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Making Sense of Sensemaking:

Requirements of a Cognitive Analysis to Support C2 Decision Support System Design

Topics: Cognitive Domain Issues; C2 Analysis; C2 Concepts and Organizations

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ABSTRACT

Conducting a Cognitive Analysis to adequately support a follow-on design effort for innovative decision support tools is a tall order and requires specific properties to exist in the CTA in order to be successful. This paper outlines requirements for analytical methodologies to satisfy this need. These requirements are based on several premises.

The first premise is that a representation shapes cognition and collaboration, which guide behavior. This is known as the Representation Effect (Norman, 1993). The representation effect summarizes a widespread psychological result that the content and context of a problem representation (i.e. its reflection in the design of user interface) can radically alter a decision-maker's responses. Thus, how a command and control system is designed influences the cognitive work that needs to be accomplished, either improving or degrading "sensemaking" performance.

The second premise is that the representation must reflect the essential characteristics of the work domain. That is, the relationship (or mapping) between the visual structure established by a particular representation and the underlying constraints and relationships within the work domain itself is fundamental to the decision-maker's effectiveness when using the visualization. Without an explicit specification of this mapping, it is impossible to determine if the visualizations are supporting user's needs as intended, or, making the "supported" task more difficult (Zhang, 1997). Woods (1991) has called this the 'Mapping Principle.'

Taken together, these two premises have a significant impact on the design of decision support systems (e.g., military command and control systems). In order to be effective, C2 systems must be based on a cognitive analysis that has identified the rich context of decision-making requirements for the resulting design artifact. Essentially, an analysis of the cognitive work must identify 'what' is necessary to represent; then the design of the interface must effectively represent that information for accurate perception/cognition by the user.

OVERVIEW

Cognitive Analysis (CA) encompasses a wide variety of specific techniques with similar diversity in their goals. From our perspective, an analytical-based design process requires an analysis methodology that successfully bridges the 'gap' between field studies (knowledge elicitation) and system development (system design requirements). Such a CA methodology must provide a framework for gathering, analyzing and structuring the resulting knowledge about end-users' information requirements and for identifying desired system functionality – particularly of system components responsible for providing decision support. Thus, any CA approach is incomplete unless it incorporates techniques for analyzing the operational decision making environment (i.e., the context in which a support system will be embedded), modeling human decision-making (i.e., the cognitive demands and strategies to perform within the operational environment), defining information requirements for effective decision-making, identifying representation requirements to satisfy the information requirements, and most importantly, explicitly linking to the follow-on design phase that generates specific decision support concepts based on the analysis. An overview of this approach is illustrated in the following figure.

