APPLYING COGNITIVE WORK ANALYSIS TO LARGE SCREEN DISPLAY DESIGN

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ABSTRACT

Large-screen displays (LSDs) have become signature features in the recent evolution of nuclear power plant control rooms. They are often introduced with the intention of enhancing situation awareness and collaboration between operators. However, an operating experience review revealed that these claims have yet to be thoroughly evaluated and validated. This paper presents the results of a three-phase cognitive work analysis (CWA) conducted to establish the information requirements for a novel LSD design to be implemented and evaluated in subsequent phases of the project. Providing a clear example of the formative stages in LSD design and evaluation can benefit human factors practitioners engaged in, and regulators evaluating, similar projects.

Key Words: Cognitive Work Analysis, Large Screen Display, Situation Awareness, Collaboration

1 INTRODUCTION

Large Screen Displays (LSDs) are a signature feature in the modernization of NPP control rooms [1]. LSDs are implemented on the basis of two central claims: 1) They enhance operator situation awareness; and 2) They enhance crew communication and collaboration [2]. Although these claims seem intuitively appealing, an operating experience review by Myers and Jamieson (2014) revealed that these claims have yet to be thoroughly and conclusively evaluated or validated in the nuclear domain [1].

This paper details the functional and task analyses that will serve as the basis for an experiment whose purpose is to evaluate the validity of the situation awareness and communication/collaboration claims. The information requirements revealed through these analyses will serve as the basis for the design of a novel interface that will employ *Ecological Interface Design* principles and practices [3]. We will evaluate task performance using this novel design compared to displays more commonly used in current control rooms. Providing a clear example of the formative stages in LSD design and evaluation can benefit human factors practitioners engaged in, and regulators evaluating, similar projects.

1.1 Analytical Framework

Cognitive Work Analysis (CWA) is an analytical framework for describing complex, sociotechnical systems from a constraint-based perspective [3]. This is achieved through the formative analysis of the physical-, task-based-, strategic-, socio-organizational-, and workers competencies-constraints [3]. It is important to note that the purpose of this study was to conduct a CWA in the service of a summative evaluation experiment. This resulted in a modified CWA, which served the needs of the end experiment.

We conducted three stages of CWA: Work domain analysis to identify purposive, functional and physical, constraints; Control task analysis to identify task-based constraints; and Strategies analysis to identify strategy-based constraints. The other two stages of CWA, Social Organization and Cooperation Analysis (SoCA) and Worker Competencies Analysis (WCA), are nested within the three phases that we conducted. The nested nature of these two stages results from the premise of the analysis, namely to serve a future experiment. SoCA examines how different tasks are allocated within a work domain while WCA evaluates what the workers need to be able to do to achieve the functions delegated to them in the SoCA. To ensure that the experimental tasks meet the criteria required to test the claims of LSDs, the SoCA and WCA will be modified as the study progresses.

1.2 Need for Analysis

The merits of CWA have been demonstrated in various domains, from air traffic control [4] to petrochemical processing [5][6][7], and more specifically, to nuclear power generation [8]. CWA has been shown to be a valuable tool in the analysis of these complex systems, as it fosters a deep understanding of the system of interest [3][4]. However, with this depth of understanding, comes the tradeoff of the effort and time needed to complete the analysis [9]. Because of this, CWA is typically only applied to large-scale analyses for complex systems.

The products of CWA are often applied to interface design for complex systems [10]. In these systems there are far too many parameters for the crew to reliably monitor. This imposes a display-based constraint, which essentially calls for a refinement of the list of parameters in an effort to find the optimal balance between complete system representation and simplicity. This is one of the areas where CWA excels [9]. It allows for designers to understand not only the critical parameters of a system, but also the way in which these parameters should be displayed to accommodate the various constraints of the sociotechnical system.

As mentioned above, the actual process of carrying out this analysis gives rise to benefits in and of itself: a deep understanding of the system. This depth of understanding, although coming at the cost of time and effort, supports all subsequent aspects of the experiment, from experimental design to participant training.

1.3 System Introduction

The target system for our analysis was a CANDU 6® nuclear reactor. This is a heavy water (D_2O) reactor, which allows natural uranium fuel to be used rather than the enriched uranium that is necessary for light water reactors. The D_2O in the system serves as a coolant, removing heat from the reactor and transferring it to light water, which is subsequently turned into steam. Excess moisture is removed from the steam to maximize efficiency and mitigate the potential for damage to the system. The dry steam then drives a turbine, which creates electricity that is sent to the grid.

