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INTEGRATION OF COGNITIVE REQUIREMENTS INTO SYSTEM DESIGN

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The products of cognitive analysis are rarely used effectively in the design of complex, first-of-a-kind systems. This project is motivated by the assumption that those products do not explicitly reveal their design the implications. On the other hand, the analyses undertaken by Systems Engineers do not capture the essential properties of cognitive requirements. The work described here is aimed at developing a computer-supported system that can support dialog between Cognitive Engineers and Systems Engineers as they seek to resolve design issues surrounding cognitive requirements. This project is in its first phase. The preliminary work has demonstrated how a Brahms model might be used to develop a prototype of a socio-technical system based on cognitive specifications developed from a Work Domain Analysis.

A GULF OF COMMUNICATION

The motivation for this project was derived from the informal observation that there is a gulf between the design specifications derived from cognitive engineering and design specifications as required by Systems Engineers. The project goal is to explore ways of strengthening communication between members of these two disciplines to bridge the gap between the cognitive requirements as specified by Cognitive Engineers and the manner in which Systems Engineers might understand those requirements as design specifications.

A VISION FOR SYSTEMS ENGINEERING

Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation.
International Council on Systems Engineering (2005)

In its draft technical vision, the International Council on Systems Engineering (INCOSE, 2005) notes a burgeoning interest in systems thinking and Systems Engineering that is being driven by a trend towards to larger, more complex systems and by demands to do more with fewer resources. The INCOSE vision stresses a design approach that starts with the development of system architecture followed by specification of and prototype implementations of requirements. That vision further notes a need for greater attention to non-traditional methods of representing and analyzing emergent and adaptive behavior and better synthesis techniques that can produce more robust and balanced system solutions.

Systems Engineering is facing new challenges of scope and complexity in a world where readily available solutions optimize local efficiency and robustness at the expense of global efficiency and robustness. While a primary directive for Systems Engineering is to design system functionality that matches stakeholder needs and desires and to ensure that systems *not only do things right but do the right things*, Ring (2004) observes that too many new socio-technical systems fail to meet sponsor expectations. According to INCOSE (2005), the two dominant causes of failure are incomplete specifications of requirements and lack of user involvement, together accounting for 25% of the problems.

System Architecture

Ring (2004) argues that although current Systems Engineering practice can be applied effectively to the design of inanimate systems, it faces significant obstacles in the design of socio-technical systems. The lack of design knowledge about how human agents behave in systems is part of the problem but the failure to design effectively for the self-adaptive and self-aligning role of human agents, the primary reason for retaining people in modern systems, is the more fundamental problem.

The INCOSE (2005) vision notes an emerging recognition within Systems Engineering for human roles within systems. It identifies the self-adaptive nature of humans as one of the motivations for developing better architectural tools to cope with the increased complexity of systems design that results when human agents are responsible for a significant portion of the system functionality. These architectural tools should be exploited in the early concept phase of system design where exploration of design alternatives can be made with low risk and minimal cost (INCOSE, 2005).

Requirements

Requirements, currently expressed in natural language, are ambiguous and incomplete. INCOSE (2005) calls for an innovative approach to develop a more effective alternative, one that leverages advances in computing power and experimentation methods that focus particularly on the concept phase of system design. The vision is one in which stakeholders specify their requirements as *black-box* system models that define the operational environment, specific scenarios in which their envisioned system will operate, system constraints, agent roles (both human and computer), performance demands, quality standards and measures of effectiveness. Suppliers demonstrate compliance with the requirements by replacing the black box model with a detailed, white-box prototype of their system concept.

A MISSION FOR COGNITIVE ENGINEERING

Much of the INCOSE vision for Systems Engineering is outside the scope of Cognitive Engineering. On the other hand, the discussion of architecture and requirements refers to many issues that Cognitive Engineers have been dealing with for some time. We have already developed methods and frameworks that constitute some progress towards resolving the human-related challenges identified by INCOSE (2005) and Ring (2004). Thus, it would be useful to examine our current position on the issues of architecture and requirements.

Architecture

The focus in the past has been on the Cartesian approach of breaking a problem into smaller components, solving each of the smaller problems, and then integrating the pieces back into a whole solution.