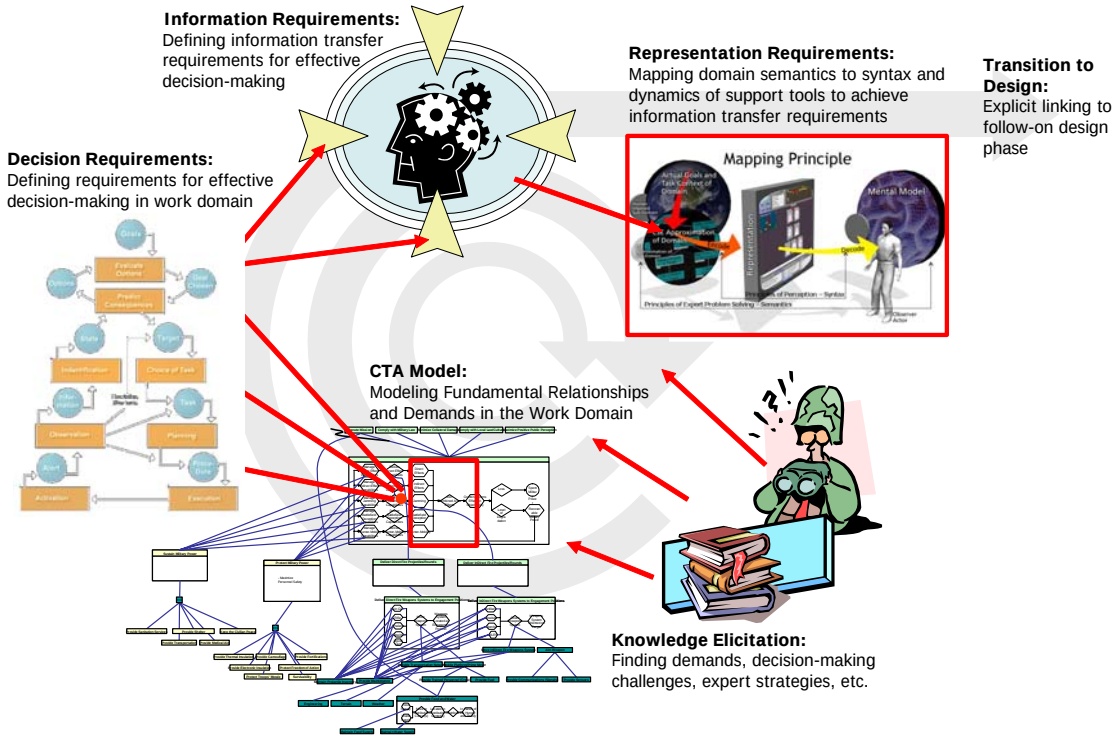

Figure 1. A framework for a cognitive analysis process as the basis for the design of decision support concepts.

This paper discusses the insights gained from the design of multiple decision support systems for military command and control with a specific emphasis on the resulting criteria for cognitive analysis to to be able to support C2 decision support system design. These criteria include:

- ***Knowledge elicitation is only the starting point*** – cognitive analysis must be based on knowledge elicitation techniques, but this is only the input for the analysis. Information from knowledge elicitation must be transformed into analytical insights to serve as an effective basis for decision support system design.
- ***Capturing the way the world works*** – cognitive analysis must capture and document the goals to be achieved in the domain and the functional means available for achieving them. This includes a representation of the functional concepts and their relationships that serves as the context for decision-making. The most challenging aspect of this task is the discovery of the most abstract concepts that are the most indicitative of expert understanding of the work domain.
- ***Building a set of complementary analytic artifacts*** – cognitive analysis must systematically transform the problem from initial insights about the demands of the work domain to support concepts for those demands. There needs to be a linkage between these artifacts to establish a sufficient design basis for the decision support concepts.
- ***Establishing a high degree of correspondence***– cognitive analysis must specify what information needs to be represented in the decision support system, as the mapping from work domain to representation design to extracted information is critical to the effectiveness of the decision support system. This mapping must be the context for the cognitive analysis effort.

The insights and lessons learned from these design efforts have a significant impact on design efforts where the objective is to design for increased "situation awareness". Only by following a structured analysis methodology followed by insightful representation design techniques can the mapping from work domain to design artifact be explicit and have any hope of supporting effective decision making and situational awareness.

CRITERIA FOR COGNITIVE ANALYSIS TO BE ABLE TO SUPPORT C2 DECISION SUPPORT SYSTEM DESIGN

#1: Cognitive Analysis must be far more than Knowledge Elicitation.

The objective of Knowledge Elicitation (KE) is to gather, through a combination of methods, a complementary set of information about the decision-making problem space under consideration. Typically, a CA is performed based on a variety of KE activities and types. This involves interactions with expert practitioners in the domain and includes face-to-face interviews with the experts, watching the experts work in the domain, and verbal protocol techniques. In practice, this is an iterative, progressively deepening process.

