How costly is your C^2 Coordination?
Assessing the coordination requirements within Command and Control

Topics: C2 Metrics and Assessment; Cognitive and Social Issues; C2 Concepts, Theory and Policy

Jay E. Peffer, James S. Tittle, James W. Gualtieri and William C. Elm
Resilient Cognitive Solutions

Martin Voshell, Brian Prue and David D. Woods
The Ohio State University

Point of Contact: Jay E. Peffer

113 South 26th Street, Suite 200, Pittsburgh, PA 15203
412.499.3064
jpeffer@resilientcognitivesolutions.com

As the size and complexity of Command and Control (C^2) domains continues to increase, new approaches (e.g., Net-Centric Warfare) have been proposed to dynamically recruit additional resources by creating distributed teams to handle rapidly changing situations. Although the added flexibility does have the potential to create C^2 structures capable of responding to a wide array of challenges, this addition of distributed team members creates new coordination costs. The performance of the C^2 team is impacted by the additional cognitive demands now required for team coordination and collaboration, in addition to the fundamental decisions of the domain.

Recently, Voshell, Woods, Prue, and Fern (2007) have proposed Coordination Loops as a means of specifying the requirements for supporting distributed cognitive work. This paper will detail an extension of Coordination Loops from a functional perspective, to understand the relationship between coordination needs and the stress they place on specific decisions within a work domain (e.g. Emergency Management). By mapping organizationally defined roles onto a functional, goal-means decomposition of the domain, both the *inherent information needs of the domain* and the *additional information needs for coordination* can be understood in the same context. This approach yielded unique insights were gathered about coordination assessment and design to reduce cognitive and coordination workload.

Introduction

Performance in many challenging and dynamic work domains depends on the interaction of a team of intelligent entities to handle the scale and complexity of such environments (Cannon-Bowers, Salas & Converse, 1993). While teams enable the monitoring and control of increasingly complex systems, the use of these collectives comes at a cost which can be measured as an increase in cognitive demand (Orasanu & Salas, 1995). With the addition of team members (either human or automated) increased cognitive demands are placed on the operator in response to the new "inter-agent" coordination demands. These demands are the result of communication and coordination requirements placed on the members of the collective to ensure integrated performance.

These coordination challenges are particularly acute within work domains that require sophisticated C^2 decision making teams. As the size and complexity of Command and Control domains continues to increase, the ability to understand the sources of coordination costs are likewise increasing in difficulty.

To assess the net decision making performance of these distributed teams, these additional coordination needs must be understood with respect to the domain specific decisions that they influence. The greater level of specificity available regarding the decisions that the distributed teams are trying to coordinate and execute, the greater the understanding of the coordination needs for future design of Decision Support Systems (DSS).

Recently, Voshell, Woods, Prue, and Fern (2007) have proposed Coordination Loops as a means of specifying the requirements for supporting distributed cognitive work. Their research focused on how different members of a distributed decision-making team were coordinating their shared goals and the information exchanges between and across echelons of the organization. This paper will detail an extension of the Coordination Loops concept, by placing organizationally defined roles in a functional framework, derived from a Cognitive Work Analysis (e.g., Elm et. al., 2007; Rasmussen, 1986; Woods & Hollnagel, 1987; Lind, 1991, 1993; Rasmussen, Petersen & Goodstein, 1994; Roth & Mumaw, 1995; Vicente & Rasmussen, 1992; Vicente, 1999) of the Emergency Management work domain. This intersection of coordination loops, organizational roles and a functional framework of the work domain provided unique and original insights for understanding, assessing and designing for coordination support.

Current technology-centered approaches to the problem

Current methods to support coordination and team decision making utilize increasingly complex technology and ubiquitous communications (e.g., immersive telepresence, video conferencing, electronic white boards, e-mail, multi-media chat) (Shope, DeJoode, Cooke & Pendersen, 2004). These technologies are employed in an attempt to deliver and replicate the perceived benefits of co-located "physical" face-to-face meetings. The underlying assumption being that virtual collocation will implicitly satisfy the underlying functional requirements of collaborative decision support without making those requirements explicit. In fact such systems routinely prove (and re-prove) that collocation does not equal collaboration; they frequently fail to satisfy "functional" requirements for effective coordination. Despite high bandwidth communication channels, team members frequently fail to effectively communicate with one another because they lack a common framework from which to exchange information.

To explicitly design support for coordination, an understanding of the inherent decisions of the domain must be established. This decision-centered context provides grounding for the joint team activities that are done to coordinate their joint decision making. Current technology-centered approaches to supporting team collaboration do not adequately focus on the underlying domain specific cognitive basis for team decision making (Guerlain, Adams, Turrentine, Shin, Collins and Calland, 2005). Applied Cognitive

Systems Engineering (ACSE) principles are ideally suited to identify the functional requirements to improve team member coordination in a domain specific context.

To improve coordination in a meaningful way focused assessment and design needs to be:

- **Grounded in the fundamental decisions of the domain,**
- **In the context of other coordination demands for the domain,**

The focus of the work presented here was to bring a multi-perspective approach to understanding coordination, to look at the intersection of the functional goals and decisions of the domain and the organizational structure of the decision making team. Using the technique, we hope to provide enough rigors to coordination assessment that will provide enough specificity that can guide future assessment, analysis and design in support of coordination.

Our Approach

Functionally Extending Coordination Loops

Voshell et. al. (2007)'s definition of Vertical and Horizontal Coordination Loops focus on how information moves between or within layers of organizational team structures. That is, information flows **vertically** between echelons in a chain of command, crossing different levels of the organizational hierarchy. When information is between elements within the same echelon of the organization, it is flowing **horizontally**.

