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A tool for estimating the costs/benefits of teamwork in different C2 structures

Topic 7
C2 Approaches and Organization

Topic 3
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A Tool for Estimating the Costs/Benefits of Teamwork in Different C2 Structures

Abstract

This paper presents a model and tool for estimating the cost and benefits of various team structures in Command and Control (C2). The method combines task analysis and data-driven modeling as a means to deal with effective team design in military C2. A hierarchical task analysis (HTA) identified the set of subtasks associated with different components of a simulated C2 task. For each team structure considered, we performed a task-to-agent mapping based on the HTA results in order to identify interpersonal task dependencies and identify the activities associated with each agent (taskwork, teamwork and interaction with tools). A mathematical model is then developed to quantify the impact of each element of that mapping on individual workload. Furthermore, the model specifies the effects of workload on team effectiveness as a function of interpersonal dependencies. The calibration of the model is based on an empirical study that tests two team structures. We then describe a tool based on this model and test its potential to estimate the effectiveness of other team structures in order to identify the optimal team design for the simulated C2 task. Finally, future work for expanding this team design tool to different C2 domains is discussed.

Keywords: teamwork, organizational structure, team design, cognition

1. Introduction

Teamwork is often essential in complex and dynamic environments such as command and control (C2). At the tactical level, the context of operations is often one of high constraints in terms of time pressure and uncertainty. Small teams of military units, security or emergency response teams are often confronted with such situations in which they must work together in order to achieve safety-critical goals and mission success. However, team functioning represents in itself an element of complexity (Arrow, McGrath, & Berdahl, 2000; SAS-065, 2010). Given the evolution of C2 towards the development of organizations which are rapidly reconfigurable, decentralized and adaptive (i.e., able to cope with unexpected events), the ability to estimate the costs and benefits associated with particular team structures has become an increasingly important topic (Atkinson & Moffat, 2005). Progress in the science of C2 and team effectiveness is leading to an increased need to combine the key approaches developed in order to obtain more powerful integrative methodologies. In the current project, our goal is to develop a tool that integrates results from a task analysis and laboratory experimentation to enable users to estimate the cost and benefits of teamwork in tactical C2 and identify team structures that support optimal team effectiveness.

1.1 Cost/benefit tradeoffs in team design

McIntyre and Salas (1995, p. 11) describe a team as a “set of two or more individuals who interact interdependently and adaptively to achieve specified, shared and valued objectives”. Each team member has to perform some tasks associated with his or her role within the team. Although there is good theoretical agreement that the structure of a team greatly influences interdependence relations and team functioning (see Price, Miller, Entin & Rubineau, 2001; Sartori, Waldherr, & Adams, 2006), much empirical work remains needed to understand the complex relationship between team structure and team effectiveness.

There is generally no major distinction in the literature between task allocation, role allocation, team structure, organization and team architecture. The main idea behind all these concepts is the distribution of task demands among team members in such a way that the organization is as effective as possible. However, the concepts of team structure/organization/architecture may be seen as being more inclusive, in the sense that they refer to the allocation of roles, tasks, information and tools (Levchuk, Chopra, Levchuk & Paley, 2005). Different team structures may involve particular benefits resulting from the leverage achieved by combining individual capabilities in different ways. These structures impose teamwork requirements. Coordination and communication among team members come with a cost in effectiveness (MacMillan, Entin, & Serfaty, 2004). Some team structures may exacerbate teamwork requirements to the point that no benefits are observed, while others can maximize the benefits without entailing extensive interaction costs. Besides the context of operations and environmental constraints, the effectiveness of different team structures depends on this interplay between interaction costs and benefits of teamwork. Since this interplay is not well understood, the aim of the present work is to develop a tool for estimating the effects of the organizational structure on team effectiveness.

1.2 Overview of the methodology

Various team structures have their particular advantages and disadvantages as related to the task and environmental conditions (Devine, 2002). These costs and benefits result in tradeoffs whose team effectiveness outcomes are very difficult to predict because they are context-specific. Nonetheless a principled approach for modeling the effects of team structure on team effectiveness within a particular context can be considerably beneficial if it can help design superior team structures. The purpose of the present project is to develop a tool for predicting the effectiveness of different team structures. The method we propose for estimating the costs/benefits of different team structures combines two distinct approaches:

1) A *data-driven* approach, based on team effectiveness in a simulated task
2) A *task-driven* approach, based on the analysis of the C2 task, teamwork requirements, and tool interactions.

The proposed methodology for the *data-driven* part of the analysis is to perform a microworld experiment using a simulated C2 task for teams and manipulating team structure. This data will later provide constraints that will help estimate the parameters of a model based on the results of the task-driven part of the analysis. Microworlds are task environments that are used to study behaviour under simulated conditions within a laboratory setting (Brehmer, 2004). They retain the basic or essential real world characteristics while leaving out other aspects deemed superfluous for the purposes at hand. Microworlds offer the great advantages of experimental manipulation and control, without stripping away the complexity and the dynamic nature of the task. We opted for the C^3Fire microworld as our testing platform (Granlund, 1998; 2003). C3 stands for command, control and communications. C^3Fire is a functional simulation tailor-designed to investigate tactical C2 in small teams, though the actual microworld simulates firefighting rather than military operations. C^3Fire is appropriate for a functional simulation of military C2 since it involves time-pressure, uncertainty and teamwork: three key considerations for tactical teams. As is the case with real tactical situations, the simulated task requires dynamic team decision making. It involves regulating a dynamic system where: 1) a series of activities are required to reach/maintain the overall goal; 2) activities depend on the outcome of previous activities; 3) task parameters are continuously varying in response to changes; and 4) tasks are accomplished in real time within the microworld.

The proposed methodology for *task-driven* modeling is based on hierarchical task analysis, or HTA (Annett, Duncan, Stammers, & Gray, 1971). We selected HTA because it is a widely used, generic approach that forms the basis of a number of more specialized methods (Crystal & Ellington, 2004; Shepherd, 2001; Stanton, 2006). While the HTA provides an informative decomposition of taskwork, it is performed independently of team structure and therefore does not identify activities related to teamwork. The subsequent step will do just that: a task-to-agent mapping will use the results of the task analysis to characterize the taskwork, teamwork, interaction with tools and interpersonal dependencies that follow from specific task allocations and role assignments.