The phrase 'bootstrapping process' has been used to describe this process and emphasizes the fact that the process builds on itself (Potter, et al., 2000). Each step taken expands the base of knowledge providing opportunity to take the next step. Making progress on one line of inquiry (understanding one aspect of the field of practice) inspires progress on

another. One starts from an initial base of knowledge regarding the domain and how practitioners function within it (often very limited). One then uses a number of KE techniques to expand on and enrich the base understanding and to evolve a CA model from which ideas for improved support can be generated. For example, one might start by reading available documents that provide background on the field of practice (e.g., training manuals, procedures). The knowledge gained will raise new questions or hypotheses to pursue that can then be addressed in interviews with domain experts and also provide the background for interpreting what the experts say. In turn, the results of interviews or exercises may point to complicating factors in the domain that need to be modeled in more detail. This provides the necessary background to create scenarios to be used to observe practitioner performance under simulated conditions or to look for confirming example cases or interpret observations in naturalistic field studies.

One key element of the Knowledge Elicitation is that it is performed iteratively with the CA effort. As interim analytical results from the modeling task (converting raw KE data to CA findings) become available, they are used as material for further elicitation. The process of constructing the CA artifacts provides requirements for the information needed to enrich the model. Ideally, the CA model provides a mechanism for integrating seemingly disparate sources of information from a KE process into a unified analysis and design framework. Thus, the focus of KE is to, in an iterative, incremental manner, provide the data necessary to construct the set of CA artifacts.

Therefore, it is important to maintain a clear distinction between KE and CA. Too often CTA researchers talk about KE as if it is CA. However, they are fundamentally two separate activities with different methodologies. Effective KE is essential to obtain the critically-needed material for the construction of the set of CA artifacts. The exact same KE data can be transformed in different ways to reveal different insights into the demands of the work domain and the decision-making of the practitioners.

As was evident in Figure 1, results from Knowledge Elicitation supports the entire set of CA artifacts. For example, during an observational investigation, one may see evidence of a specific information requirement for a particular decision. Or, in an interview the SME may verbalize an especially difficult problem that may provide insights into fundamental demands in the work domain.

#2: Cognitive Analysis must capture the fundamentals of the work domain and resulting decision-making.

In performing CA, two mutually reinforcing perspectives need to be considered. One perspective focuses on the characteristics of the domain and the cognitive demands they impose. The focus is on understanding the way the world works (the fundamental, underlying basis) and what factors contribute to making practitioner performance challenging. Understanding domain characteristics is important because it provides a framework for interpreting the second perspective – practitioner decision-making (Why do experts utilize the strategies they do? What complexities in the domain are they responding to? Why do inexperienced practitioners perform less well? What constraints in the domain are they less sensitive to?) and because it helps define the requirements for effective support (what aspects of performance could use support, what are the hard cases

where support could really be useful) as well as the bounds of feasible support (what technologies can be brought to bear to deal with the complexities inherent in the domain, which aspects of the domain tasks are amenable to support, and which are beyond the capabilities of current technologies).

The challenging aspect of this task is the systematic discovery of the most abstract of the concepts (Rasmussen, 1986) as the most indicative of expert understanding of the domain, most challenged during unexpected situations, and least likely to be captured in existing documentation or decision aids. The physical aspects of the domain can be viewed and touched and inspected, the abstract functional concepts require understanding. An effective CA properly discovers these essential, elusive abstract concepts and how they relate to each other.

The second perspective focuses on how practitioners respond to the demands of the domain. Understanding the knowledge and strategies that expert practitioners have developed in response to domain demands provides a second window for uncovering what makes the world hard and what are effective strategies for dealing with domain demands. These strategies can be captured and transmitted directly to less experienced practitioners (e.g., through training systems) or they can provide ideas for more effective support systems that would eliminate the need for these compensating strategies.

A comprehensive CA needs to encompass analysis and modeling of both of these perspectives. The focus is on building a model that captures the cognitive task analyst's evolving understanding of demands of the domain, knowledge and strategies of domain practitioners, and how existing support tools influence performance that can be used to guide specification of requirements for improved performance.

