimal C2 design models (Levchuk et al., 2002, 2006) that we developed over the years. The Army modular force concept and corresponding force tailoring process presented a unique domain for our empirical study in which expert planners have to constantly adjust C2 structure to the mission at hand. In this domain, novel C2 constructs are often emerging as the result of manual force organizing, but the sheer multitude of factors that need to be considered make the manual C2 design a time- and manpower-consuming process, and may lead to errors or unnecessary redundancies in the final C2 designs.

In the considered domain, instead of comparing algorithm-derived C2 structure to a “traditional” C2 organization as in previous research (Kleinman et al., 2003; Entin et al., 2006), we allowed expert planners to manually define any C2 architecture they considered fitting the mission at hand, as usually required during Army’s force tailoring process. We thus tested the ability of the algorithms to come up with C2 architecture solutions versus the ability of human expert C2 design decision making.

Our results showed that algorithms are able to derive C2 architectures that are as good as those defined by experts. Moreover, algorithm-derived C2 organizations significantly outperformed the organization defined by an expert planner. The analysis of processes in OPTIMAL and SME-defined organizations indicated that algorithmic solutions were better able to balance the workload and coordination metrics, which are one of the key considerations also used by expert planners during C2 structure design. Our results suggest that quantitative algorithms, with some tuning of parameters for the domain and organization participants, can represent well the complex interactions within the organization executing a mission, and could significantly improve the C2 design solutions.

One of the reasons that OPTIMAL organization was able to outperform the SME-based organization was due to the fact that algorithms were able to model at a more detailed level of granularity the elements of the organization, including the units, commanders, their capabilities and expertise. It is hard to account for all these variables when manually developing the organizational design, while the software is able to handle such complexity. For example, optimization models consider all expected missions, tasks and their resource requirements, while expert planners have to do manual aggregation of operations when deciding about resources needed in the organizations and what commanders to allocate those resources to.

While we had two phases of the mission in our experiment, this was not sufficient to test the quality of adaptive C2 designs that can be developed by algorithms; more rigorous empirical validation studies are needed that can test adaptation policies that span several phases of the mission. In addition to empirical validation, our current research focuses on the ability to define C2 design policies that adapt to external events, the state and performance of the organization and its members, and changing needs of the commanders. Such adaptation policies require accurate estimation of the state of the organization. However, during dynamic military engagements the knowledge of what tasks and operations have been executed, which operations are ongoing, who is involved in them and what are dynamic roles of commanders is often incomplete. Accordingly, our current research efforts include dynamic estimation of the mission progress and roles of commanders to support automated process and performance measurement.

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