# Tradeoffs Between Performance and Adaptability for $C^3I$ Architectures

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## Abstract

$C^3I$ architectures are characterized by personnel, resources and tasks and the set of relationships linking them. This is the PCANSS formalism. A set of units – simulated and real – are represented in this way and a series of design metrics measured. Performance and adaptability measures are also captured. The data is then analyzed to examine whether there is a tradeoff between performance and adaptability. Results indicate that this is the case to the extent that factors leading to a common operational picture actually serve to retard experiential learning and so minimize performance but enable higher adaptability.

## 1. Introduction and Motivation

$C^3I$ architectures can be characterized by personnel, resources and tasks and the set of relationships linking them. Previous work has demonstrated that it is possible, using this representation, to design architectures for command and control that meet various

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performance criteria [Levchuk, Pattipati & Kleinman, 1997]. Some of the performance criteria include communication silence, uniform distribution of workload, accuracy and timeliness in response. Studies of the way in which these $C^3I$ architectures adapt have indicated that that adaptation is frequent, that not all change is adaptive, and that redundancy (in personnel or resources) increases adaptability [Carley & Lee, 1998]. This paper examines the link between adaptation and performance. We ask is it possible to design for both high adaptation and performance.

Motivation for this study came from the results of the study done by the A2C2 team as part of Bridge to Global, 2000. The mission being fought had two phases. . The participants were divided into 4 cells Alpha, Bravo, Charlie and Flag. For this event, the A2C2 team had designed a $C^3I$ that was optimized for overall performance across both phases of the mission and leveling of workload. This included assigning resources to each of the cells. Field and questionnaire data was collected from the game participants.

Previous results about organizational adaptation done using the computational model ORGAHEAD led to the theory of effort conservation and error cascades. Using the theory of conservation of effort and error cascades we predicted that emergent leaders will arise in each phase based on where the cognitive load is the highest. By leadership we mean taking charge of the situation and directing other cells to support their cells activities. Since individuals want to be on par with others – not too much higher or lower in amount of effort, if their cognitive load is higher than others they will seek to conserve their effort and reduce their cognitive load. In order to do these they will need to take on a leadership role convincing others that a change in personnel, resources or tasks is needed. Error cascades suggests that the number of possible errors and changes evoked by a single change in either personnel, resources or tasks is reduces as you move from personnel to resources to tasks. Hence changing tasks is the least likely to upset the current organization's operation. This suggests a preference ordering in changes; prefer shedding tasks, to moving resources to moving personnel. As leadership shifts we thus further predicted that when the load is high, individuals will prefer to shed tasks over resources and taking on new personnel.

During phase 1 in Bridge to Global the Bravo cell had the highest load. We expected Bravo to be the location of an emergent leader. Similarly, the high load for Charlie in phase 2 should lead to leadership shifting from Bravo to Charlie. We observed that in phase 1, that leadership did emerge in Bravo in phase 1 and in Charlie in phase 2. During phase 1 Bravo continually directed others, requested their support, and in particular kept shedding tasks. Tasks were shed by asking other units to take on those tasks. Bravo was offered additional personnel and resources but refused to take them on, preferring instead to handoff tasks. Charlie exhibited similar behavior in phase 2. The predictions of the theory thus held, providing some support for the computational model.

However, we observed an interesting anomaly. During phase 1, even though Bravo kept asking others to take on tasks, the transitions did not always go smoothly. Some tasks were missed. Errors occurred. Other cells were confused as to why they should take on those tasks. After phase 1, a questionnaire was distributed to all participants that contained the following question: "What do you think cell *x* is doing?" This question was asked for all four cells. The results indicated that the members of each cell had little understanding of what the other cells were trying to accomplish. In this sense, there was no common operational picture. Before moving to phase 2 an intervention was conducted. Each cell provided a briefing saying what they would be trying to accomplish in phase 2. During phase 2 as Charlie attempted to shed tasks, the process went more smoothly. Answers to the same question provided to participants after phase 2 indicated a greater awareness of what each other was doing. This anomaly suggests that there may be a tradeoff between designing for performance and designing for adaptability.