The final part of the methodology is to integrate results from the data-driven and task-modeling components of the methodology to produce a mathematical model characterizing the relationship between team structure and team effectiveness. The mathematical model quantifies the impact of each element of the task-to-person mapping on individual workload and specifies the functional relationship between individual workload, individual efficiency, and team effectiveness while taking into account interpersonal dependencies between team members. Once calibrated on experimental data, the model can be used to predict the effectiveness of other possible team structures on the same task.

The approach taken here to estimate the costs/benefits of teamwork is somewhat similar to the EAST methodology (Event Analysis of Systemic Teamwork) proposed by Baber and Stanton (2004). EAST combines a number of human factors research methods to study team activity in a C4I work context (command, control, communications, computers and intelligence):

> "EAST provides an assessment of agent roles within the network, a description of the activity including the flow of information, the component tasks, communication between agents and the operational loading of each agent. Coordination between agents is also rated and the knowledge required throughout the task under analysis is defined" (Stanton, Baber, & Harris, 2008, p. 54).

Two of the methods employed in EAST, namely HTA and observation/measurement, correspond to those used in the present study. The task-to-agent mapping accomplishes a purpose similar to coordination demands analysis (defining taskwork and teamwork) in the EAST methodology. The EAST methodology is an assembly of distinct techniques capable of providing multiple views on team activity. The descriptive capabilities of this approach are extensive. Stanton et al. (2008) note however that the method it is very time consuming because it is so exhaustive. Our goal is to use a more simple and focused approach for the purpose of developing a team design tool.

2. Simulated C2 task

The C^3Fire microworld is a simulation of a complex and dynamic task in the firefighting domain. It is considered dynamic because the fire evolves autonomously over time, with or without human intervention. The task is considered complex because several interacting variables must be considered to make appropriate decisions. The high level of time pressure also adds complexity to the task: time taken to make a decision or to gather more information necessarily comes with a cost since the fire continuously grows with the passing of time. Despite some lack in the "face value" of C^3Fire for simulating tactical C2, there is good evidence that this microworld reproduces many of its critical aspects and provides a challenging and engaging arena for team decision making (Granlund, 2003).

2.1. Method

Twenty-four 3-person teams performed a 2-hour experiment including instructions, 2 practice scenarios (15 min each), 4 test scenarios (15 min each) and a workload questionnaire. Participants were recruited from the student population at Université Laval. They received 15 dollars for participating in the experiment. Teams were randomly assigned to a functional or multifunctional team structure. Participants were randomly assigned to a computer station (X, Y or Z) at their arrival in the research laboratory. Figures 1 and 2 summarize the unit (and role) allocation in each team structure. In a functional team structure, individuals have different complementary roles: coordinating either firefighters (FF) or water-tankers (WT). In a multifunctional team structure, individuals have both roles. Note that the total number of units is constant.

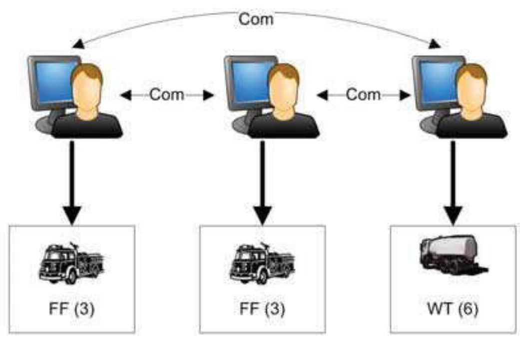

Figure 1. Functional team structure

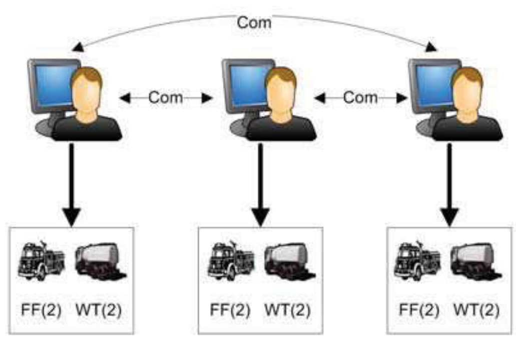

Figure 2. Multifunctional team structure

The key challenges in C^3Fire are related to two objectives: put out fires and save houses. To do so, the team must select the most important fires to extinguish first, protect houses, ensure that firefighters are refilled in a timely manner, and re-supply water tankers at appropriate times. To exchange information, participants communicated using headphones with an integrated microphone. Scenarios also included unexpected critical changes (the sudden appearance of a new fire, or a radical change in wind strength and direction) which required adaptability. At the end of the experiment participants completed a questionnaire asking them to rate their perceived workload on two dimensions: mental load and time-pressure. These two dimensions of workload are part of the NASA TLX workload rating scale (Hart & Staveland, 1988). Each dimension was rated on a scale from 1 (very low) to 10 (very high). This workload measure will be important to calibrate the mathematical model and team design tool presented below.

Team effectiveness in C^3Fire is defined by the team's success in managing both the *defensive* and the *offensive* aspects of the task, namely protecting the houses from the fire and putting out at many fire cells as possible. Effectiveness is calculated by multiplying the proportion of saved houses by the number of extinguished cells. Higher values correspond to a better overall effectiveness. The proportion of saved houses corresponds to 20 (the number of houses that are set to burn out if participants do nothing) minus the number of houses which are burned out at the end of a scenario, divided by 20:

Effectiveness = number of extinguished cells X (number of houses saved/20)

2.2 Results

Team effectiveness differed significantly between the multifunctional and functional structure, $t(22) = 2.92$, $p < .01$. Multifunctional teams obtained on average a better score ($M = 49.36$, $SD = 12$) than functional teams ($M = 32.73$, $SD = 15.64$). Functional teams ($M = 15.13$, $SD = 2.28$) showed similar *average* workload ratings (no statistically significant difference) to those of the multifunctional teams ($M = 14.50$, $SD = 2.04$). However, workload *distribution* among the team members was not the same in the two organizational structures. We compared the perceived workload of Participant X_F (the one in the functional structure with 6 WT units) to the averaged perceived workload of Participant Y_F and Z_F, who each controlled 3 FF units. We performed the same comparison for Participant X_M (in the multifunctional structure) and the average workload rating of Participants Y_M and Z_M. In the multifunctional structure, no difference was expected since all three participants controlled 2 FF and 2 WT units. Indeed, no significant difference in workload distribution was found in the multifunctional structure, $t(22) = .218$, ns. However, for the functional structure, the workload rating of Participant X_F was found to be significantly greater than that of his two teammates, $t(22) = 3.296$, $p < .01$. Workload was distributed unequally in the functional structure.

