EVALUATING DESIGN SOLUTIONS WITH WORK DOMAIN ANALYSIS

*Neelam Naikar and **Penelope M. Sanderson

* Aeronautical and Maritime Research Laboratory (AMRL)
Defence Science and Technology Organisation (DSTO), Melbourne, Australia

** Swinburne Computer-Human Interaction Laboratory (SCHIL)
Swinburne University of Technology, Melbourne, Australia

ABSTRACT

A demanding task in procuring complex military platforms is determining whether proposed designs will function effectively in the relevant work context. Conventional evaluation methods offer a limited perspective that focuses on the technical performance of designs in a small range of predictable mission scenarios. In this paper, we advocate Work Domain Analysis, a technique which describes the functions, priorities and values, and purposes of a work domain independently of particular scenarios. This framework focuses the evaluation of designs on functional properties that are relevant to a wide variety of situations, including unanticipated contingencies. Work Domain Analysis also offers a useful framework for examining human-system integration solutions. We illustrate how these concepts were used by Australian Defence Force for the procurement of an Airborne Early Warning and Control system.

INTRODUCTION

The procurement of complex military platforms, from initial identification of the need for a new capability to the eventual introduction of the system into service, is a lengthy, challenging, and complex process. In this paper, we focus on one of the most demanding processes in the acquisition of complex systems: determining whether design solutions that have been tendered by various system manufacturers will fulfil the functions and purposes of the intended platform. We highlight the unique demands that complex sociotechnical systems place on the evaluation of designs, and we discuss the limitations of standard evaluation techniques in light of these requirements. We then present a new framework for evaluation based on Work Domain Analysis (WDA; Rasmussen, Pejtersen & Goodstein, 1997; Vicente, 1999). We put forward a theoretical case for using WDA, and we also discuss how these concepts were implemented by the Australian Defence Force (ADF) during the acquisition of an Airborne Early Warning and Control (AEW&C) system.

EVALUATING DESIGNS FOR COMPLEX SOCIOTECHNICAL SYSTEMS

Complex sociotechnical systems have special characteristics that place unique demands on the evaluation of designs. First, the technical component of a complex sociotechnical system is not an isolated unit but a resource for fulling the requirements of some broader work context (Figure 1; Rasmussen et al., 1994; Vicente, 1999). Hence, evaluators of designs must be concerned with whether proposed solutions will fulfil the contextual constraints within which the technical component must operate. Second, as unpredictable or unanticipated events pose a serious threat to system performance and safety (Perrow; 1984; Pool, 1997; Rasmussen et al., 1994; Reason, 1990; Vicente, 1999), evaluation must also determine how designs will deal with the requirements of the work domain under novel as well as anticipated conditions.

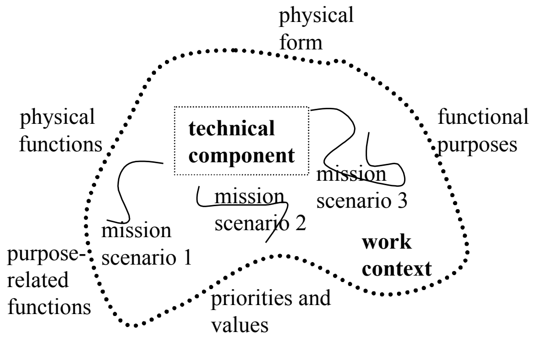

Figure 1: The technical component of complex sociotechnical systems is a resource for fulling the requirements of a broader work context. Standard methods focus on the technical solution and its performance in a small range of anticipated mission scenarios. In contrast, WDA is concerned with whether a design fulfils the requirements of fundamental functional boundaries on system performance and safety; boundaries that are relevant to a broad range of situations, including unanticipated events.

STANDARD EVALUATION TECHNIQUES

Standard approaches include *technical* and *operational* evaluation techniques (Department of Defence, 1995; Gabb and Henderson, 1996). Technical evaluation involves examining whether the designs of particular physical subsystems, such as radar and mission computer, fulfil pre-specified technical requirements. For example, the technical requirements for a mission computer include storage capacity and speed of processing. This method provides a valuable understanding of the technical strengths and weaknesses of each of several physical subsystems. However, it does not promote an appreciation of the performance of design solutions in the relevant work context. In many acquisition projects in the ADF, the selection of winning designs is based mainly on this assessment of technical properties.

Operational evaluation involves examining the results of the technical evaluation in light of a set of predefined mission scenarios (eg. conduct and control a maritime strike in blue water ocean) and associated sequences of tasks. This technique provides an understanding of the technical performance of designs in a useful range of mission scenarios. However, as the relationships between physical subsystems and mission scenarios are not mapped out, it is difficult to trace the effect of the technical solution on the operational requirement in a systematic and explicit fashion.