An impact of this issue is in the nature of the knowledge being sought and in the nature of the analysis of the raw data collected resulting in design progress. Virtually any of the Knowledge Elicitation practices can form the input data, the true value comes in resolving it against the analytical representation in the CA model and the resulting conversion of that data into the formalisms of the model.

This issue is at the heart of a distinction within the CSE community with respect to the differences between Cognitive Task Analysis (CTA) and Cognitive Work Analysis (CWA). Rasmussen and his colleagues (Rasmussen, 1986; Rasmussen, et al., 1994) developed a framework for CWA that addresses the issues of how to analyze human work in order to derive implications for designing computer-based decision support systems explicitly to support adaptation to novelty rather than to support current task sequences. This is the essence of what Woods and Hollnagel (2005) refer to as ***resilience*** – the ability to anticipate and adapt to surprise and error. This includes issues such as failure-sensitive strategies, exploring outside the current boundaries or priorities, overcoming the brittleness of automation, and maintaining peripheral awareness to maintain flexibility. For this reason, we argue that any cognitive analysis must model the fundamental, unchanging properties of the work domain that must be supported independent of any specific task demands. This is the fundamental analysis issue to achieve resilience in the resulting Joint Cognitive System (Woods and Hollnagel, 2005).

In addition, the problem is even harder in the case of designing decision support tools for revolutionary systems (in which there is no currently existing system), CA must deal with

the problem referred to as the *envisioned world problem* (Woods, 1998). That is, the introduction of any computerized support system will change the nature of the users' tasks (i.e., make some (hopefully many) easier, some (hopefully few) more difficult, eliminate some, and introduce others). The envisioned world problem means that CA faces a challenge of prediction – i.e., how will the new decision support tools shape cognition and collaboration? In the envisioned world problem, we cannot simply rely on the expertise of subject matter experts of the current system. We must have some mechanism for defining the fundamental, unchanging properties of the work domain that will need to be supported in the envisioned world.

The envisioned world problem is the basis for the argument by Potter, et al., (2000) for CTA processes to extend into the prototype design phase. In this way, understanding of the demands of the work environment is enriched by the analysis of how the envisioned tools change the cognitive tasks faced by the users.

In Figure 1 we include a Functional Abstraction Network (FAN; Elm, et al., 2003) as a representative CA model to capture the fundamentals of the work domain. While there are several related methodologies (including function-based CTA (Roth & Mumaw, 1995), goal-means decomposition (Woods and Hollnagel, 1987), multi-level flow modeling (Lind, 1993), cognitive work analysis (Vicente, 1999), cognitive systems analysis (Flach, 1998) and cognitive function analysis (Boy, 1997)) we advocate the Applied Cognitive Work Analysis (ACWA; Elm, et al., 2003; Potter, et al., 2003). This methodology creates a function-based goal-means decomposition that models the goals to be achieved in the domain and the means available for achieving them. The critical benefit of this approach is the systematic discovery of the most abstract of the concepts (through the construction of a FAN) as the ones most indicative of expert understanding of the domain, most essential during unexpected situations, and least likely to be captured in existing decision aids.

A FAN is a recursive goal-means representation, specifying the goals to be accomplished, the relationships between goals (e.g., goal-sub-goal relations, mutually constraining or conflicting goals), and the means available to achieve the goals (e.g., alternative methods available, pre-conditions, side-effects, preferred order) at ever more increasing levels of abstraction. From this model of system functioning, it is possible to derive, organize, and preserve the goals, processes, critical decisions, and information requirements.

The rationale for this approach is twofold. First, it has been shown that an explicit Functional Abstraction Network model closely parallels the mental models of some of the best human problem solvers, faced with high-stress, high-value, uncertain (naturalistic) decision making conditions. Second, this approach has been shown to be extremely valuable in designing decision support tools for complex processes such as those faced by C2 teams by modeling the essential underlying concepts and relationships in the work domain that need to be an integral part of the decision support system.