International Council on Systems Engineering (2005)

With the exception of the stage of Work Domain Analysis within Cognitive Work Analysis, architecture is essentially ignored within Cognitive Engineering. Nevertheless, those who do Cognitive Work Analysis are occasionally criticized for their emphasis on Work Domain Analysis, it often being the only phase of Cognitive Work Analysis that is completed. In their recent book, Burns and Hajdukiewicz (2004) ignore the remaining four phases on their way to developing an approach to Ecological Interface Design. While this emphasis might be seen as a weakness, it has resulted in the relative maturation of Work Domain Analysis and its analytic product, the Abstraction-Decomposition matrix. While concerns remain, most notably for example in the definition of terms that are central to the construction of an Abstraction-Decomposition matrix, some benefit may accrue from this emphasis on the Work Domain Analysis.

Decomposition is used to extensively, systematically and explicitly within Systems Engineering (e.g., Blanchard and Fabrycky, 1990). In contrast, the commitment to functional abstraction is less clear. Activity-independent analyses that use dimensions of classification somewhat like the abstraction dimension of Work Domain Analysis (e.g., Attributes Lists, Hierarchal Objective Lists and Morphological Charts) are available but it is not clear that they are widely used or that their products are well integrated into the analytic processes of Systems Engineering. For example, the Department of Defense architectural framework does not include a dimension of abstraction in any of its 26 different forms of representation (DOD Architecture Framework Working Group, 2004).

Abstraction is a challenging concept. The potential contribution of the abstraction dimension may be little appreciated because it is poorly understood and is readily confused with decomposition. Sarcedoti (1974) is one who, in proposing a hierarchy of abstraction spaces as a means of reducing combinatorial complexity for planning, appears at first to appreciate the contribution of an abstraction analysis. However, having outlined this proposition, Sarcedoti then proceeds to treat abstraction in terms of decomposition. I suggest that the distinction between abstraction and decomposition, although logical, is not obvious and those who analyze complex socio-technical systems will not turn their attention to it unless there encouraged to do so. This is possibly a contribution that Cognitive Engineers can make to Systems Engineering practice.

Requirements

Cognitive Engineers have generally not done well with requirements generation. We often present the products of our analysis without reference to statements about requirements and where requirements are addressed, they are typically statements about what is required absent any suggestion regarding how that might be achieved. In the terms of the INCOSE vision, these are black-box specifications that do not suggest the form of white-box implementations. One possibility is to specify requirements via a storyboard narrative that demonstrates how the human agents will interact with each other and with the technological features of the system (Lintern, 2005). The INCOSE vision calls for operational prototypes in the form of directly executable models as a means of detailing the white-box solution. This is an area where we might strengthen our approach to dealing with requirements by adapting the evolving practice of Systems Engineering.

Prototyping

Prototyping is promoted as a method for revealing the viability of a system design prior to the expense and difficulty of actually fabricating a system in its entirety. To that end, prototyping should be rapid and inexpensive. However, prototyping has an additional and unheralded contribution that we need to exploit, especially in the design of complex, revolutionary systems. Cognitive Engineers rarely have the opportunity to build anything and we remain separated from the fabrication process even when involved with systems under development. Because we never have an opportunity to build anything, we never confirm the value of our analytic products firsthand. Rapid prototyping has value for Cognitive Engineering, far beyond that of demonstrating the viability of a design, by allowing us to be fully involved in prototype development and thereby permitting us to evaluate our own design methodologies in practice.

PROJECT OUTLINE

A cursory glance at any Systems Engineering text or document will reveal a considerable number of different representational forms (e.g., as noted above, 26 in all for the Department of Defense Architectural Framework). While some of these representations allude to cognitive issues, they do not represent them in the detail that most Cognitive Engineers would think necessary. This project I describe here is aimed at exploration of the cognitive design artifacts that would reveal to Systems Engineers the issues relevant to designing support for cognitive work.

The Air Operations Center, a large-scale military Command and Control system that employs several hundred service and technical personnel, is the domain of interest. An Air Operations Center is a complex information system that is rich in cognitive demands. It has evolved as weapon systems in concert with advances in information technology but this evolution has been a fragmented. There is now considerable interest in redesigning the system to support fully integrated analysis, planning and execution. Because the cognitive issues of this socio-technical system cannot be separated from the technological issues, there is need for a design approach that integrates Cognitive Engineering with Systems Engineering.