Moreover, from a logistical perspective it is impossible to consider large numbers of scenarios during evaluation. Thus, scenario-based techniques can only focus evaluation on a small number of mission scenarios relative to the total work space of possibilities (Figure 1). Moreover, the mission scenarios that are defined are necessarily restricted to events that can be anticipated by domain experts. Hence, this method has little to offer about design performance under unanticipated contingencies (see Vicente, 1999 for similar arguments with respect to prototype testing and scenario-based design).

A WDA-BASED APPROACH TO EVALUATION

In this paper, we propose a new framework for evaluation based on WDA. This technique accommodates the fact that complex sociotechnical systems are subject to a great many events, both routine and abnormal, that cannot be predicted or specified in detail. Hence, rather than concentrating on particular scenarios or trajectories of behaviour, WDA focuses on the fundamental physical and purposive boundaries on system performance (Figure 1). As these functional properties are both device and event-independent (Vicente, 1999), they can accommodate diverse system responses to a wide range of situations, including unpredictable events. A system that is designed to these intrinsic boundary conditions will allow workers to engage in flexible, adaptive action to deal with a broad range of contingencies.

Abstraction hierarchy

The functional boundaries of a work domain may be described in an abstraction hierarchy (Figure 2). Typically, the functional properties described at each layer of abstraction include: (1) functional purposes or high-level objectives, (2) priorities and values, (3) purpose-related functions or general work functions, (4) physical functions, and (5) physical objects or devices. These functional properties remain constant irrespective of particular mission scenarios or specific features of devices.

The links between different layers of abstraction represent means-ends or "how-why" links (Figure 2). Thus, if one focuses on a function at a given level of abstraction, links to functions at lower levels indicate the means or "how" the target function is achieved. Conversely, links to higher levels of abstraction indicate the ends or "why" the target function exists.

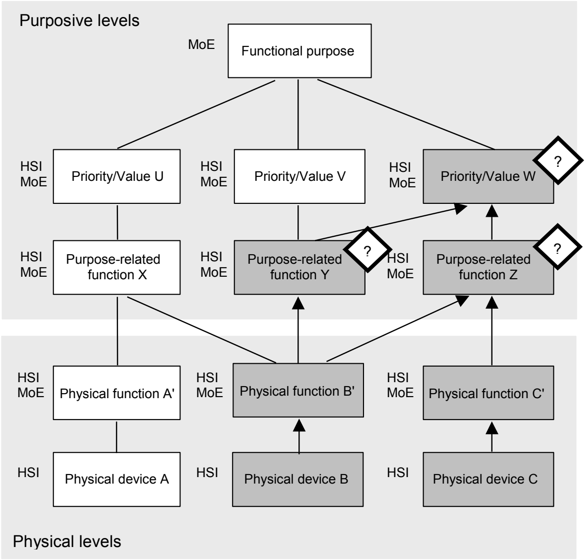

Figure 2: A generic abstraction hierarchy with five levels of abstraction and means-ends links. This framework can be used to characterize human-system integration (HSI) solutions and to define appropriate measures of effectiveness (MoEs) for evaluating these solutions.

Using the abstraction hierarchy for evaluation

By using the abstraction hierarchy, design solutions relating to particular physical resources (bottom two layers) can be evaluated in terms of how well they support the purpose-related functions of the work domain (third layer) -- functions which specify "why" those physical resources are needed in the work domain. In turn, the impact of the design solutions on purpose-related functions can be traced to the priorities and values and functional purposes of the work domain. Thus, rather than simply focusing on technical properties, WDA focuses evaluation on how well the purpose-related functions, priorities and values, and functional purposes of a system are satisfied, given the technical solution. As these functional properties are both device- and event-independent, evaluators can appreciate how designs will deal the requirements of a broad range of situations, including events that cannot be specified up front.

The means-ends relations between different levels of abstraction allow the effect of physical properties on higher-level functions to be traced in an explicit and systematic fashion. WDA also makes the propagation of integrative effects through the work space clear. To illustrate, Figure 2 shows that physical functions B and C are both used to achieve purpose-related function Z. The design solutions for physical functions B and C, when taken alone, may satisfy technical requirements. When put together, however, it may be very difficult to perform purpose-related function Z. In turn, once purpose-related function Z is compromised, the ability to conform to a key priority or a key value of the system such as priority/value W may also be compromised.

WDA also provides a useful framework for evaluating human-system integration solutions. Each of the functional properties described in an abstraction hierarchy can be annotated with details of human-system integration solutions relating to those constraints (see Figure 2 for annotations reading "HSI"). This representation would provide a summary of the degree of data integration, data fusion, decision support, and automation that a design solution offers. Then, as higher-level constraints indicate the reasons that functions at lower levels exist, measures of effectiveness for each of the human-system integration solutions can be defined in terms of the higher-level functions which those solutions must fulfil (see Figure 2 for annotations reading MoE).