The resulting FAN is independent of the particular agents (human or machine) required to perform the work. Rather, it specifies the specific domain objectives and the functions that must be available and satisfied in order to achieve these goals. These functions may be abstract entities that need to have other, less abstract functions available and satisfied in order that they might be achieved. This creates a decomposition network of functional

objectives or purposes that are linked together from abstract goals to specific means to achieve these goals. The intrinsic work tasks that are present in the work domain can be mapped to the goals and processes identified in the FAN.

The FAN is a key artifact that serves as the initial scaffolding that comprises the structure of the remainder of the analysis effort. All subsequent phases in the analysis then add depth and substance onto the structure (e.g., cognitive work and associated information requirements overlaid on the relevant goal/process relationships). This structure defines the shape of any future DSS knowledge model, and thereby, the shape, nature, and ultimately the content and form of the communication between the DSS and the domain practitioners.

#3: Cognitive Analysis must systematically transform knowledge elicitation into a set of complementary analytic artifacts.

In order to achieve this criterion, it is necessary to have a structured, principled methodology accompanied by a set of analytical artifacts to systematically transform the problem from initial data from multiple KE sources to an analysis of the demands of a domain to design basis for decision-aiding concepts that will provide effective support for the identified demands.

This is typically accomplished by creating a set of artifacts that capture the results of each of these intermediate stages in the CA process. The continuous thread formed from these artifacts provides a principled, traceable link from KE to cognitive analysis to design basis. However, the progress occurs in the thought and work in accomplishing each step of the process; by the process of generating these artifacts. The artifacts serve as a mechanism to record the results of the thinking and as stepping stones for the subsequent step of the process. Each intermediate artifact also provides an opportunity to evaluate the completeness and quality of the analysis effort, enabling modifications to be made early in the process. The linkage between artifacts also ensures an integrative process; changes in one-artifact cascades along the thread necessitating changes to all as the process is repeated in several expanding spirals.

As was evident in Figure 1, there should be a linkage between the complementary set of artifacts. As mentioned earlier, there may be a link between an observation during a KE event and an information requirement. The next step in the CA process is the construction of links between the CA artifacts. In this case, it would need to be links in both 'directions' – backward to the decision(s) calling for that information requirement as well as forward to the representation requirements for that particular information requirement.

One of the primary impacts of this issue is an identification of the critical issues in the transition from CA to system design. This includes the need for:

- CA to go well beyond analytical insights. A CA needs to provide results that are able to be transformed to design artifacts, preserving linkage at an atomic level. For example, an effective CA model should define and organize the information space for the decision support system (based on the premise that the information space should mimic the decision space). This requires a CA model that is robust

enough to also serve as a design model. In addition, an effective CA for design needs to define specific information requirements (and ideally, representational requirements) as the key step in positioning the CA as a design basis.

- An understanding of the artifacts used by system designers (e.g., system requirements) and how results from a CA can be integrated into these artifacts (and effectively support system design activity). Given these artifacts form the underlying specification for system development, they are the critical targets if CA is to effectively impact design. Therefore, CA results need to be in a set of evolving requirements.
- Artifacts for capturing design rationale in order to maintain the underlying basis for design concepts resulting from CA effort (in order to separate the design basis from the instantiation). This is important to separate the information requirements from the proposed presentation (in order to isolate the source of the problem in an ineffective design).

#4: Cognitive Analysis must serve as the basis for innovative decision support system design concepts.

The use of cognitive analysis as the principal component of defining the requirements of cognitive work and to provide a foundation for design of new decision-support systems has become the approach for a significant number of programs. While cognitive analysis techniques have proved successful in illuminating the sources of cognitive complexity in a domain of practice and the basis of human expertise, the results of the cognitive analysis are often only weakly coupled to the design of support systems (Potter, Roth, Woods and Elm, 2000). A critical gap occurs at the transition from cognitive analysis to system design, where insights gained from the cognitive analysis must be translated into design requirements.