Our Applied Cognitive Systems Engineering (ACSE) methodology (see Elm, Potter, Gualtieri, Roth, and Easter, 2003; Potter, Gualtieri, and Elm, 2003 for earlier versions of this methodology) was used to extend the concept of Coordination Loops from a functional perspective. The ACSE methodology established the functional analysis of the domain to make explicit the goals and decisions of our Emergency Response domain. These goals are the basis of a Functional Abstraction Network (FAN). We then mapped the organizationally defined roles onto the FAN to understand how coordination needs were created by the interaction of the organizational structure/role definitions and the fundamental cognitive work (decisions) of the domain.

Applied Cognitive Systems Engineering Overview

The ACSE process is a structured, principled analysis and design methodology to systematically transform the cognitive demands of a domain into decision-aiding concepts. ACSE begins with a cognitive analysis that "support(s) the development of revolutionary systems unconstrained by previous solutions" (Sanderson, Naikar, Lintern, & Goss, 1999). Cognitive analyses are powerful because they abstract away the organizational partitioning of the work domain to model the underlying goals, functional relationships, and cognitive work.

These functional goals, and the relationships between them, are captured within a function-based goal-means decomposition of the problem space. This provides a representation of the cognitive work domain as an abstraction network (e.g., Rasmussen, 1986; Woods & Hollnagel, 1987; Lind, 1991, 1993;

Rasmussen, Petersen & Goodstein, 1994; Roth & Mumaw, 1995; Vicente & Rasmussen, 1992; Vicente, 1999).

The functional goals are connected to one another through support-supported links. These links are two way conduits for information support being past from up from one goal to another goal's process, or demands being past down from a process to another goal. The existence of a support-supported link is a requirement that explicitly expresses that one goal, for it to be successful, requires support from another goal.

A FAN is a goal-means decomposition, to emphasize the levels of abstraction as a fundamental characteristic, as well as the rich, network topology inherent in the model. Once the functional goals of the domain are represented in the FAN, the next step in the ACSE methodology involves overlaying Cognitive Work Requirements (CWR) on the functional model as a way of identifying the cognitive demands, tasks, and decisions that arise in the domain and require support. The system requirements that follow from these CWRs must allow users to accomplish this cognitive work with the decision support tools. Identifying the functional relationships in the work domain and their associated cognitive work leads to sufficiently detailed requirements specification to support the relevant decision-making within the resulting system design.

The ACSE methodology yields a fully traceable, analysis to design to testing process. A process that allows design elements to be uniquely tracked back to decisions in the domain and forward to specific decision centered testing.

The FAN provides a structure, or framework, for several future activities, including:

- Future targeted knowledge elicitation activities (observation focus points, context specific questions, decision difficult areas) to better the understanding of the domain,
- Used as an explicit structure to identify and register the cognitive work needed to achieve the goals of the domain,
- Development decision support and representation requirements for future software development,
- Testing decision support designs that are specifically tied to the decisions of the domain.

Traditionally, ACSE is a full analysis to design process, with the analysis of the domain yielding a decision support design for decision makers in a domain. In this coordination loop research, we added an additional step of analysis, using the FAN as a structure to map the organizationally defined roles. The mapping of these roles onto the FAN revealed some interesting insights about how additional coordination needs between roles (or even inter-role) compound the decisions being made within the domain – providing a different way to assess and then design for coordination.

Mapping Organizational Roles onto a Functional Abstraction Network

With the FAN as the framework for the goals and decisions for a specific domain, the ACSE process can be extended by inspecting how the organizational structure impacts the decision makers. Often organizational roles are prescribed based on historical successes or evolution based on failure, managerial efficiency or current commander's preferences.

These organizationally defined roles can have a major impact on the net-decision making effectiveness of the teams that are coordinating within that organization. Through a series of observation events, a review of doctrine and training manuals we attempted to map how the roles overlap the goals within the decision space. This mapping serves as a critical step in identifying potential locations for functional coordination

loops.
A functional analysis of a domain can also serve as the basis to establish functionally defined roles that leverage the attributes of the goal relationships within the domain.

Taking advantage of the natural divisions between sets of decisions has a reduced impact on cognitive work requirements. In previous work, the FAN has served as the basis for role allocation and team structure decisions, even detailing the physical room layout of a command center (Peffer, Gualtieri, Elm and Potter 2006).

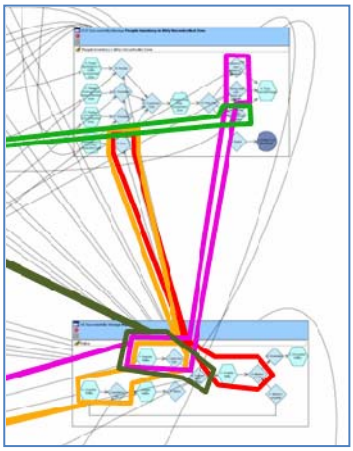


Figure 1 – Organizational Roles mapped onto a FAN

Case Study – Emergency Response

For this research, coordination was explored across distributed teams within the emergency response domain. Knowledge elicitation included major training observations, real time ride a-longs and interviews with a major metropolitan fire department, previous work with the U.S. Marines' Chemical, Biological, Incident Response Force (CBIRF) and the walking wounded class of scenarios that the Ohio State University research team had used for previous coordination loop research (Gunawan et. al. ,2007, Voshell et al. 2007).

Walking Wounded Scenario: Chemical Incident Response

To illustrate coordination loops across distributed human (and robot) teams we leveraged a search and rescue scenario where the testing is based on a new learning lab jointly developed by OSU CSEL and by MMI, TUDelft which simulates coordination demands over a variety of "walking wounded" scenarios.