In this paper, we examine this tradeoff using simulation analysis conducted with the ORGAHEAD [Carley & Svoboda, 1996] and the ORGMEM models. If the models are reasonable predictors of performance and adaptability we should be able to observe this tradeoff and examine the design factors that differentiate between the two. ORGAHEAD and ORGMEM are multi-agent models of organizations as complex adaptive systems. In these models it is possible to examine both performance and adaptability of $C^3I$ architectures under external change processes and internal communication and resource flows. Both models take as their starting point units with the same $C^3I$ architecture. ORGAHEAD is used to predict the way in which the unit alters its architecture over time and the effect of that change on performance. ORGMEM is used to predict the way in which agents in that unit alter their transactive memory over time and the effect of that change on performance.

## 2. PCANSS Representation of $C^3I$ Structure

Any unit's $C^3I$ architecture, whether it is an organization, a team, a group, a joint task force etc. can be represented using the PCANSS formalism. Using the PCANSS formalism we mathematically represent the $C^3I$ architecture of a unit as a set of matrices linking personnel, resources, and tasks. For ease of exposition in this paper we will refer to the units as teams and the personnel as agents. The reader should keep in mind that the arguments hold for units of varying sizes, regardless of our use of the term team. Moreover, the reader should keep in mind that the personnel can be thought of as decision making units comprised of a single human being or a small team making a single decision, or a collection of humans and technology making a single decision. We refer to these personnel as agents. Herein, we represent the $C^3I$ architectures in both the computational models and in the actual war game using the PCANSS formalism [Carley & Krackhardt, 1999].

In the PCANSS formalism the overall meta-matrix is a multi-color multi-link matrix in which the there are three colors (i.e., three types of nodes – personnel, resources and tasks) and six types of links (each identified with a specific sub-matrix). The 6 matrices are: precedence (TxT), capabilities (PxR), assignments (PxT), needs (RxT), social networks (PxP) and substitutes (RxR). The sub-matrix networks can be operationalized as either authority – who reports to whom – or communication – who contacts whom. For each of these matrices, measures of the $C^3I$ architecture exist. For example, for networks common measures are span of control and the degree of organizational hierarchy. For assignments a common measure is redundancy.

These measures can be divided into three categories — standard network, multi-color, and multi-color multi-link. Standard network measures are calculated on matrices where the rows and columns are the same entity such as precedence, networks, and substitutes. An example is complexity – which is operationalized as density the number of actual links divided by the number of possible links. Multi-color measures are calculated on matrices where the row and column entities differ such as capabilities, assignments, and needs. An example of a multi-color measure is workload. Workload measures the average number of tasks assigned to an agent. Finally, multi-link measures are calculated using data from two or more of these matrices and so two or more types of relations. Examples are cognitive load and task-congruence. Cognitive load is a complex measure taking into account the number of others, resources, tasks the agent needs to manage and the communication needed to engage in such activity. Task congruence takes into account the number of errors in whether an individual has access to the resources that are actually needed to do the task.

Previous work indicated that of the set of commonly used measures, both multi-color and multi-link had more power in predicting both performance and adaptability than did standard network measures [Carley, Ren & Krackhardt, 2000]. The reason is simple. Performance and adaptability are a complex function of the entire architecture. No one sub-matrix controls the overall behavior of the system. Rather, all aspects of the $C^3I$ architecture interact in a complex adaptive fashion to effect a well tuned architecture. Standard network measures which are based on a single matrix in the overall meta-matrix do not predict performance and adaptability except in rare circumstances as they ignore two of the three entities in the overall (where the three entities are personnel, resources and tasks) meta-matrix. Multi-color measures are similarly based on only a single matrix in the overall meta-matrix, but the matrices of concern are off diagonal and so reflect relations among two of the three entities. Since they reflect such a small fraction of the overall architecture seem to capture performance or adaptability only under specialized circumstances. In contrast, multi-color multi-level measures utilize information from multiple sub-matrices – often capturing some of the complex interactions among all three entities.