In order to avoid this critical gap, the practice of CA as an initial, self-contained work product that is handed off to system designers must change. In fact, Woods (personal communication, 2004) knows of only one CA that has been successfully handed off to an independent DSS development team. The CA-based design practice needs to evolve into a process of modeling not only the demands of the domain, the strategies and knowledge of practitioners, but also the informational and representational requirements to support these demands, and how envisioned artifacts will shape these strategies and coordinative activities.

From a Cognitive Systems Engineering perspective, it is only when we are able to design appropriate support that we truly understand the way the world works and the way people will operate in this world. This is the essence of the claim by Winograd (1987) that designing "things that make us smart" depends on "…developing a theoretical base for creating meaningful artifacts and for understanding their use and effects." This is also consistent with Tufte's (1997) discussion about the need for a "causal theory" as context for assessing information. Therefore, the key objective of a CA in this respect is a structured representation of the functional concepts and their relationships to serve as the context for the support system to be designed. This structure defines the shape, nature,

and ultimately the content and form of the communication between the decision support system and the domain practitioner.

The relationship between the visual structure established by a particular visualization and the constraints and relationships of the domain itself is fundamental to the effectiveness of the visualization. Without an explicit specification of this mapping, it is impossible to determine if the visualizations are supporting users' needs as they intended, or making the "supported" task more difficult. Compared to the research that has been done on human cognition, very little work has been done describing the representational nature of visualizations in complex information processing tasks (Zhang, 1996).

The key is to develop a mapping between information on the behavioral state of the domain and the dynamic syntax of the visualization. Woods (1992) has called this the 'Mapping Principle' (Figure 2). The mapping principle means that one cannot understand information displays in terms of purely visual characteristics, but that it also must include an understanding of the representational requirements of the work domain. From an interface design perspective, the goal is to reveal the critical information requirements and constraints of the decision task through the user interface in such a way as to capitalize on the characteristics of human perception and cognition.