The size and complexity of the Air Operations Center (AOC) made it necessary to identify a subset of activities for this first analysis. The selected subset involved the structure and processes in support of Time Sensitive Targeting.

Three documents (Anonymous, 2004; Science Applications International Corporation, 2001; McCormick, undated) were consulted to initiate this work. The major conclusion drawn from them is that planning, deciding and communicating constitute the essential cognitive processes, all of which involve information use (storage, access, fusion, transformation, and transfer). This conclusion prompted a search for a design artifact that would clarify how information resources could be structured and how they could be used.

A DESIGN STRATEGY

Although each of the five phases of Cognitive Work Analysis provides recommendations for different classes of systems design intervention (Vicente, 1999, p. 115), a full set of those recommendations does not specify the system completely. Many degrees of freedom remain so that a number of different design configurations are possible, some of which may work well while others may not. The preceding arguments suggest the value of a rapid prototyping tool that would enable a multidisciplinary design team to explore the implications of various cognitive specifications and to evaluate various system configurations. This mutual exploration, supported by a dynamic prototype, might promote the essential sense-making closure that is required for two disciplines to collaborate effectively.

Brahms, a multi-agent modeling and simulation language for work system analysis and design (Clancey, Sachs, Sierhuis & van Hoof, 1998), is the modeling tool of choice because it is designed around a theory of Situated Cognition compatible with the ecological work practice ideas on which Cognitive Work Analysis is based. It is a prototyping tool that can be used to develop a computer model of a socio-technical system. The modeling process links tasks to work requirements and to functional structure. The thoughtframe-workframe structure of Brahms, in which activities are executed and beliefs modified contingent upon satisfaction of conditions, supports a modeling strategy of higher-level abstractions acting as selective constraints on lower-level abstractions as consistent with the means-end structure of an Abstraction Hierarchy.

The Abstraction-Decomposition matrices developed from analysis of Time Sensitive Targeting were used to identify the functional components to be included in the Brahms model. Tasks, agents and the work requirements were identified from discussions with subject matter experts and associated with functional levels of abstraction. As demonstrated below, Brahms workframes and thoughtframe are structured so that execution of activities and modification of beliefs relevant to functions from one level of abstraction can be constrained by pre-conditions drawn from higher-level abstractions.

WORK DOMAIN ANALYSIS

Figure 1, depicting a high-level Abstraction-Decomposition view of Time Sensitive Targeting, shows the overall purposes, the constraining values and several purpose-related functions. When completed, an Abstraction-Decomposition matrix has two more levels, a physical function level and a physical description level. With these additional two levels completed, the Abstraction-Decomposition matrix fully specifies the functional structure of the system. This matrix permits the designer to think about various options for implementing and supporting functions and to explore how functions interact with each other.