## 2.1 Factors Affecting Performance and Adaptability

In this paper we use a set of graph theoretic measures to explore whether there is a tradeoff between performance and adaptability. We use those measures that are commonly used in other settings as well as multi-link multi-color measures that appear to be better overall predictors of performance and adaptability. These measures are described in Table 1. A number of alternative graph theoretic measures such as in and out degree centrality, in and out degree closeness centrality, betweeness centrality, and density of command were also examined. These measures, which are all standard network measures, are highly correlated and load on a single factor along with size. Hence, in this study we only use size. Similarly, resource specialization, access redundancy and need for negotiation load on the same factor, so we use only need for negotiation.

**Table 1. Measures of Organizational Architecture**

| Variable | Meaning |
|---|---|
| **Standard Network Measures** | |
| Size | The number of agents in the team. |
| Level | The number of levels in the hierarchy in the authority network. |
| Span of Control | Average number of agents who report to each other agent averaged across all agents with subordinates. |
| Least Upper Boundedness | How far disagreements among personnel need to go up the chain of command to be resolved. |
| **Multi-color measures** | |
| Resource Load | Average number of resources assigned to the same agent. |
| Consensus | For each resource, count the number of agents who are in the majority, sum the counts across all the resources, and divide the sum by the number of resources and the number of agents. |
| Assignment Redundancy | Average number of excess personnel (more than 1) assigned to the same task. |
| **Multi-link, multi-color measures** | |
| Need for Negotiation | The extent to which personnel need to negotiate with each other because they do not have the resources to do the task to which they are assigned. |
| Cognitive Load | A complex measure taking into account the number of others, resources, tasks the agent needs to manage and the communication needed to engage in such activity. |
| Under Supply | The extent to which the resources needed to do the task are unavailable. |
| Task Congruence | Task congruence takes into account the number of errors in whether an individual has access to the resources that are actually needed to do the task. |

In addition, we use four measures of organizational performance. There are described in Table 2. These measures serve as our dependent variables when we address the following two questions. What factors influence performance? Can teams be designed to exhibit both high adaptability and high performance?

**Table 2. Measures of Organizational Performance**

| Variable | Meaning |
|---|---|
| **Performance Measures** | |
| Common Operational Picture | The fraction of the available information that is shared by everyone. |
| Adaptability | The percentage difference in performance accuracy for pre- and post- shifts in mission. |
| Sustainability | The standard error in performance accuracy given all decisions ever made. The lower the value the more sustainable the overall accuracy level. |
| Performance (Accuracy) | Percentage of 25 tasks prior to shift in mission for which the team made the right decision. |

## 2.2 Virtual Experiment

In order to examine the tradeoff between performance and adaptability we conducted a virtual experiment. Using random network generation techniques a set of initial $C^3I$ architectures were created. These are described in Table 3. Each architecture represents the initial architecture of a different team. Then the natural evolution of these teams is simulated. Multiple simulation engines are used to evolve these teams and so create different possible change paths under different scenarios of what the future might bring. One of these engines is ORGAHEAD [Carley & Svoboda, 1996]. The other is ORGMEM [Carley, Ren &Krackhardt, 2000]. These simulation engines were used to do a series of "what if" analysis, answering the question "what if 'x' happened, then how is the team likely to change it's $C^3I$ structure?". The scenarios examined differ in the "x" that is happening. These scenarios include: downsizing due to attrition, increased workload, and natural change due to individual learning.

**Table 3. Virtual Experiment**

| Variable | Values of Categories | Number |
|---|---|---|
| Group size | 5, 19, 30 | 3 |
| Number of Resources (RC) | 5, 13, 25 | 3 |
| Density of Social Network Sub-Matrix | 10%, 30%, 75% | 3 |
| Density of Capabilities Sub-Matrix[1] | for RC = 5; 10%, 30%, 75% | 3 |
| | for RC = 13; 10%, 20%, 30% | |
| | for RC = 25; 10%, 15%, 20% | |
| Number of Architectures Simulated | | 81 |

[1] Different densities are chosen for different resource complexity based on the assumption of bounded rationality. In other words, we assume that the number of resources that a person can manage is limited.