The walking wounded class of scenarios enables us to introduce probes to elicit adaptation in this unique kind of convoy challenge (Cohen and Levesque, 1991). The goals of prioritizing care while conducting a convoy of walking wounded requires escort team and distant groups to think about how triage and mobility constraints influence decisions as the disaster situation changes.
This set of situations includes many aspects of horizontal coordination loops such as in-team /out-team interactions as some evacuees may be able to assist injured, incorporating additional people in the column, encountering new rescue personnel. The interaction of vertical and horizontal loops is critical if the threat situation changes or resource accessibility changes (e.g., dynamic hot zone, threat updates, uncertainty about decontamination sites).

Figure 2: Sketch from the Walking Wounded Scenario: Chemical Response (Gunawan et. al., 2007)

Building a Functional Abstraction Network for Emergency Response

The first step in understanding the coordination of a team of decision makers is to understand the domain context of their decisions. This step is especially important when trying to assess the coordination of team members, where it is critical to discriminate between the *inherent information needs of the domain*

and the additional *information needs for coordination* between team members.
The domain context is fundamental to the decision space, regardless of the team composition and organizational roles, we must first understand the key decision making required to effectively achieve relevant work domain goals. To understand the coordination of decision making, the decisions have to be understood first.

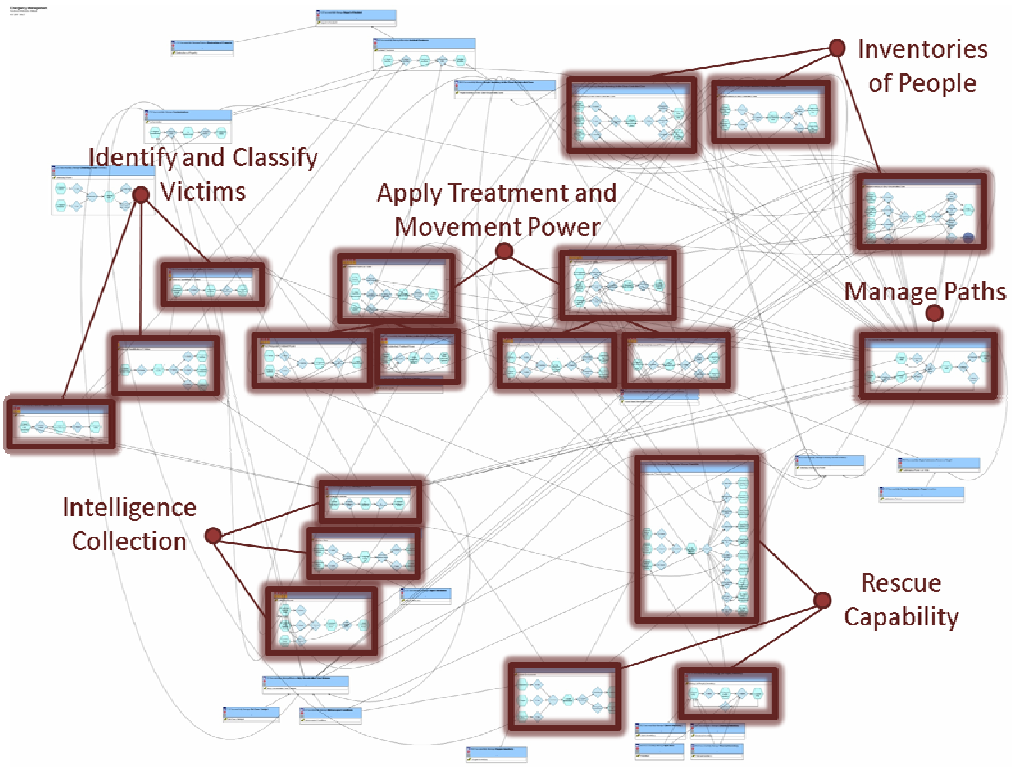


Figure 3 - Emergency Response Functional Abstraction Network serves as the framework to understand coordination in a functional manner – the 6 major regions are labeled

There are six major regions of the FAN for the Emergency Response domain, which include; the functions that are related to the management of people (rescue personnel and victim) within the different zones of the chemical incident, the functions that pertain to treating and moving victims in need, functions related to the identifying and classifying the victims in the incident, the functions that pertain to energy and capability available in the rescue personnel, the functions related to the intelligence collection process and finally the function that manages the paths in and out of zones, between first responders and victims, etc.

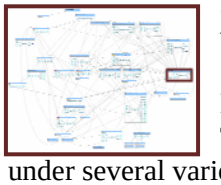
The first three functions are managing the three inventories of people within the incident. These goals are some of the higher level goals within the domain, because they pertain to the fundamental premise of locating the victims of the incident and moving them away from harm as soon as possible. Functionally, a person in these inventories could be rescue personnel or a victim, since they both require the same types of support to move into and out of the different zones, although the amount of support may vary.

The inventories are defined as the Dirty-Uncontrolled (D-U), Dirty-Controlled (D-C) and Clean-Controlled (C-C) Zones. The zone boundaries are defined based on the supporting function requirements for a person to pass from one zone to another within the incident. A person in the D-U Zone is in the range of the chemical agent (Dirty) and is not accounted for and being guided/helped out of the dangerous

area (Uncontrolled). A person needs guidance (via a path to take), movement assistance and (medical) treatment (if applicable) to move from the D-U Zone to the D-C Zone. For a person to move from the D-C Zone to the C-C Zone, that person will need to be decontaminated and possibly (medically) treated again. After a person is in the C-C Zone, if they require additional medical attention, they are sent out into the surrounding civilian medical system.