EVALUATION OF AEW&C DESIGNS USING WDA

So far, we have presented a theoretical argument for the use of WDA as an evaluation framework. We will now show how these concepts were applied to the acquisition of an AEW&C system by the ADF. AEW&C is a complex, airborne platform which is similar in capability to the United States Airforce's Airborne Warning and Control (AWACS) aircraft. It is expected that this platform will be manned by approximately 7 crew members whose key responsibilities will be surveillance and control of air defence assets. The suite of physical devices on AEW&C will include onboard sensors, voice and data communication systems, and electronic warfare protection systems.

AEW&C is expected to be introduced into the ADF by the year 2004 or 2005. Three aircraft manufacturer's tendered for this contract, and WDA was a key framework used for evaluation of the three designs and selection of the winning contractor in 1999. We emphasize, however, that due to its late introduction into this project (in the final year of tender evaluation) WDA was "retrofitted onto the end of a long and complex acquisition process. Moreover, the characterization of AEW&C in work domain terms, and the use of WDA itself as an evaluation technique were essentially being realized alongside the tender-evaluation process.

In the remainder of this paper, we will describe the process by which WDA was used for the evaluation of AEW&C designs. Although we do not provide a full description of the AEW&C acquisition project in this paper, we should note that there were two other evaluation techniques used on this project: (1) technical evaluation, and (2) operations modeling, a form of scenario-based analysis, whereby physical-subsystem designs were modeled and evaluated in a small range of mission scenarios using monte carlo simulation. This technique complemented WDA by providing a detailed assessment of the technical performance of designs in a useful range of mission scenarios.

AEW&C abstraction hierarchy

The primary sources of information used for developing the AEW&C abstraction hierarchy were various documents prepared by the ADF and input from subject matter experts. A global view of the resulting abstraction hierarchy (figure 3) shows that the WDA identified two functional purposes, 10 priorities and values, 12 purpose-related functions, 77 physical functions, and 61 physical systems. Many potential means-ends relations between different layers of abstraction are also shown.

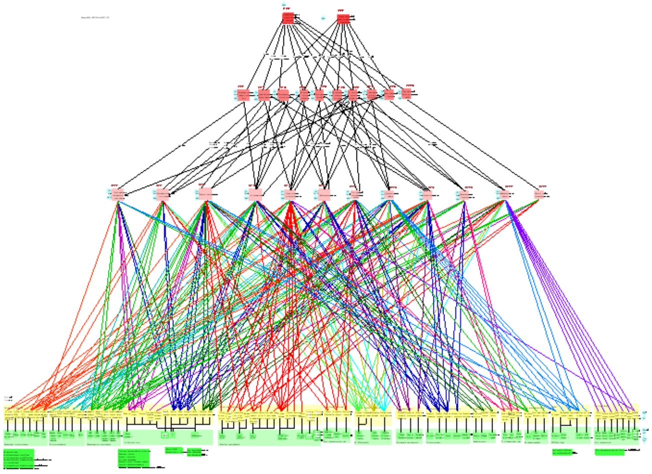

Figure 3: A global view of the entire AEW&C abstraction hierarchy

In figure 4 we present a sample of functions from the AEW&C abstraction hierarchy in order to illustrate two key points. First, WDA provides an explicit and systematic framework for tracing the impact of the physical properties of designs on the entire work context. For example, a radar with a longer range will improve the timeliness of detections, tracking, and associations, but it will also generate more data for storage, and communicate the presence of the platform more broadly (by emitting over a longer range), thus compromising the safety of the platform, its sensors, and information systems. Second, readers can observe that the functional properties described for AEW&C are both device- and event-independent. Hence, these functional boundaries are relevant to a broad range of situations, including scenarios that cannot be specified up front.

Evaluation Process

WDA was used by the Operations and Technical Tender Evaluation Working Group of the AEW&C Project Office. This group was divided into smaller teams who were responsible for evaluating designs relating to particular physical subsystems (eg., radar, communications). In accordance with standard techniques, each team assessed whether the designs complied with, exceeded, or were deficient with respect to pre-specified technical requirements. WDA was then used to perform an evaluative "roll-up" that better reflected the functional structure of the AEW&C work