Each of these architectures was simulated 5 times in ORGMEM and 25 times in ORGAHEAD to generate stable ensemble averages of performance. For each architecture, for each change path, the set of metrics identified in Tables 1 and 2 are calculated.

## 3. Adaptability or Performance

Each of the 81 organizations was simulated in both ORGMEM and ORGAHEAD. The results are summarized by a series of regressions in Table 4.

**Table 4. Simulation Predictions of Organizational Outcomes**

| Variable | Common Operational Picture | Adaptability | Sustainability | Performance |
|---|---|---|---|---|
| **Standard Network Measures** | | | | |
| Size | 0.50*** | 0.14* | 0.16 | 0.47*** |
| Level | 0.03 | 0.12 | 0.09 | -0.08 |
| Span of Control | 0.41*** | -0.16 | 0.00 | -0.18** |
| Least Upper Boundedness | -0.03 | 0.06* | 0.12* | 0.18*** |
| **Multi-color measures** | | | | |
| Resource Load | -0.09*** | -0.09 | 0.02 | -0.10 |
| Consensus | 0.02 | -0.08 | 0.21*** | 0.05 |
| Assignment Redundancy | -0.26 | 1.01* | -1.45*** | -1.47*** |
| **Multi-link, multi-color measures** | | | | |
| Need for Negotiation | -1.16** | 0.33* | -0.29* | 0.43* |
| Cognitive Load | -0.163*** | 1.19* | -1.83*** | -1.58*** |
| Under Supply | 0.29*** | -0.01 | 0.09 | 0.06 |
| Task Congruence | 0.03 | -0.08 | -0.25*** | 0.07 |

* <= .12, ** <=.05, *** <=.01

Results indicate that it is difficult to design for both high performance and adaptability. Different factors lead to adaptation and to high performance. As can be seen in Figure 1, multi-color and multi-link measures have the most predictive power, even when multiple factors are taken into account. In figure 1 the dotted lines indicate a negative relation, and the solid lines a positive relation. As can be see, while high cognitive load, assignment redundancy and least upperboundedness degrades performance it actually enhances adaptability. Task congruence supports sustained high performance.

Essentially adaptability is supported by agents having sufficiently complex positions that they need to interact with others, resources and tasks that they have the cognitive capability to change when adaptation is required. Increasing redundancy and pushing the power to handle exceptions (least upper boundedness) as low in the team as possible also enhances adaptability. In contrast, performance is enhanced by designing a team that is tuned for the specific set of tasks, has a low span of control, low cognitive load, little redundancy – all factors that promote rapid but narrow learning.