2.3 Discussion

The relatively lower effectiveness of functional teams observed in our experiment may partly be explained by *workload imbalance* and *interpersonal dependency*, which may have offset the benefits of task specialization. First, while there was no significant difference in the overall workload of functional and multifunctional teams, there was a *workload imbalance* among members of functional teams. Participant X_F, in charge of controlling all six water-tankers, generally reported having a higher workload than Participants Y_F and Z_F, who were each in charge of 3 firefighters. This result can be easily explained by the fact that a distribution of 4/4/4 units in the multifunctional structure may produce a more balanced workload than a distribution of 6/3/3 units. It is therefore possible that functional teams were disadvantaged compared to the multifunctional teams in part because Participant X_F was overloaded. Second, functional teams are characterized by *interpersonal task dependency*. A functional task allocation tends to make some team members depend on others due to interpersonal dependency. In the case of C^3Fire, Participants Y_F and Z_F need water from Participant X_F to perform their task correctly, so overloading Participant X_F can be very detrimental to overall team effectiveness. For the purposes of the present research, these results are especially useful as constraints for data-driven modeling in Section 4.

3. Task structural modeling

Since the primary difference between team structures is task allocation among agents, it is essential to carry out some form of task modeling to identify the set of subtasks that can be allocated to different team members. The task structural analysis presented in this section aims to provide an important set of constraints for the ulterior development of the analytical method aimed at estimating the cost/benefits of different team structures. This task-driven modeling phase includes two successive steps. The first step mainly relies on the hierarchical task analysis methodology to characterize taskload (i.e., workload associated to taskwork – decomposed into subtasks). The second step essentially aims to associate this taskload to specific team members as a function of team structure.

3.1. Extended hierarchical task analysis

The main goal of the current analysis is to identify and document the subtasks that must be performed to successfully operate in the C3Fire microworld. This analysis does not focus on a particular team structure: it represents the generic tasks that must be performed regardless of the actual assignment of units and subtasks, either to a single agent or to several team members. Hierarchical Task Analysis (HTA) has the benefits of being readily understandable and provides few constraints on the analysis (Annett et al., 1971). A hierarchical structure is a central component of most approaches to task analysis and task modeling.

The HTA of the task simulated in the C^3Fire microworld relied on three information sources: 1) existing documentation, 2) observation, and 3) interviews of subject matter experts (i.e., two experienced C^3Fire players who helped design the scenarios). In an initial stage of the analysis, two versions of the task decomposition were independently sketched and then put together. A draft was then computerized using Mindjet MindManager Pro 6 and revised to improve precision and internal coherence. A second stage of the task analysis was to validate/revise each element in the task decomposition using replays of the C^3Fire scenarios. There are two possible roles in the current C^3Fire experiment: firefighting and water-provisioning. A third stage of the analysis was to extend the task decomposition by associating each low-level subtask to “tools” (or information sources) required to accomplish it. Additionally, for each subtask on the last level of the hierarchy, the subject matter experts indicated whether it was relevant for the supervisory control of firefighter units (FF), of water-tanker units (WT), or both. This subtask-role assignment constitutes a necessary input for the upcoming task-to-agent mapping. Figure 3 presents the results of this extended HTA. These results will form the main content of the task-to-agent mapping described below.

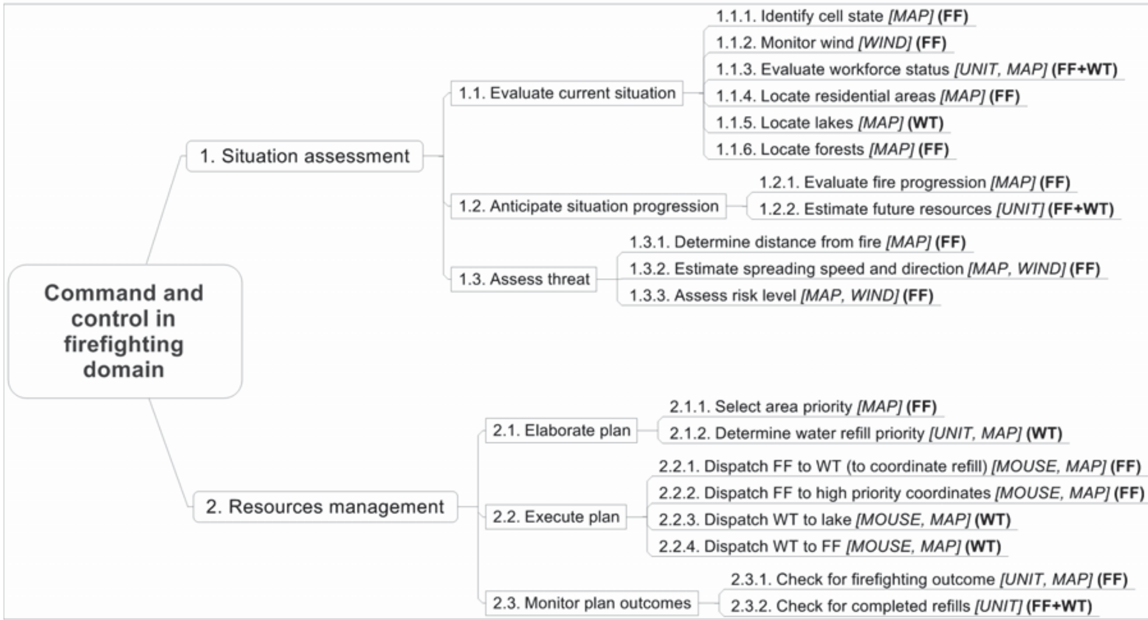

Figure 3. HTA representation, with tasks associated to specific roles and tools. FF = firefighting role, WT = water-provisioning role, MAP = Geospatial information display, UNIT = Unit information panel, WIND = Wind information panel, MOUSE = Computer mouse.

3.2. Task-to-agent mapping

In order to model the effects of team structure, it is necessary to identify how various structures differ. The essential difference between team structures is how sub-tasks are allocated. However, different *task allocations* also have an impact on the *teamwork* required to accomplish the task. An integrative representation of the workload of each individual must therefore include both the *taskwork* and *teamwork* required to accomplish the mission (Essens et al., 2005; Salas, Dickinson, Converse, & Tannenbaum, 1992; Shanahan, 2001). Task allocation also influences the *tools* that each participant must interact with and *interpersonal task dependencies*. The task-to-agent mapping aims to characterize the demands made on each individual with respect to taskwork, teamwork, tools, and interpersonal task dependency. More precisely, we submit that taskwork, teamwork and tool interaction are three forms of workload, and that interpersonal task dependencies can constrain the efficiency of certain individuals within the team.