The second subset of functions within the domain pertains to the management of available treatment and movement power for the incident. Treatment and movement power can come from either the rescue personnel sent into help the victims in the incident, or from victims that have been deemed stable enough to assist the rescue personnel.

These assets not only have to exist within the D-U and C-C Zones, but they have to be in the proper place to apply their value as a movement or treatment power asset. So any victims or rescue personnel that have movement power to spare (assist a victim in walking out), has to spend their own resources getting to the victim (or receive mechanical assistance).



For rescue personnel to move into and out of the D-U Zone, move to the location of a victim to apply treatment and/or movement power and/or guide a victim out of the D-U Zone they need their own guidance. This guidance is captured in the functional goal of Managing Paths.

The management of paths supports many other functions within the domain, and is under several various types of demands at all times. At some points, it even may be the NON use of a path that is desired, such as bystanders being protected by cutting off paths into the D-U Zone, so that they do not become victims after the fact.

For rescue personnel to have the treatment or movement power to assist victims, they must manage their rescue capability. This rescue capability is spent as rescue personnel walk to a victim's location, carry a victim out of harm's way, etc. The main point is that as a rescue worker performs activities in the D-U Zone, the capability to be available for other functions will diminish.

This includes maintaining a livable environment (chem. bio suit), having oxygen to stay within the livable environment as well as having the energy and strength to do the activities. There are trade offs between the amount of protection a rescue worker might have and its impact on their capabilities. The more gear they carry to hold oxygen and protect themselves reduces their rescue capability.

The fifth subset of goals pertains to the identification of possible victims of the incident, classifying and determining their capabilities (if any). These decisions focus on taking information, gathered either by electronic collection assets or direct reporting from first responders and rescue personnel, and using it to task available resources to rescue or direct the victims to assist in the rescue efforts.

The final subset contains the functional goals related to the intelligence collection process. These functions are supporting the identification of paths into and out of zones, the identification and classification of victims, specific paths to those identified victims, and the contamination nature and size of the threat (not discussed above).

This set of functions, must address the same over-tasked, resource constrained, issues that plague all intelligence collection operations in complex and uncertain domains.

Functional Coordination Insights from the Analysis and Role Mapping

After establishing the functional layout of the Emergency Management domain, we mapped roles found in the rescue personnel/fire fighting groups that we observed during training and real time situations. Mapping organizationally defined roles onto the work being conducted on a daily basis allowed us to identify specific handoffs between decisions that would be difficult within the current role structure.

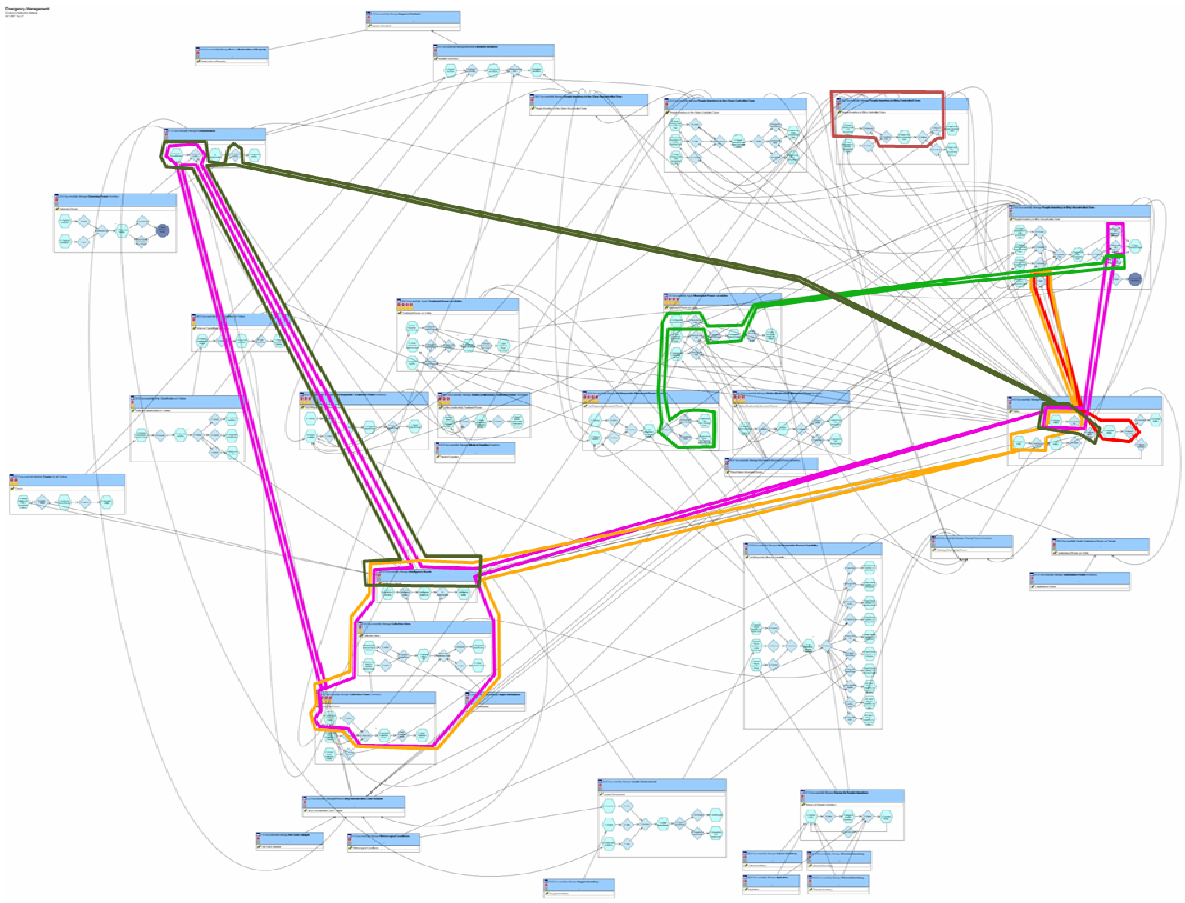


Figure 4: Emergency Management Functional Abstraction Network with a selected set of organizational roles mapped onto it. Several roles span several goals and functions within the domain

These specific situations allowed us to generalize a couple of initial, first of its kind functional coordination loop insights.