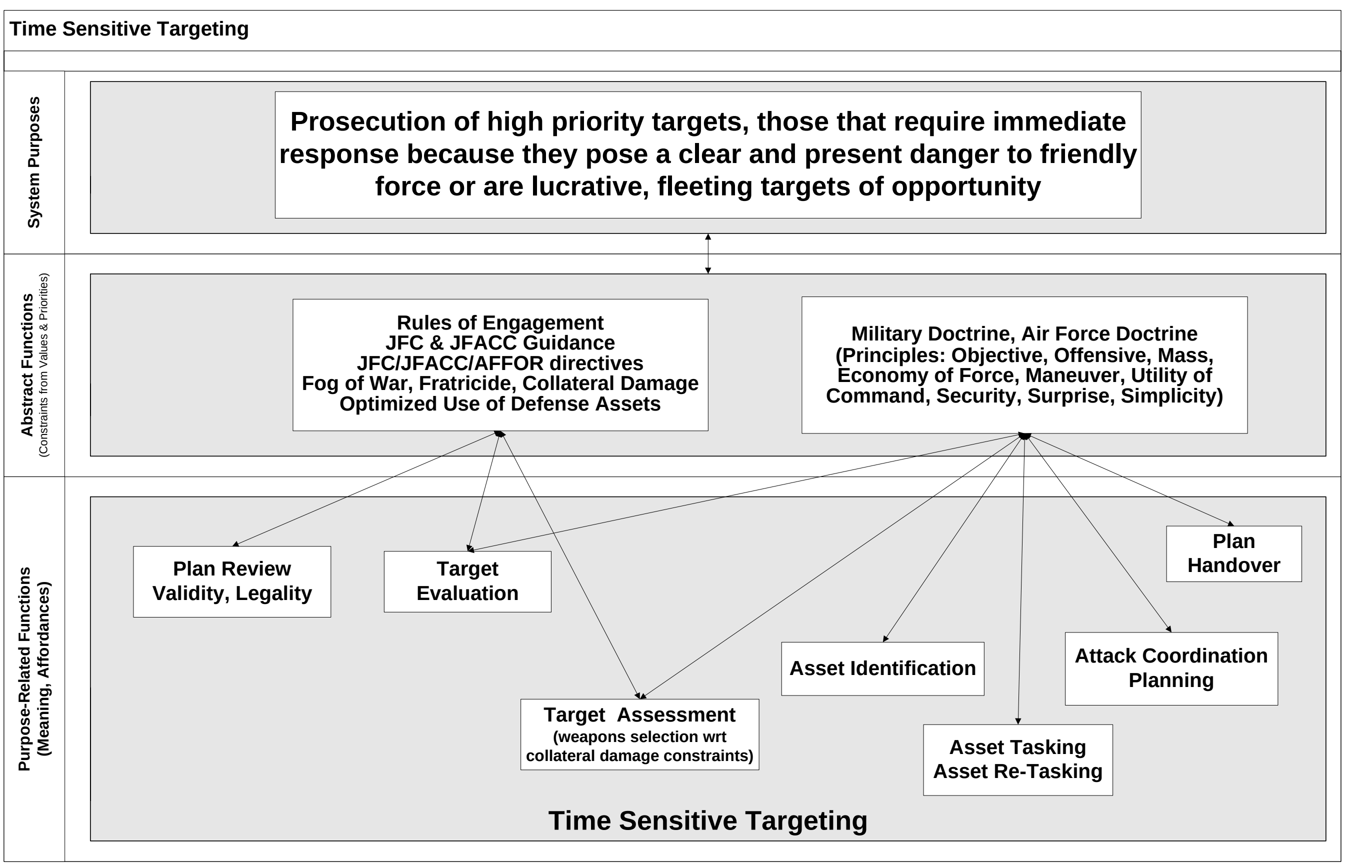

Figure 1; A high-level view of Time Sensitive Targeting as represented by an Abstraction-Decomposition matrix, showing the overall purpose, the constraining values and several purpose-related functions.

A Watch Commander, a Targeteer, a Rerole Coordinator, an Attack Coordinator and a representative of the Judge Adjutant General (JAG) provide the typical staffing for the purpose-related functions of Figure 1.

The Watch Commander routinely reviews potential targets to assess them in relation to published time-sensitive criteria.

The Targeteer, who is the first in the cell to be notified of a potential Time Sensitive Target, reviews the target in relation to Rules of Engagement and potential for collateral damage. If the target falls within the rules of engagement, s/he identifies munitions and platform types suitable for this specific target and, if there is a potential for collateral damage, s/he adjusts the selection of munitions and attack strategies to minimize that risk. The Targeteer then hands the target to the Rerole Coordinator who plans the attack and identifies the specific assets to prosecute the target (either from a pool of assets on standby or by re-tasking assets already committed elsewhere).

Finally, the Attack Coordinator reviews the plan and then seeks an execute authorization from the Watch Commander, who may also request a legal opinion from the JAG representative. Once the attack is authorized, the Attack Coordinator transmits the plan to the operational units tasked to execute it.

A BRAHMS MODEL

The workflow of a Time Sensitive Targeting scenario fragment has been modeled in Brahms. That modeled fragment commences with a shift change and so there is a Shift_Handover workframe. The centerpiece of the fragment is a workframe in which Time Sensitive Targets are developed. When not working on Time Sensitive Targets, cell members build situation awareness and undertake generic target development activities. In the modeled fragment, these activities are executed within Build_Situation_Awareness and Develop_Targets workframes.