Figures 4 and 5 show the task-to-agent mapping of the multifunctional and the functional team structures along the four dimensions hypothesized as key structural factors of team workload and effectiveness: taskwork, teamwork, tool interaction, and prerequisites (i.e., interpersonal task dependency). For clarity, taskwork is subdivided in two distinct functions: situation assessment and resource management. Participants who perform many roles (i.e., who control both FF and WT) have more information requirements than those who perform a single role (i.e., with only one type of unit to control). For example, participants who only control WT do not require information about the localization and state of households. Participants who only control FF do not need information on the position of lakes. More precisely, participants having a pure water-provisioning role will need to perform only 3 out of the 11 third-level subtasks.

Participants with only the firefighting role will need to perform 10 out 11 tasks. Participants with both roles will need to perform 11/11 subtasks. Information requirements (in terms of situation assessment) are therefore greatly reduced when a participant specializes in water-provisioning but only marginally reduced when a participant specializes in firefighting, compared to a participant performing both roles.

The contents of the *taskwork* and *tool* nodes in the task-to-agent mapping are determined by the HTA diagram shown in Figure 3 based on the role(s) of each participant (firefighting, water-provisioning, or both). For resource management, taskwork also depends on the number of units to control. Three important tools in C^3Fire were not identified in Figure 3 because they are related to teamwork rather than taskwork. The *coordinate system* (letters and numbers on the left and top of the geospatial map) and the *pointer position panel* are essential when two individuals must coordinate the movements of their FF/WT units to perform a water refill (team members do not see their respective units on the map unless they are very close). While the participant controlling a FF unit can simply provide the FF unit's coordinates to his teammate using the information displayed in the unit info panel, the one sending the WT unit to that position must use the coordinate system and the pointer position panel to dispatch his unit to the correct location. The third tool is the *communication button* (together with the headphones), which is essential for goal-oriented and resource-oriented coordination, information sharing and backing up behaviours.

The *teamwork* node lists the collaboration processes that each participant must perform and how many resource-oriented coordination processes are required as a function of the number of units controlled. Four key teamwork processes were identified by studying communication recordings from the C^3Fire experiment: Information sharing, backing up behaviours, goal-oriented coordination and resource-oriented coordination. Information sharing (Garstka & Alberts, 2004; Jobidon, Tremblay, Lafond, & Breton, 2006) occurs for example when a participant detects and communicates a critical change such as a new fire or a change in wind strength and direction. Backup behaviours (Porter et al., 2003) include directing a teammates' attention to an unattended unit, making suggestions on how to perform better, finish extinguishing another teammates' fire when he/she runs out of water. Goal-oriented coordination is when participants make decisions about priorities or develop strategies on how to fight the fire. Resource-oriented coordination refers in C^3Fire to the need to communicate the need/offer for water, provide unit position and confirm one's intentions when the firefighting and water-provisioning roles are distributed in an exclusive manner between team members. Our distinction between these two forms of coordination is inspired by Coordination Theory (Crowston, 1997):

> "According to coordination theory, [team activities] can be separated into those that are necessary to achieve the goal of the process (e.g., that directly contribute to the output of the process) and those that serve primarily to manage various dependencies between activities and resources" (p.159).

Finally, the *prerequisite* node identifies interpersonal task dependency. Clearly, a key precondition of firefighting is having water. In functional teams, the efficiency of Participants Y_F and Z_F necessarily depends on the efficiency of Participant X_F in providing water to the FF units. Unlike the other elements of the task-to-agent mapping, a prerequisite is not seen as a factor that contributes to an individual's workload, but rather as a constraint on the efficiency of a team member who depends on the actions of a teammate. Individual efficiency is defined here as the skillfulness in achieving one's role without wasting time or effort or expense. Other possible prerequisites occurring before the event are not included here, such as the need to train together, understand each other's roles and responsibilities, and develop a mental model of the other tasks/team members so that the operation has a chance of running smoothly (Huber, Eggenhofer, Römer, Schäfer, & Titze, 2007; Kozlowski & Ilgen, 2008).

We underlined some key elements in the task-to-agent mapping and placed a star besides them to identify those components that are not constant for all participants across the two team structures. It is what varies here that helps the most in explaining workload differences either within a team or between two structures. There are three distinct task-to-agent mappings amongst the six ones described in Figures 4 and 5. The three participants in the multifunctional team structure have the same mapping. In the functional team structure, Participant X is different from Participants Y and Z.