Davey (2000) notes that during normal operations, C6 operators tend to focus their efforts on five main systems: R[1]eactor power control, heat transport pressure and inventory control, secondary steam generator level control, secondary steam generator pressure control, and turbine control [11]. Figure 1 presents a simplified block diagram of these systems. By amalgamating different system diagrams, we created a unified representation of the entire system at a consistent level of detail; something that was missing from prior literature. We chose this level of detail to convey the depth of knowledge that the eventual experimental participants - process operations students - will be expected to have of the system.

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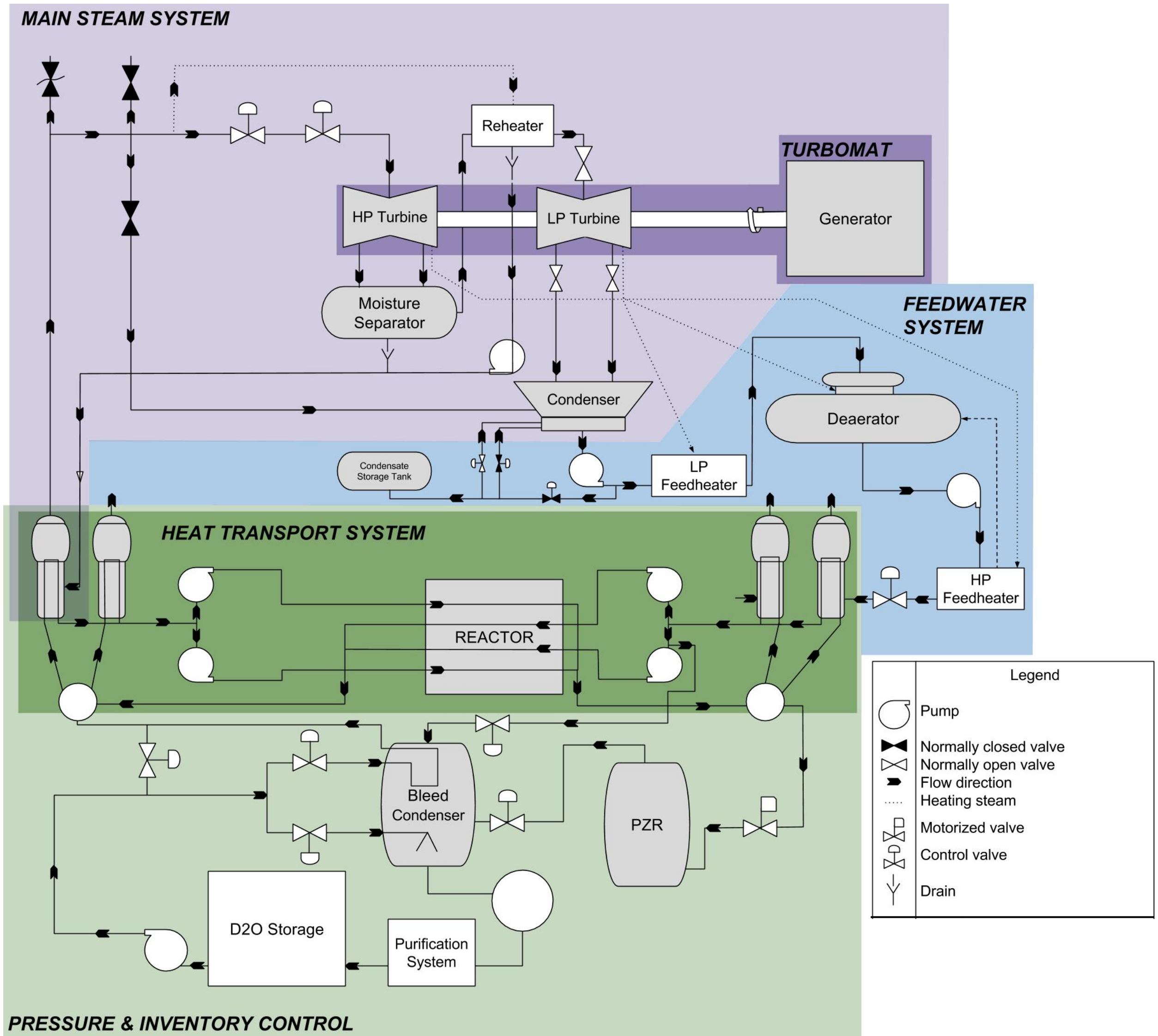

Figure 1. A simplified block diagram of the CANDU 6® power plant created at the level of detail reflecting the degree of understanding expected of experimental participants.