These insights are not the solution to supporting coordination across a distributed decision making team, but the insights that highlight interactions between roles and decisions of the domain can explicitly identify decisions that need additional focus during KE exercises, analysis work and focused design efforts that must account for coordination. They are a step down the path to assessing coordination in a manner that allows for the design of systems to more effectively manage coordination costs, in the context of the inherent decision needs and other coordination pressures of the domain.

Functional Coordination Loop – Insight 1: Function-to-Function Coordination Loop

When organizational roles intersect support-supported links between goals of the domain, new coordination demands are created to keep those functions synchronized (i.e. keeping the requested

support from one function/role coordinated with the availability of that support from another).
Within a FAN, the support-supported links represent explicit domain requirements showing the relationship between goals within the domain. These links express the dependencies and critical relationships between the functions. In order for a goal to be achieved, demands are passed down to lower level goals to request required support. The goal responding to those demands must gear its process to respond to these demands (and any other additional support it's providing).

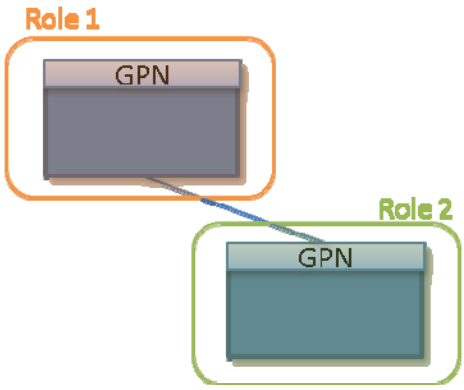


Figure 5 - A support-supported link between two functional goals describes a domain need. If an organizational role splits a set of connected functions from another, that would be an area for additional "coordination" design to support the coordination loop information handoff needs

Within the Emergency Management domain, an example of this support-supported link loop that would be needed can be found between the Successfully Manage People Inventory in the Dirty-Uncontrolled Zone GPN and the Successfully Apply Movement Power on Victim GPN. To remove a victim from the Dirty-Uncontrolled Zone, there needs to be functional support from the Apply Movement Power on Victim GPN to apply movement power on the victim in question. That GPN identifies appropriate movement power, gets it to the victim's location, and applies to the victim to get them out of the zone. From the Coordination Loop perspective - the Incident Commander would task a 1st Responder to get a specific victim out of the Dirty-Uncontrolled Zone (communicating the demand downward), the 1st Responder that receives that demand then proceeds to the victim and engages it (communicates status to the IC that they are in route or engaged with the victim), and then reports to Incident Command of the completion of the tasking (closing the loop).
Any location within a FAN where roles divide a single or set of support-supported links, there is an opportunity for observation to understand the coordination costs and how well they are coordinating their efforts so that both sets of decisions are informed with the pertinent and timely information. In future work in the domain, the Cognitive Work Requirements that are at the terminating end of a support-supported links that are divided by a role boundary is the exact spot for observation related to the coordination that exists between the two or more roles involved.

Functional Coordination Loop – Insight 2: Goal-Process Coordination Loop

When organizational roles divide portions of the same goal-process node, additional information handoffs are created to keep the process in check. We would expect a tight time cycle for this loop, as these handoffs would need to happen rapidly and often.
Another example of a functional coordination loop that is needed for effective decision making within a domain is a Goal-Process Coordination (GPC) Loop. A GPC Loop is needed when a single goal-process node within the domain has been organizationally partitioned between two different roles. This artificially

causes a division of decisions and information needs and therefore creates additional cognitive work to manage handoffs. Since parties in both roles are making tightly coupled decisions to achieve the same goal, the two roles need to have a proper GPC Loop. This GPC loop ensures that all parties involved in achieving a particular goal have accurate goal satisfaction information to avoid redundant effort, and communicate which demands received from other goals are being met. A shared understanding of the process is needed when a goal is divided amongst different roles.

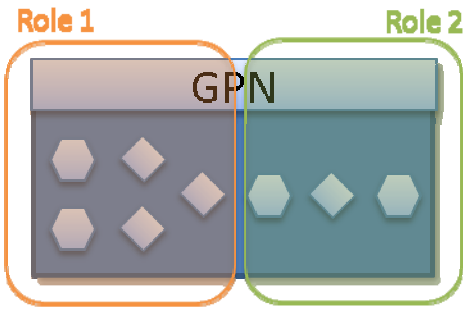


Figure 6 - When the Incident Commander and 1st Responder share portions of the "Apply Treatment Power on Victim" and "Apply Movement Power on Victim", designs to support a tight coordination handoff must be done in context of the decisions being made

An example of this can be seen within Successfully Apply Movement Power on Victim GPN. The first portion of this goal-process (selecting available movement power and tasking them to go to the location of a victim) can be done by Incident Command (IC), but then the 1st Responders on the ground are the people that have to execute that plan (moving to the victim and then engaging them with movement power).

The important return leg of this coordination loop is the 1st Responders updating IC, based on the fact that they are on the ground and are still performing the role of the eyes-on collection power. In this role the 1st Responders can: better appreciate the amount of movement power available to engage the victims (one responder spent more energy than expected coming in), determine the amount of movement power needed to move the victims (e.g., if five victims require rescue, rather than an initial report of only two victims), and especially in the Walking Wounded scenario – report back to IC the amount of victim movement power available to the 1st Responders. All information needed to support IC decision making within this GPN, but information not directly collected by the IC – thus, calling for the creation of a coordination loop.