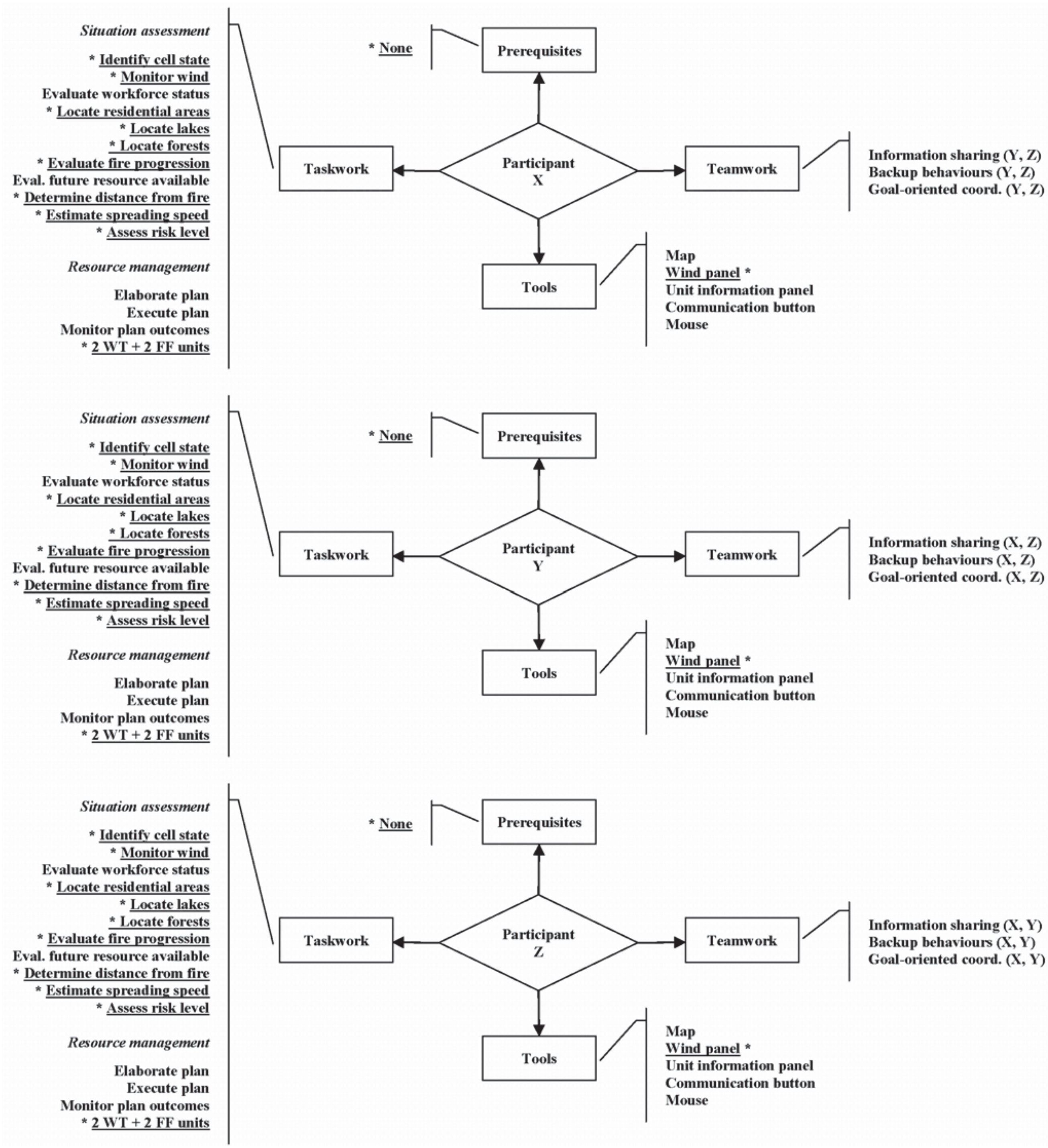

Figure 4. Task-to-agent mapping: Multifunctional team structure

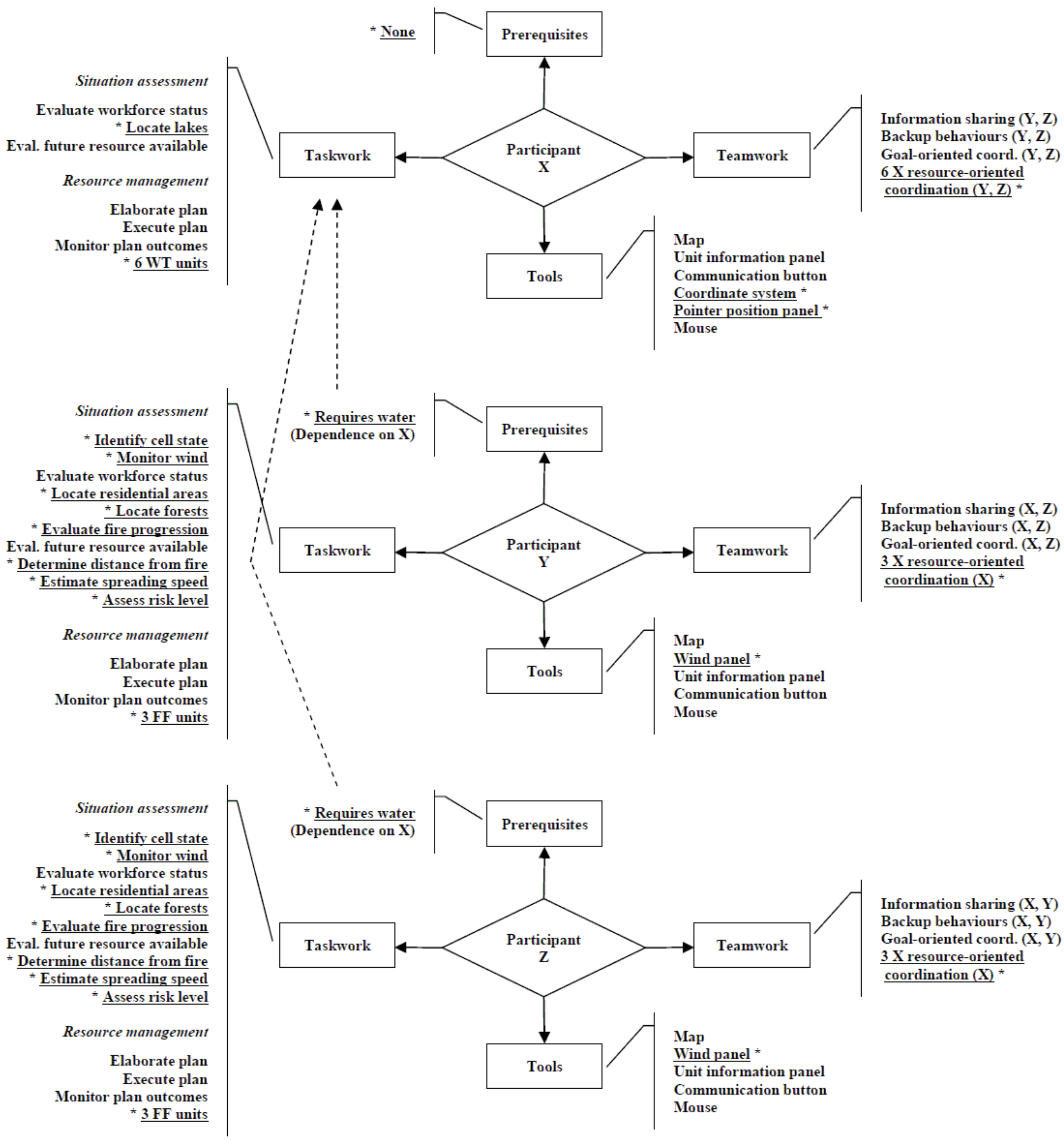

Figure 5. Task-to-agent mapping: Functional team structure

Table 1 summarizes the various sources of workload identified in the task-to-agent mapping for the multifunctional and the functional team structure. The numbers correspond to the (unweighted) sum of workload elements associated with the tasks or processes relevant to each dimension. For situation assessment, tool interaction, and teamwork, values simply correspond to the number of workload elements in each node (i.e., counting the number of tasks listed). For resource management, workload is obtained by multiplying the number of units controlled by the number of subtasks (three in all cases). For example, if a participant controls four units, management workload is determined by multiplying 4 (units) by 3 (subtasks), giving a workload estimate of 12. The numerical summary shows that the main benefit of functional specialization comes from having reduced workload in terms of situation assessment, especially for the water-provisioning role (Participant X_F). The main cost of functional specialization appears to be the increased amount of teamwork necessary to coordinate with others. Overall, if we assume that all these factors have an equal weight, total team workload is about the same (93 for multifunctional teams and 96 for functional teams). The participant with the highest workload is participant X_F who, despite a reduced situation assessment workload, must deal with a very high resource management workload (i.e., he controls all 6 WT units). These two results (similar overall workload across team structures yet higher workload for X_F) are clearly in line with the experimental results reported in Section 2. The values shown in this table constitute the input for the mathematical model presented hereafter.