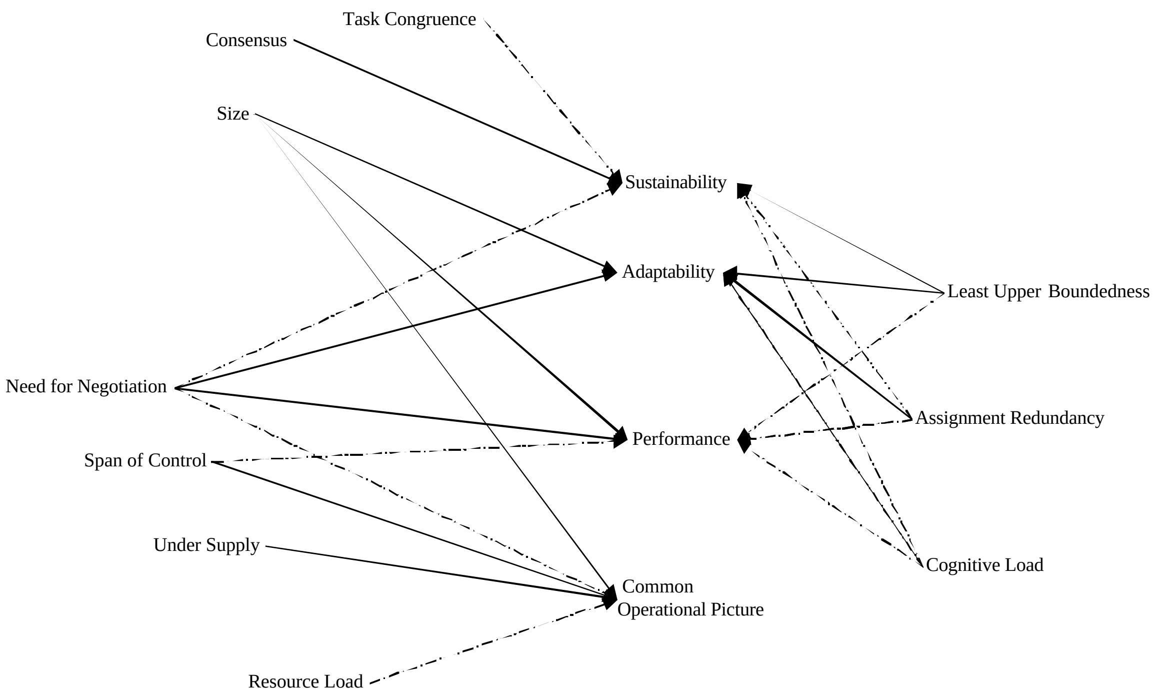


**Figure 1: Predicting Performance and Adaptability**

## 4. Synopsis

This analysis suggests that it is difficult, and perhaps impossible to design for both adaptability and high performance. Different aspects of the $C^3I$'s architecture affect different organizational outcomes. Further, the same aspect of design, such as Need for Negotiation, may serve to enhance adaptability but decrease performance. Thus trying to optimize a team for both performance and adaptability may be a losing prospect. The distinction between performance and adaptability hinges on flexibility and learning. High performance is enhanced, particularly in a rapidly changing environment or in the short term by rapid learning. For example, both low span of control and low cognitive load both enable rapid learning. In contrast, adaptability is enhanced by the agents having complex situation and excess (redundant) access both of which enable flexibility. High cognitive load and redundancy slow learning and provide over time insight into different situations thus enabling broader training and greater generalization.

An alternative strategy may be to train the team on two structures – one good for performance of the specific task in question and one good for adaptation. Practice switching between the structures may help the unit be both adaptive and high performing.

## References


[Carley & Svoboda, 1996] Carley, Kathleen M. & David M. Svoboda, 1996, "Modeling Organizational Adaptation as a Simulated Annealing Process." *Sociological Methods and Research*, 25(1): 138-168.

[Carley & Krackhardt, 1999] Carley, Kathleen M. & David Krackhardt, 1999, "A Typology for $C^2$ Measures." *In Proceedings of the 1999 International Symposium on Command and Control Research and Technology*. June, Newport,RI.

[Carley, Ren &Krackhardt, 2000] Carley, Kathleen M., Yuqing Ren & David Krackhardt, 2000, "Measuring and Modeling Change in C3I Architecture." 2000 Command and Control Research and Technology Symposium, Naval Postgraduate School, Monterey, CA, June 26-28, 2000

[Carley & Lee, 1998] Carley, Kathleen M. & Ju-Sung Lee,1998, "Dynamic Organizations: Organizational Adaptation in a Changing Environment." Ch. 15 (pp. 269-297) in Joel Baum (Ed.) Advances in Strategic Management, Vol. 15, Disciplinary Roots of Strategic Management Research. JAI Press. Pp. 269-297.

[Levchuk, Pattipati & Kleinman, 1997] Levchuk, Y. ,K.R. Pattipati, M. Curry and D.L. Kleinman, "Design of Congruent Structures: Theory and Algorithms," *Proc. IEEE Conf. on SMC*, Orlando, FL, October 1997.