2 EXPERIMENTAL DESIGN

The experimental objectives and design help to explain and contextualize the analyses described in the following sections. The primary goal of the experiment is to evaluate whether or not LSDs 1) enhance operator situation awareness, and 2) improve collaboration and communication between operators. The second goal of the experiment is to evaluate the efficacy of different display design frameworks in achieving these two claims. These goals informed the selection criteria for the experimental tasks and resulted in the following two task requirements: 1) They require situation awareness and collaboration between operators; and 2) They represent a level of complexity that will challenge the novice operators, without overburdening them.

Experimental scenarios were derived from combination of a shutdown system 1 trip testing (SdST) task, and a steady state monitoring (StSM) task. SdST involves evaluating whether or not the system reacts in the intended manner when it is fed false data pertaining to potential trip scenarios. Although SdST is a fairly straightforward procedure, the act of ensuring that the rest of the system does not accidentally trip is more difficult since SdST requires reducing the trip criterion for the rest of the system. StSM consists of participants monitoring an array of parameters without actively performing any control task. Therefore, in one experimental scenario, StSM will occur concomitantly with SdST. In the other, StSM will be performed in isolation. Predefined deviations imposed during these experimental tasks will require active problem solving by the participants. To adequately perform these tasks participants will need to demonstrate situation awareness as well as communication and collaboration. The participants will complete these tasks under two principal manipulations: 1) The type of group view display present in the control (i.e., LSD present vs. redundant display); and 2) The way in which information is displayed (i.e., EID vs. mimic-based displays). The experiment will be designed to yield data that will provide answers to the research questions.

2.1 Description of Analytical Framework

Cognitive work analysis (CWA) [3][12][13] is a popular framework for analyzing complex sociotechnical systems. Through multiple analytical stages, CWA models the target system by defining the layers of constraints that limit its effective operation. Each of these stages aims to define a different form of constraint and uses a specific modeling tool. CWA is formative rather than normative or descriptive in nature; it describes the systems in terms of opportunities for meaningful action as opposed to capturing how work is currently conducted or how it should be conducted.

The first stage, Work Domain Analysis, documents the constraints governing the purpose, function and physical features of a system, while remaining context independent [14][3]. The primary modeling tool employed in Work Domain Analysis is the Abstraction Hierarchy, which describes a system at five levels of abstraction, with the physical form and then function of its components at the bottom levels, followed by the functions it performs, its base principles, and finally its overall goals at the top. Entities are linked between levels with means-ends connections, which enables a concise depiction of how each individual subsystem or component achieves one of the higher level system purposes.

Control Task Analysis builds on the Work Domain Analysis by identifying the recurring tasks that need to be done within the work domain, independent of how or by whom they are done [3]. For this purpose the Decision Ladder is used to describe the different states of knowledge a decision maker moves through and the processes that lead from one state to the next when carrying out a specific task. It also includes shortcuts taken by expert decision makers. Control Task Analysis works best for tasks with undefined initial conditions that require operators to use judgment and deal with ambiguity. Procedural tasks typically do not require significant decision making and are therefore generally unsuitable this stage of analysis. For this reason a Control Task Analysis was conducted for StSM, but not for SdST as the latter is highly procedural.

The final stage that we conducted, the Strategies Analysis, models the different strategies that an operator can employ to accomplish the tasks outlined in the Control Task Analysis, together with their mental models and how they process information. These strategies are not necessarily unique to any given situation, but are rather general templates that can be applied to a variety of situations. Strategies Analysis employs the Information Flow Map, which describes the sequence of activities and information processing steps that go into enacting a strategy for a given situation. As with the Control Task Analysis, this stage is most suitable for tasks that require dynamic decision making and was used for StSM, but not SdST.

3 PRODUCTS OF ANALYSIS

The three phases of Cognitive Work Analysis conducted formed the majority of our analysis and was based upon operating manuals, training literature, and SME knowledge. The systems analyzed were selected based on relevance to the experiment and interface design, rather than relevance to the tasks under normal operating procedure. Similarly, stages in the methodology that did not provide useful information were not conducted.