An interesting, related observation came out of the Ohio State University observations with a major metropolitan police department. In a small scale event, the IC will be in the fight (in the burning building) while the response to the fire is happening – doing first hand intelligence gathering as the situation develops. But when the scale grows, and more resources (firefighters) are needed, the IC's coordination responsibilities increase and he has less opportunity for hands-on intelligence collection. The IC role retracts, and the need for coordination with the collection assets (firefighters) in the incident grows.

When the organizational roles not only divide the process, but also require their own supporting goal work (i.e. intelligence collection), there is an even greater need for a tight GPC Loop. This becomes particularly clear from our example in which the 1st Responders providing movement power executing the plan are also collection power assets in the world – because they will then have higher fidelity information than the IC has back at the command center.

Functional Coordination Loop - Insight 3: Demand Balance Observability Loop

The greater the number of support-supported links coming out of a single GPN, the greater the amount of functional balancing of demands that GPN must do. When different roles own different demands on one GPN, the roles need to understand what other demands that GPN is attempting to satisfy, giving context

to any time lags or variation in demand response.
Functionally, as a goal receives demands from other goals, it must gear its achievement to satisfy those demands in potentially a set satisficing manner. The greater the number of support-supported links carrying demands, the greater the balancing act and potential increase in the amount of cognitive work within a specific GPN.
This increase in cognitive work is only exacerbated in such a GPN when organizational roles divide the various support-supported links for a specific goal from above. If there is a Role 4 (see Figure 6), a large portion of their workload becomes a coordination workload; a juggling of receiving the multiple requests, determining the allocation of response and updating the requestors of the response status.

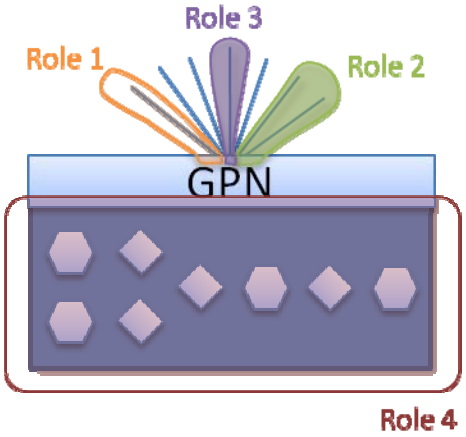


Figure 7 - With numerous goals demanding support from the "Successfully Manage Paths" GPN, all decision makers need Observability into of the other demands for the Paths, so that any time lags or variations in response have the proper context into "why"

An example of this is found in the Successfully Manage Paths GPN. This GPN is concerned with the identification, creation and use of paths in and out of the Incident's Dirty-Uncontrolled Zone (i.e. the Hot Zone). This includes 1st Responders moving between the control zones, victim(s) moving out of the contaminated area, the transport vehicles (movement power), etc. all of which require paths to get safely and efficiently to where they are needed. These demands often come in different flavors with different needs; a large truck needing a wide flat road, a 1st Responder with a victim stabilized on a robot mule following behind them, or a 1st Responder with a full chem.-bio suit - so these demands must be handled in the context of each other, so that the best decisions are made for the set of demands.
With a large number of support-supported links for a single goal, and the support-supported links between GPNs divided amongst roles – this situation would not only need tight goal-process coordination, but also potentially some goal-process wide Observability. If the requestors understand why certain paths were not available to them – through proper coordination loops sharing their process and the other demands they are trying to juggle, the higher order goal decision makers could be more willing to accept the decisions that were made by other people, with less effort spent double checking and second guessing the support they are given.
This insight also leads to a question regarding the coordination load – if, like in this case, the GPN provides a high degree of support (many support-supported links leaving the top of the GPN) versus a GPN receiving a high degree of support – where does the burden to coordinate across roles and GPNs? Which GPN and related role has more of a need for accurate and up to date coordination to perform their job?

We described above how the Coordination Loop concept (Voshell et. al., 2007) was extended by looking at the coordination between organizationally defined roles on top of a functional analysis (Elm et. al. 2003) of the domain. These initial insights within the Emergency Management domain indicate value in

considering coordination loops from a functional perspective, as a means to identify decisions and goals that are under additional coordination stress. These areas for coordination consideration can shed light on domain specific, coordination-decision support needs that can lead to design specifications to support coordination. The next section will discuss the potential for some of these functional insights to translate into potential coordination assessment metrics for future research and development.

Potential Collaboration Assessment Metrics

One of the most valuable benefits of an analysis to understand coordination from a functional perspective, is the guidance it provides for future observation and the development of metrics for evaluating coordination. The overlap of organizational roles can point out specific decisions that are under heavy coordination pressure. Before getting to that level of specificity, the following potential assessment metrics could be used to help shape future coordination analysis and design of decision support systems to effectively manage coordination costs.