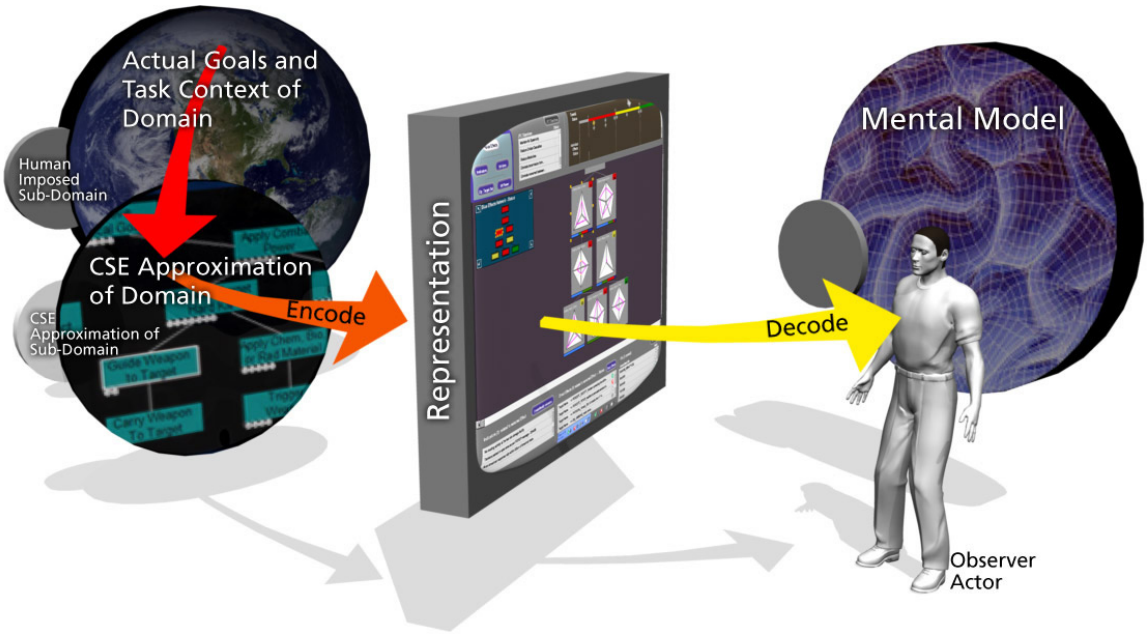

Figure 2. The Mapping Principle (adapted from Woods, 1991) dictates that design of a decision support system must be based on the informational requirements of the work domain, how they are reflected in the representation, and ultimately how they are observed by the user.

There are two fundamental issues involved in the Mapping Principle:

- ***Correspondence*** – an issue of content. What information should be present in the interface in order to meet the cognitive demands of the work domain? This is the mapping from the work domain to the representation of the problem in the visualization. This is the issue that is the focus of Cognitive Work / Task Analysis efforts.

- ***Coherence*** – an issue of the visual properties of the representation. Is the visual representation (the visualization) allowing the human to effectively perceive and extract the information? Coherence addresses the question of how the various elements within a visualization compete for attentional and cognitive resources of the perceiver. For example, are the intended distinctions conveyed by the visualization actually discriminable by the operator? Do the elements combine to produce the desired global properties?

Thus, the effectiveness of visualizations is determined by both correspondence and coherence. More specifically, a visualization's effectiveness is a function of the mapping between the work domain, the presentation elements contained in it, and the extracted/perceived information. So, a CA must be to identify relationships between the types of cognitive work requirements (i.e., decisions) being supported and the form (e.g., visualization technique) for presenting the information to support those demands. The critical property is how the underlying cognitive work requirements map into the structure and behavior of the visual elements. This has several critical implications:

- The need for an approach to uncover the essential cognitive work requirements to be supported by the visualization;
- The dynamic nature of the mapping – one must consider how the display behaves or changes as the state of the problem domain changes;
- The constraints of the 'virtual perceptual field' offered by the computer-based display system that exacerbates the mapping challenge.

Our ACWA approach explicitly addresses this issue by maintaining relationships between the types of cognitive work requirements (i.e., decisions) being supported and the form (e.g., visualization technique) for presenting the information to support those demands through the specification of Representation Design Requirements. These requirements define the shaping and processing for how the information / relationships should be represented to practitioner(s); in essence, a formalization of Woods' mapping principle.

CONCLUSIONS

Developing effective C2 decision support systems is a significant design challenge and requires a deft design hand and a leading edge decision centered cognitive analysis methodology as the basis. Key to the redesign challenge is the highly dynamic and open environment in which the system must operate, and consequently the varied and unpredictable demands imposed on the human operators. Undoubtedly, the system must support operators in following established principles and recommended procedures, but it must also avoid over-constraining operators and avoid hampering them from taking advantage of their abilities to improvise, reason, and respond. Thus, the major focus of this type of effort must the application of a principled and coupled methodology geared towards bridging the gap between analysis and the design of decision support for C^2 decision making.

Our Applied Cognitive Work Analysis methodology has been used across a wide range of domains, from classically designed process control systems, like nuclear power plants,

to so-called 'intentional' domains, such as military command and control. In each case, it has developed decision support concepts that, in hindsight, appear intuitively obvious (as an ideal decision support system should), and yet remained undiscovered prior to the application of ACWA. In ACWA, decision support design concepts are based on an explicit analysis and modeling of the work that is to be supported. Work analysis is therefore not an end in itself but rather a means to derive implications for design. For tool-based design concepts (e.g., a computer-based decision support system), this is valuable to the extent that it gives designers insights into how to create tools that effectively support human work.

Only when decision-centered approaches are cost effective, directly contribute to the value of the end decision support system, and have the reliability and credibility of an engineering process (rather than based on epiphanies) will cognitive analysis make an effective impact on the systems being built every day.

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