Figure 2 and Figure 3 show sections of a timeline produced by Brahms for two agents, a Targeting Officer (not a member of the TST cell) and a Targeteer. Once notified of a Time Sensitive Target by the Targeting Officer, the Targeteer must confirm that it falls within the Rules of Engagement and must identify issues related to collateral damage. The basis of the ensuing judgments lies in the values identified in the second level of the Abstraction-Decomposition matrix. More often than not, the Targeteer's experience and situation awareness will enable an immediate confirmation (Figure 2). In other cases, s/he will have to consult appropriate sources (Figure 3).

In the Brahms model that produced this timeline, the confirmation criteria are modeled as preconditions within an Identify_TST_Assets workframe in which the Targeteer identifies suitable munitions and platform types for the target. These preconditions must be satisfied before the Targeteer can execute this workframe. Prior to testing these preconditions, the Targeteer executes an Acknowledge_TST thoughtframe in which s/he acknowledges the TST and assesses whether s/he can proceed immediately. These two preconditions, initially set false, can be set true in this thoughtframe with defined probabilities ranging from 0 to 1.0 (for the current exercise, they were set at 0.5).

The timeline in Figure 3 depicts what happens when the Targeteer cannot immediately confirm the judgment on either dimension. The two relevant preconditions remain false and two other workframes (Review_Legal_Status and Minimize_Collateral_Damage) must be completed to reset each true. Once both preconditions are set true, the Identify_TST_Assets workframe is executed. Because the reset within the Acknowledge_TST thoughtframe is probabilistic and the two probabilities are independent, the Targeteer will, at different times, be required to execute one, both, or neither of the preliminary workframes. Factors that might preclude target authorization have not yet been modeled.

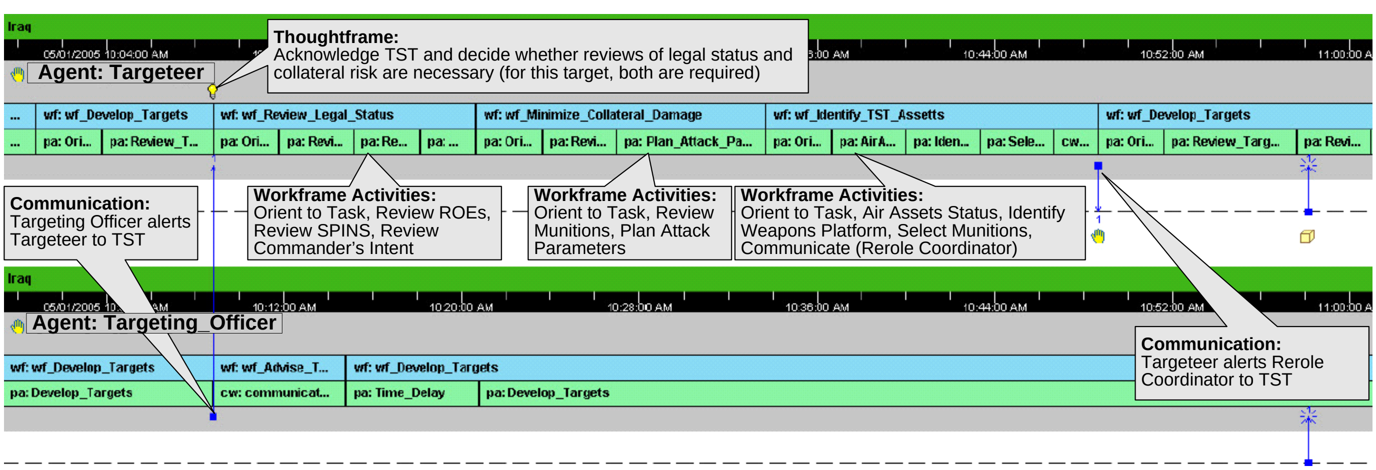

Figure 2; a section of the timeline produced by Brahms for two agents, a Targeting Officer and a Targeteer, in which the Targeteer assigns assets without reviewing legal status or collateral damage status (the callouts were added to the figure to illustrate features of the Brahms output).