Potential Metric 1: Organizational-Functional Fit

The intersection of organizational roles with the functional analysis provides a potential measure of the expected need for coordination. The support-supported links of a FAN show key dependencies within the work domain. In order for a goal to be achieved, demands are passed down to lower level goals to request required support. The goal, which is a response to those demands, must be implemented through a process tailored to the requirements of the goals it supports. Thus, when an organizational role boundary intersects these support-supported links it creates a need for coordination. From this perspective it becomes clear that heavily linked functions, should be in the same role if possible, to reduce the crossing of multiple support-supported links and thus creating unnecessary coordination demands. Regions of the FAN where roles divide a single or set of support-supported links provide excellent opportunities for observation to understand the coordination costs created by the mismatch between functions and organizational roles. When we see groups of nodes in the FAN that are highly connected with support-supported links, the tight coupling suggests significant coordination demands. When we overlay organizational roles on a FAN a mismatch between organizational roles and functions becomes apparent if these groups of tightly coupled nodes are divided amongst multiple roles. The **Organizational-Functional Fit** metric would entail measuring the number of support-supported links intersected by organizational role boundaries. Such an *Organizational-Functional Fit* metric would not only provide an overall sense of how well an organization's roles meet the functional goals of the domain, but it could identify specific coordination loops as having particularly high coordination demands based on intersecting a significantly larger number of functional support links than other loops in the work domain.

Potential Metric 2: Coordination Loop Asynchrony

One of the greatest challenges to coordination occurs when processes that operate on different time cycles must synchronize to provide crucial support when it is needed. Each coordination loop has a characteristic cycle time that is determined by both functional demands of the domain and organizational constraints. Because demands are more tightly coupled, one might expect coordination loops within a GPN to generally have shorter cycle times than loops between GPNs. When considering the coordination demands of integrating two coordination loops, the ratio of these cycle times provides a measure of

coordination loop asynchrony. In particular the key cycle time may relate to what Clark (1996) refers to as phases of coordinated activity. A phase refers to a joint action with an entry, a body of activity, and an exit. When coordination loops within a GPN must be synchronized with loops between GPNs it may be particularly challenging to align the entry and exit phases of joint activity. Overlaying organizational roles on a functional analysis, as we have done for the walking wounded scenario, will allow researchers to find these key roles in coordination loops where phase synchronization is crucial, but most challenging because of differences in tempo of operation. These asynchronies can be even more challenging when one considers the changes in the tempo of events for co-workers trying to achieve coordinated activity. If anomalous conditions cause escalation to occur in one part of the coordination before the other, the asynchronies can become extreme before the tempo changes propagate throughout the loop. A similar problem occurs during shift changes when part of establishing common ground involves communicating atypical operations tempo during an escalating situation during a shift hand-off (Patterson and Woods, 2001). Furthermore, effective teams have been observed to use strategies which can assist in communicating collaborator's current tempo such as: monitoring system status and sensor data prior to shift change, and listening in on verbal updates from other team members (Patterson, Roth, Woods, Chow, and Gomes, 2004).

Potential Metric 3: Coordination Loop Support Asymmetry

Key functional GPNs must support many other functions, and can represent choke points because of the costs of simultaneously being part of numerous coordination loops. Our analysis of the Emergency Response FAN suggests that such functions are characterized by a large difference between the number of supporting versus supported links. Thus, we propose **Support Asymmetry** across GPNs as a measure of the ratio of support to supported links for each GPN in a coordination loop. This Support Asymmetry could become particularly important because of differences between different stakeholders in terms of the importance placed on establishing, maintaining, and repairing common ground with their teammates (Klein, Feltovich, Bradshaw, and Woods, 2004). A large Support Asymmetry might suggest the possibility that one party may come to see that they "own" a particular coordination loop because it is much more critical for their operations than for their co-worker. Another difficulty arising from large Support Asymmetries in coordination loops occurs because one party maybe much less interruptible than another. Consequently, when the analysis shows a large Support Asymmetry, it suggests that researchers should focus their observations to understand what mechanisms, such as voice-loops (Patterson, Watts-Perotti, and Woods, 1999), exist for allowing team members to gauge the workload of their colleagues without interrupting them.

Conclusion

As C^2 domain problem spaces become increasingly complex, we must develop a greater understanding of the coordination costs incurred when recruiting additional resources through the formation of distributed decision making teams. The scaling of the team brings additional coordination demands onto team members layered on top of the decisions required for success by the domain. In order to assess and improve the coordination across a decision making team, support must be created for the inherent domain decisions, but also to decrease the workload for the needed coordination.

To effectively support the net decision making effectiveness of the team as a whole, both the decisions of the domain and the coordination of those decisions must be designed as part of an intimately coupled C^2 system. Having a functional analysis of the domain provides the basis that allows just that. It provides a type of fundamental framework to understand coordination in relation to its decision specific context. Specific locations where organizational roles meet or overlap within decision space provide requirements for increased design support, for not only the decisions within the domain, but also the coordination of

distributed decision-making teams. The locations where organizational roles divide a support-supported link, or parts of the same process mode within a goal of the domain, are precisely where additional emphasis on coordination design support must occur. These designs become hypotheses of support needed for good coordination and if the analysis is done properly can be traced through the next assessment of team coordination.
Researchers and designers have to understand the ***cognitive demands of coordination in the context of the cognitive demands of the domain***, so that attempts to improve coordination are understood in the same context of the distributed teams making those decisions.
Also, ***coordination loops need to be assessed in the context of other coordination loops*** – so that a design implementation to support coordination (along one loop) does not make other coordination even more difficult along another loop.

Coordination Loops are a means to identify and discuss coordination needs within an organization. Coordination Loops in a functional context provide an extension of the Coordination Loop concept that takes assessment of coordination in a specific decision-centered context. This context is critical for the future design and development of C^2 systems that aims to support coordination and the related decisions in a complimentary manner. Appreciating both, the support for the domain decisions and the additional cognitive work to coordinate those decisions is a step in the right direction towards increasing net decision making effectiveness.

References

Cannon-Bowers, J. A., Salas, E., & Converse, S. (1993). Shared mental models in expert team decision making. In J. Castellan Jr. (Ed.), *Current issues in individual and group decision making* (pp. 221-246). Hillsdale, NJ: Erlbaum.