Table 1
Structural factors influencing workload in functional and multifunctional teams

Participant & structure	**Situation assessment**	**Resource management**	**Tool interaction**	**Teamwork**	**Prerequisites**
Multifunctional					
Participant X_M	11	12	5	3	-
Participant Y_M	11	12	5	3	-
Participant Z_M	11	12	5	3	-
Functional					
Participant X_F	3	18	6	9	-
Participant Y_F	10	9	5	6	Water from X
Participant Z_F	10	9	5	6	Water from X

4. Data-driven modeling

The mathematical modeling approach adopted here consists in estimating the workload of each participant based on the task-to-agent mapping and modeling the relation between workload and individual efficiency. Next, the model relates individual efficiency to team effectiveness by taking into account interpersonal dependencies imposed by the team structure. After calibrating the model using results from the C^3Fire experiment, we demonstrate how it can be used to estimate the effectiveness of other possible team structures. We conclude with a discussion of the potential and limitations of the present approach and propose directions for future work.

4.1. Model overview

The proposed model seeks to predict the average effectiveness of teams as a function of team structure. The model does not attempt to explain differences between teams having a same team structure (other *non-structural* factors are responsible for this, e.g., motivation, skill, cohesion, leadership, etc.). The purpose of the mathematical model is to provide a tool for predicting the effectiveness of different team structures. The data used for parameter estimation comes from the C^3Fire experiment. Appendix A shows the average effectiveness of each team on the four test scenarios in the experiment. Team effectiveness was defined by the number of fires put out (i.e., offensive aspect) multiplied by proportion of houses saved (i.e., defensive aspect). The raw score was converted in percent rank scores to make comparisons more intuitive (i.e., observed score was divided by the maximum observed score of 63.21). The average rank of multifunctional teams was 76% compared to 24% for the functional teams. By calculating the coefficient of determination (R^2 value) between team structure and team effectiveness, we found that team structure explains 72% of the variance in the observed effectiveness of the 20 teams analyzed (two outliers were eliminated in each team structure to ensure that the model was calibrated on quality data – otherwise variance explained would be 28% due to excessive noise). This means that the model can at best explain 72% of the variability in team effectiveness observed in the present study (which can be considered excellent considering that many other uncontrolled factors may influence team effectiveness). The model will attempt to account for team effectiveness by:

1) Estimating individual workload;
2) Mapping workload to individual efficiency;
3) Constraining individual efficiency as a function of interpersonal task dependencies;
4) Aggregating the constrained individual efficiency to determine team effectiveness.

4.2. How team structure determines individual workload

The first assumption in the model is that the relative workload of each individual depends on taskwork (situation assessment and resource management), teamwork, and interaction with tools required to accomplish the task. The workload associated with each of these factors was characterized in the task-to-agent mapping and then summarized in numerical form. The mathematical model requires estimating the relative weights of these factors to determine the total workload of each participant on a scale from one to ten (similar to the NASA TLX workload scale). Individual workload is computed by summing the four following subtypes of workload:

$$\text{Individual workload} = SA_{workload} + Management_{workload} + Teamwork_{workload} + Tool_{workload}$$

At first, we assumed that the relative importance of each of the four workload factors would not necessarily be equal. The modeling procedure was supposed to involve estimating distinct weights for each subtype of workload, hence

$$\text{Individual workload} = (\text{no. of SA subtasks x } w_1) + (\text{no. of management subtasks x no. of units x } w_2) + (\text{no. of teamwork subtasks x } w_3) + (\text{no. of tool interaction subtasks x } w_4)$$

However, preliminary modeling results showed that the model successfully fitted the data with only one weight parameter (plus two other free parameters described later to define a non-linear function that relates individual workload to efficiency). Surprisingly, there was no gain in allowing different weights values for each factor. This leads to a remarkably parsimonious quantitative model. Since the single weight value is the same for all factors, it basically plays the role of a scaling parameter whose purpose is simply to resize the numerical workload assessment to better fit perceived workload, hence,

Individual workload = w ((no. of SA subtasks) + (no. of management subtasks x no. of units) + (no. of teamwork subtasks) + (no. of tool interaction subtasks))

The value of the weight parameter was estimated by least-squares minimization using a quasi-newton optimization algorithm. The estimated value was 0.249. The unweighted workload is thus approximately divided by 4 in order to fit subjective workload. There is a linear relationship ($y = w \cdot x$) between perceived workload and the simple unweighted workload metric derived from the agent-to-task mapping. In fact, the unweighted workload assessment successfully explains 100% of the variance in perceived workload. This is a remarkable result suggesting that the workload metric based on the task-to-agent mapping represents very accurately the actual workload of individuals. Table 2 shows the observed and estimated workload for each participant in the multifunctional and functional team structures.

Table 2
Average workload ratings reported by participants in the C^3Fire study and model fits

Structure	Participant	Perceived workload	Modeled workload	Unweighted workload
Multifunctional	Participant X_M	7.73	7.74	31
	Participant Y_M	7.73	7.74	31
	Participant Z_M	7.73	7.74	31
Functional	Participant X_F	9.00	8.99	36
	Participant Y_F	7.50	7.49	30
	Participant Z_F	7.50	7.49	30

Note. Perceived workload was rated on a scale from 1 (very low) to 10 (very high). We calculated the average workload ratings of Participants X_M/Y_M/Z_M in the multifunctional structure (since they all have the same objective workload), of Participant X_F in the functional structure and of Participants Y_F/Z_F in the functional structure (since these two participants have the same objective workload).