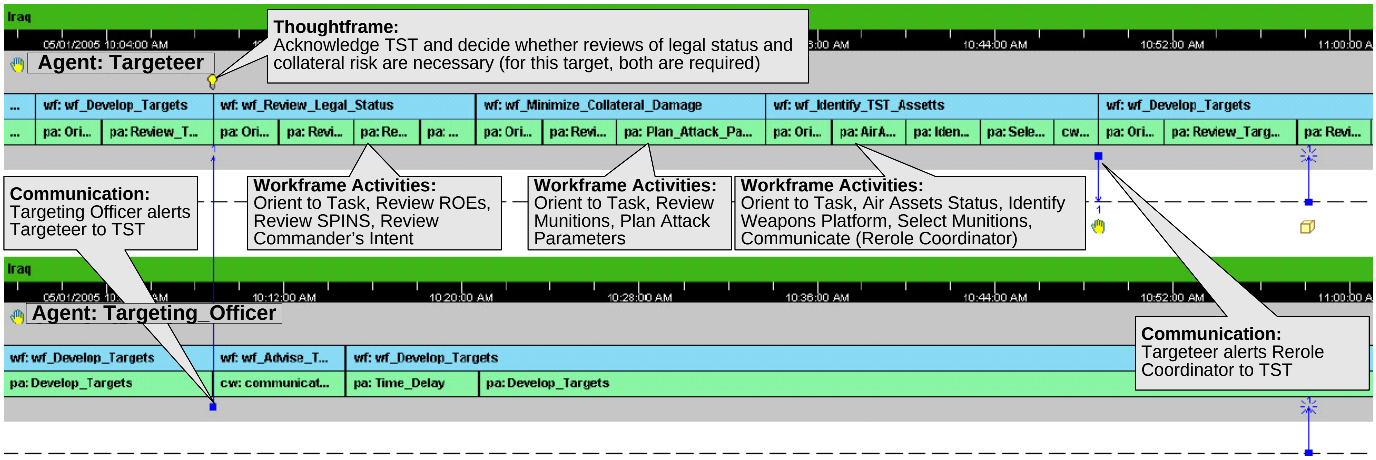

Figure 3; a section of the timeline produced by Brahms for two agents, a Targeting Officer and a Targeteer, in which the Targeteer must confirm legal status and collateral damage status before assigning assets (the callouts were added to the figure to illustrate features of the Brahms output).

Figure 2 illustrates another useful feature of Brahms. The Targeteer is routinely engaged in developing generic targets except when dealing with a Time Sensitive Target. In the modeled scenario, s/he stops work on generic target development immediately s/he is alerted to the Time Sensitive Target. The current Develop_Targets workframe is discontinued in this timeline segment, but this can be modeled so that the workframe is completed before the agent attends to the alert or after s/he deals with it.

CONCLUSION AND FUTURE DIRECTIONS

The focus of this project is on cognitive requirements for complex socio-technical systems that rely for their effectiveness on emergent properties generated by human flexibility and self-organization, a context in which the ambiguity and incompleteness of natural language specifications are particularly evident. The goal of the project is to develop a dynamic alternative that will permit multidisciplinary teams to explore how constellations of cognitive requirements can be accommodated within the envisioned system.

The final product of the research will be an interactive, computer-supported modeling tool that will help multidisciplinary teams explore the design implications of cognitive requirements. The preliminary work reported here has demonstrated how Brahms might be used to develop a prototype of a complex, socio-technical system based on cognitive specifications developed from a Work Domain Analysis. Because development of a Brahms workflow model is actually a design activity, the modeling process in itself will help us understand a good deal about how to design the physical system. In addition, this design activity will provide valuable feedback that can help refine the methods of Cognitive Work Analysis and, more generally, of Cognitive Engineering.

There are a number of issues to be examined in the future research. The problem of combinatorial complexity is one that challenges workflow modeling. There has been a suggestion that use of an abstraction hierarchy to structure a model will reduce combinatorial complexity. This proposition will be explored in the coming months. In addition, the target domain selected for this research requires the modeling of hundreds of agents. It will be necessary to confirm that a Brahms model can be scaled up to the required size.

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