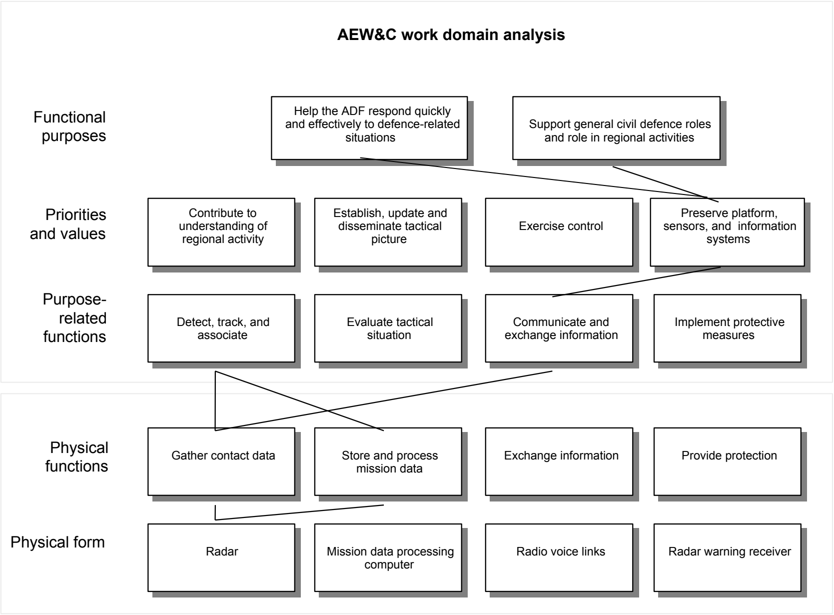

Figure 4: A sample of functions from the AEW&C abstraction hierarchy with means-ends links illustrating how properties of the radar system propagate through the work context.

domain. Each team assessed the impact of physical-subsystem solutions on the purpose-related functions of AEW&C. The Tender Evaluation Working Group leader and his assistants then summarized the results at the purpose-related functions layer across different physical subsystems or sub-groups. Finally, the combined impact at the purpose-related functions layer was evaluated for its effect on the priorities and values, and the functional purposes of AEW&C.

This process was not considered an extra burden on the already high workload of evaluators. In fact, the benefit of evaluating against higher-order functional properties was not only recognized in advance but also appreciated in retrospect by the AEW&C Project Office. When Project Office staff briefed the Deputy Secretary of the Department of Defence just prior to contract announcement, WDA was an area singled out for mention because of its usefulness.

One of the challenges that emerged in using WDA on this project was that the framework had to be modified to fit the ADF's acquisition protocol. For example, the priorities and values determined by WDA were modified by the AEW&C Project Office to reflect system priorities that had been endorsed by high-level defence committees prior to the start of acquisition. These priorities did not reflect functional constraints but tended to resemble broad operational roles. This problem may be avoided in the future by adopting a top-down approach where commitments to WDA are obtained at an organizational level rather than at the project level. Part of this process will involve developing well-defined WDA-based evaluation procedures and training the evaluation community in the WDA approach. Currently, there appears to be good support from high-level defence personnel for a WDA-based approach to evaluation.

CONCLUSION

In this paper, we have discussed how a WDA-based approach to evaluation can overcome the limitations of conventional techniques. We have detailed our arguments at a conceptual level, and we have discussed the application of these concepts to the acquisition of AEW&C, highlighting both the benefits and challenges of this process. Moreover, we have made some recommendations for more powerful uses of WDA in future acquisitions.

While we have conducted our discussion in the context of the ADF acquisition process, we perceive that the issues we have raised are applicable to the acquisition of complex systems by other defense forces as well as by non-defense industries. We also note that WDA can be used during other stages of a system's lifecycle, for example, to develop functional requirements, design, and training (Naikar & Sanderson, 1999; Sanderson, Naikar, Lintern, & Goss, 1999).

REFERENCES

Department of Defence (1995). *The Capital Equipment Procurement Manual* (CEPMAN). Canberra, Australia: Defence Publishing Service.

Gabb, A., & Henderson, D. (1996). *Technical and operational tender evaluations for complex military systems* (Defence Science and Technology Organisation Rep. No. DSTO-TR-0303). Salisbury, Australia: Electronics and Surveillance Research Laboratory.

Naikar, N., & Sanderson, P. M. (1999). Work domain analysis for training-system definition and acquisition. *International Journal of Aviation Psychology* **9**(3), 271-290.

Perrow, C. (1984). *Normal accidents: living with high-risk technologies.* New York: Basic Books.

Pool, R. (1997). *Beyond engineering: How society shapes technology*. New York: Oxford University Press.

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

Reason, J. (1990). *Human error*. Cambridge, England: Cambridge University Press.

Sanderson, P. M., Naikar, N., Lintern, G., & Goss, S. (1999). Use of cognitive work analysis across the system life cycle: requirements to decommissioning. *Proceedings of the 43rd Annual Meeting of the Human Factors and Ergonomics Society,* 318-322.

Vicente, K. J. (1999). *Cognitive work analysis: Towards safe, productive, and healthy computer-based work.* Mahweh, NJ: Lawrence Erlbaum & Associates.