4.3. How workload determines individual efficiency

The goal of estimating the workload of individual participants as a function of team structure is that it can then be related to individual efficiency. We assume that the relationship between workload and individual efficiency is not just linear, but rather that efficiency remains high as humans compensate (i.e., with increased effort or adaptive strategies) for increasing difficulty and time pressure, then rapidly drops past a point of overload, and stabilizes at some minimum (see Adelman, Miller, Henderson, & Schoelles, 2003). We assume that this relationship follows an inverse sigmoid function (see Levchuk et al., 2005, for a similar assumption). This function can drop more or less steeply or at different points on the x-axis depending on its parameters. The equation for the reverse sigmoid is:

$$y = max \cdot k^n / (k^n + x^n)$$

where "*y*" corresponds to the output of the function: individual efficiency. The *max* parameter corresponds to the maximum value of *y*. The *k* parameter is the "half-maximum" of the curve and has the following meaning: when $x = k$, $y = 1/2 \cdot max$. The "*n*" parameter controls how steeply the curve falls. When modeling the data from the C^3Fire experiment, the exact shape of the function is estimated by the model using least-squares minimization. The modeled function has one fixed parameter and 2 free parameters whose value is estimated based on the experimental data:

- *max* is set to *one* (i.e., the optimal effectiveness)
- the estimated *k* value is 8.39
- *n* is estimated to be 14.20

Figure 6 illustrates the functional relationship between individual workload and efficiency estimated by the model.

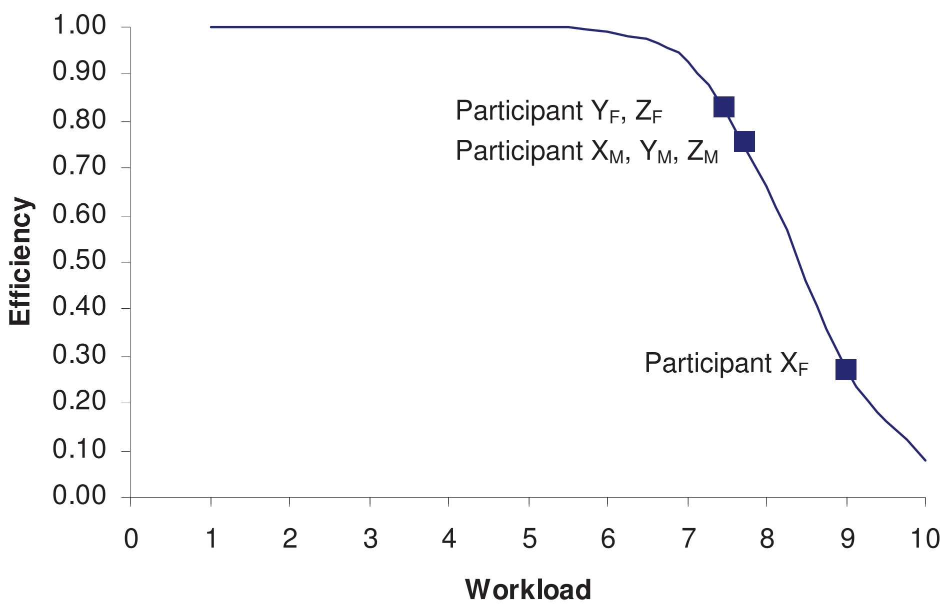

Figure 6. Estimated relation between workload and individual efficiency

Therefore,

$$\text{Individual efficiency} = \frac{1 \times 8.39^{14.20}}{8.39^{14.20} + \text{individual workload}}$$

where

Individual workload = 0.249 ((no. of SA subtasks) + (no. of management subtasks x no. of units) + (no. of teamwork subtasks) + (no. of tool interaction subtasks))

Table 3 shows the predicted efficiency of each team member as a function of workload. Note that participant X_F is clearly overloaded compared to other participants.

Table 3
Individual workload and predicted efficiency as a function of team structure

Structure	Participant	Efficiency	Workload
Multifunctional	Participant X_M	0.76	7.74
	Participant Y_M	0.76	7.74
	Participant Z_M	0.76	7.74
Functional	Participant X_F	0.27	8.99
	Participant Y_F	0.83	7.49
	Participant Z_F	0.83	7.49

4.4. How individual efficiency is constrained by interpersonal dependency

Despite the very low efficiency predicted for Participant X_F, the model still cannot adequately account for the large gap between the average effectiveness of functional and multifunctional teams. A key structural difference remains to be added. In the functional structure, Participants Y_F and Z_F, who control three FF units each, cannot adequately perform their task if Participant X_F does not accomplish his water-provisioning role in a timely manner. This constraint on the efficiency of Participants Y_F and Z_F is operationalized by multiplying their efficiency with that of Participant X_F (we also considered setting the constrained efficiency to that of the other participant if it was lower, but it was argued that a participant's efficiency still needs to be constrained by his own workload, hence the multiplication). The actual efficiency of Participants Y_F and Z_F is 0.83 (their baseline efficiency) multiplied by 0.27 (the efficiency of Participant X_F), for a result of 0.23. Team effectiveness is computed by averaging the (constrained) efficiency of all three team members. Table 4 shows the main modeling results: estimated workload, constrained efficiency and predicted team effectiveness.

Table 4
Workload and predicted effectiveness as a function of team structure

Structure	Predicted and observed team effectiveness	Constrained efficiency	Estimated workload	Participant
		0.76	7.74	Participant X
Multifunctional	0.76 (0.76)	0.76	7.74	Participant Y
		0.76	7.74	Participant Z
		0.27	8.99	Participant X
Functional	0.24 (0.24)	0.23	7.49	Participant Y
		0.23	7.49	Participant Z

The average effectiveness of multifunctional teams in the C^3Fire experiment was 0.76. The average effectiveness of functional teams was 0.24. The mathematical model successfully accounts for the average effectiveness of each team structure using only three free parameters. Although the model does not account for individual team variability (which depends on other factors than team structure) it successfully explains 72% of the variability in the observed effectiveness of the 20 teams tested. Now that the model parameters are calibrated, it can be used to generate predictions about the effectiveness of other team structures.