Clark, H. H. (1996). *Using Language*. Cambridge University Press

Elm, W.C., Potter, S.S., Gualtieri, J.W., Roth, E.M., & Easter, J.R. (2003). Applied Cognitive Work Analysis: A pragmatic Methodology for Designing Revolutionary Cognitive Affordances. In E. Hollnagel (Ed) *Handbook for Cognitive Task Design*. London: Lawrence Erlbaum Associates, Inc.

Guerlain, S., Adams, R. B., Turrentine, F. B., Shin, T., Guo, H., Collins, S. R., and Calland, J. Forrest (2005). Assessing Team Performance in the Operating Room: Development and Use of a "Black Box" Recorder and Other Tools for the Intraoperative Environment. *Journal of the American College of Surgeons*, 200:29-37.

Gunawan, L. T., Voshell, M., Oomes, A. H. J., and Woods, D. D. (2007). Envisioning Collaboration at a Distance for the Evacuation of Walking Wounded. *Proceedings of the 4th International ISCRAM Conference* (B. Van de Walle, P. Burghardt and C. Nieuwenhuis, eds.), Delft, the Netherlands, May 2007.

Klein, G. Feltovish, P., Bradshaw, J., and Woods, D. (2004). Common Ground and Coordination in Joint Activity. In W.R. Rouse & K.B. Boff (Eds.), *Organizational simulation*. New York: Wiley.

Lind, M. (1991). Representations and abstractions for interface design using multilevel flow modeling. In G. R. S. Weir and J. L. Alty (Eds.), *Human-Computer Interaction and Complex Systems*, London: Academic Press.

Lind, M. (1993). Multilevel flow modeling. *AAI93 Workshop on Reasoning about Function*, July 11-15, Washington, DC.

Orasanu, J., & Salas, E. (1993). Team decision making in complex environments. In G. A. Klein, J. Orasanu, R. Calderwood, & C. E. Zsambok (Eds.), *Decision making in action: Models and methods* (pp. 327-345). Norwood, NJ: Ablex.

Patterson, E. S., Roth, E. M., Woods, D. D., Chow, R., & Gomes, J. O. (2004). Handoff strategies insettings with high consequences for failure: Lessons for health care operations. *International Journal for Quality in Health Care*, 16(2), 125-132.

Patterson, E. S., Watts-Perotti, J. C., & Woods, D. D. (1999). Voice loops as coordination aids in Space Shuttle Mission Control. *Computer Supported Cooperative Work*, 8, 353-371.

Patterson, E. S., & Woods, D. D. (2001). Shift changes, updates, and the on-call model in space shuttle mission control. *Computer Supported Cooperative Work: The Journal of Collaborative Computing*, 10(3), 317-346.

Peffer, J. E., Gualtieri, J. W., Potter, S. S., and Elm, W. E. (2006). Decision-Centered Command and Control: Designing Large Scale Decision Support Environments to Enable Effective Team Decision Making, *Proceedings of the Eleventh Command and Control Research Technology Symposium 2006*, San Diego, CA: Command and Control Research Program.

Potter, S. S., Gualtieri, J. W., and Elm, W. C. (2003). Case studies: Applied cognitive work analysis in the design of innovative decision support. In E. Hollnagel (Ed.). *Cognitive Task Design*. New York,

NY: Lawrence Erlbaum.

Rasmussen, J. (1986). Information processing and human-machine interaction: An approach to cognitive engineering. *North Holland Series in System Science and Engineering*, Elsevier Science Publishing Co., Inc., New York, New York.

Rasmussen J., Pejtersen, A. M., & Goodstein, L. P. (1994). *Cognitive Systems Engineering*. New York: Wiley & Sons.

Roth, E. M. & Mumaw, R. J. (1995). Using Cognitive Task Analysis to Define Human Interface Requirements for First-of-a-Kind Systems. *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting*, (pp. 520 – 524). Santa Monica, CA: Human Factors and Ergonomics Society.

Sanderson, P. M., Naikar, N., Lintern, G. & Goss, S. (1999). Use of cognitive work analysis across the system lifecycle: Requirements to decommissioning. *Proceedings of the 43rd Human Factors and Ergonomics Society Meeting* (pp. 318-322). Santa Monica, CA: Human Factors and Ergonomics Society.

Shope, S. M., DeJoode, J. A., Cooke, N. J., and Pederson, H. (2004). Using Pathfinder to generate communication networks in a cognitive task analysis. *Proceedings of the Human Factors and Ergonomics Society 48th Annual Meeting.*

Vicente, K. (1999). *Cognitive Work Analysis*. Mahwah, NJ: Lawrence Erlbaum Associates.

Vicente, K. J. and Rasmussen, J. (1992). Ecological interface design: Theoretical foundations, *IEEE Transactions on Systems, Man and Cybernetics*, vol. 22, pp. 589—606.

Voshell, M., Woods, D.D., Prue, B., and Fern, L. (2007). Coordination Loops: A New Unit of Analysis for Distributed Work, *Proceedings of the Eighth International NDM Conference (Eds. K. Mosier & U. Fischer), Pacific Grove, CA.*

Woods, D. D. and Hollnagel, E. (1987): Mapping Cognitive Demands in Complex Problem-Solving Worlds. *International Journal of Man-Machine Studies*, 26 (2) pp. 257-275.

Woods, D. D. & Hollnagel, E. (2006). *Joint cognitive systems: Patterns in cognitive systems engineering.* Boca Raton, FL: Taylor & Francis Group.

Woods, D. D., Tittle, J., Feil, M. and Roesler, A. (2004) Envisioning Human-Robot Coordination for Future Operations. *IEEE Transactions on Systems, Man, and Cybernetics- Part C*, 34(2), 210-218.