4.5. Application to new team structures

According to Navarro and Lee (2004) a good model should 1) provide accurate descriptions of the available data; 2) confer meaning or offer substantive insight into the phenomena being investigated; and 3) provide predictions and generalize to new or different situations where data are not available. The mathematical model developed here – now that it has been successfully calibrated on empirical data – can serve as a tool to extrapolate how teams should perform on the same task when organized according to other possible structures. The tool is basically an extension of the model that can automatically recalculate the workload, constrained effectiveness, and team effectiveness for novel team structures. In principle, the tool can predict team effectiveness for any team structure that assigns exactly 6 WT units and 6 FF units to various team members (i.e., the workforce/resources managed by the team must be constant for results to be comparable). Three candidate team structures come to mind:

- An alternate form of the functional team structure
  (X = 6FF // Y = 3WT // Z = 3WT)

- A hybrid team structure (part multifunctional, part functional)
  (X = 2FF and 2WT // Y = 4WT // Z = 4FF)

- A four-person functional team structure
  (W = 3WT // X = 3WT // Y = 3FF // Z = 3FF)

Based on the units assigned to each team member, the tool performs a new task-to-agent mapping for each of these test structures. The prediction tool then infers the relative effectiveness of each team structure. Predictions were obtained using the parameters that were estimated earlier using results from the functional and multifunctional teams in the C^3Fire experiment. Table 6 shows the predicted effectiveness for each of these team structures.

Table 6
Model extension as a tool for estimating the effectiveness of three team structures

Structure	Predicted team effectiveness *	Constrained efficiency	Estimated workload	Participant
Alternate functional	0.69	0.07	10.00	Participant X
		0.99	5.99	Participant Y
		0.99	5.99	Participant Z
Hybrid	0.70	0.76	7.74	Participant X
		0.93	6.99	Participant Y
		0.42	8.49	Participant Z
4-person functional	0.91	0.99	5.99	Participant W
		0.99	5.99	Participant X
		0.83	7.49	Participant Y
		0.83	7.49	Participant Z

* Effectiveness (in percent rank) relative to the effectiveness of the 20 teams in the C^3Fire experiment.

Alternate functional team. In the alternate functional team structure, Participant X has 6 FF, Participant Y has 3 WT, and Participant Z has 3 WT. Participant X depends on both of his teammates for water and he has a maximal workload (the estimated value would be higher but it has been limited to 10). Despite his low effectiveness, Participant X seldom lacks water due to the high effectiveness of Participants Y and Z in replenishing the water reserves of his units. This functional structure is predicted to be much more effective than the original functional team structure used in the C^3Fire experiment.

Hybrid team. It is possible to mix a functional and a multifunctional task allocation within a same team. In this hybrid structure, Participant X is multifunctional. He controls 4 FF and 4 WT units. Participant Y controls 2 WT units and Participant Z control 2 FF units. The model predicts that Participant Z should be overloaded and that this will reduce overall team effectiveness. This hybrid structure, while not optimal in terms of predicted effectiveness, may benefit from a greater adaptability to various situations.

4-Person functional team. An interesting possibility offered by the model was to explore how increasing the number of team members may impact the effectiveness of a given team structure. While a functional division of labor in a three-person team resulted in an overloaded individual, the same may not be true for a four-person team. In this team configuration, Participants W and X control 3 WT each, while Participants Y and Z control 3 FF each. The model predicts that a 4-person functional team should perform markedly better than a three-person multifunctional team (91 vs. 76 percent rank).[1]

[1] The model currently assumes that teamwork workload remains the same despite the addition of a fourth person (since the total number of units to control is also the same). However it could be argued that this addition may come with an increased cost in terms of teamwork requirements and that the model needs to be extended to account for this (e.g., by scaling teamwork requirements as a function of the number of people in the team). Such an extension would require experimental data from teams of various sizes.

In summary, the mathematical model predicts the following ordering of team effectiveness as a function of team structure:

- *4-Person functional (91%)*
- *Multifunctional (76%)*
- *Hybrid (70%)*
- *Alternate functional (69%)*
- *Functional (24%)*

The model may not produce perfectly accurate quantitative predictions since the calibration sample is relatively small and there may be noise in the experimental data, yet demonstrating that the model can correctly predict the qualitative ordering of team effectiveness in these team structures would constitute an impressive result which would validate the present methodology as a useful approach for team design.

5. Discussion

The present work has shown that combining experimental measurement using a microworld, hierarchical task analysis and mathematical modeling can provide a systematic method for estimating the costs/benefits of different team architectures. Costs/benefits were modeled in terms of higher/lower workload associated with tool interaction, information requirements and teamwork requirements. Although specialized roles (in the functional team structure) reduced workload in terms of tool interaction and SA requirements, it augmented teamwork requirements and constrained the efficiency of some individuals due to interpersonal dependencies. The functional team structure also created a workload imbalance resulting in excessive pressure on one team member. By providing clear quantitative predictions, the model is highly refutable are can therefore be improved if some predictions do not turn out to be correct. The model should also be calibrated on more than just two team structures to increase the reliability of its predictions. Thanks to its relative simplicity, this modeling approach has shown that it can obtain stable estimates of its three adjustable parameters without requiring excessive empirical data. This method therefore compares well with other more complex methodologies with similar objectives (e.g., Freeman, Pharmer, Lorenzen, Santoro, & Kieras, 2002; Levchuk, Pattipati, & Kleinman, 1999; MacMillan, Paley, Levchuk, Entin, Serfaty, & Freeman, 2002).

The simple and focused approach developed herein has produced a mathematical model and tool capable of predicting team effectiveness as a function of team structure. The tool helps identify how to balance the workload of C2 teams and can help determine how many team members are necessary to optimize team effectiveness in complex and dynamic situations. Future work will involve identifying optimal team structures by supplementing the prediction tool with a genetic algorithm, engaging in further data collection to test the predictive accuracy of the model, and applying this approach in the context of a large-scale multi-team or multi-organizational experiment pertaining to a strictly military operation or to an operation that includes military and non-military organizations.

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APPENDIX A

Observed effectiveness and percent rank for each team in the C^3Fire experiment

Team structure	Team	Observed effectiveness	Percent rank
Multifunctional	1	57.75	0.84
	2	48.30	0.63
	3	63.21	1.00
	4	45.23	0.58
	5	39.10	0.47
	6	51.44	0.68
	7	56.44	0.79
	8	53.95	0.74
	9	58.33	0.89
	10	61.84	0.95
Functional	11	32.80	0.32
	12	34.18	0.37
	13	38.89	0.42
	14	20.75	0.11
	15	23.23	0.16
	16	7.99	0.00
	17	16.53	0.05
	18	26.75	0.21
	19	29.86	0.26
	20	44.48	0.53