The first experimental task, Steady State Monitoring (StSM), consists of monitoring the entire plant to ensure all systems are performing as expected. Abstraction Hierarchies at three levels of aggregation were used to capture the systems necessary to complete this task. An overall plant hierarchy formed the highest level and provided basic context for each system analyzed. The second level consisted of the main systems that are monitored in the plant: reactor power control, pressure and inventory control, heat transport system, main steam system and feedwater system. The third level consisted of the boiler (nested under heat transport system) and turbines (nested under main steam system), which Davey (2000) identified as also being key to StSM. Figure 2 shows an example hierarchy for the Boiler/Steam Generator. There are four Functional Purposes of the boiler. As the connections are traced down, the level of abstraction decreases until, at the lowest level ("Physical Function"), the physical elements that constitute the boiler are described.

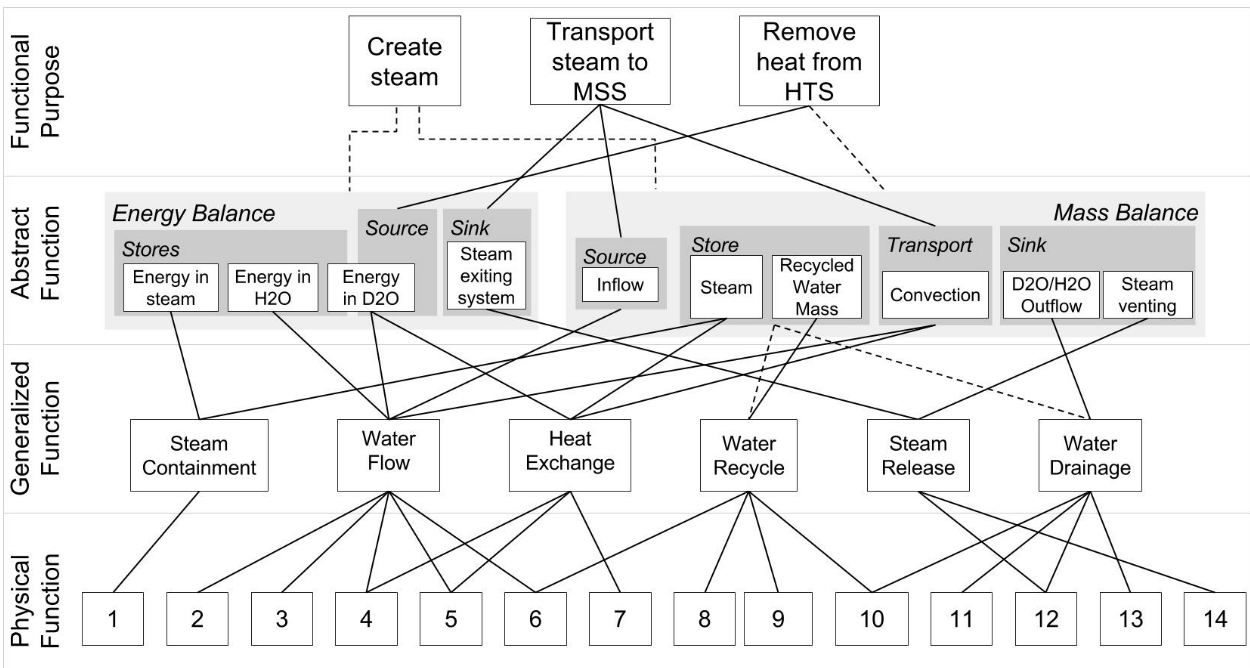

Figure 2. Simplified abstraction hierarchy for the Boiler/Steam Generator (with numbers substituting for labels due to size constraints). The general structure and notation is constant for the AHs of the five critical subsystems. A dashed line connected to the exterior box indicates that the element is connected to all of that box's constituent nodes.

The breadth of this work domain's scope, coupled with the depth of understanding required, presented a challenge for student analysts working under a time constraint. The use of nested hierarchies at different levels of detail, allowed for a balance of both breadth and depth. It also allowed each system to be viewed within the context of the overall system.

However, as each hierarchy spans only a single system in isolation, it can become difficult to capture the interactions between the different systems being analyzed when using multiple hierarchies. The physical function block diagram presented in Figure 1 was therefore used to provide context to the systems and include the processes that connect them. This diagram also demonstrated more effectively the details of the current processes, which further helped to focus our efforts on analyses that will be valuable to the project. While CWA traditionally attempts to be independent of current state, the analysis conducted did not have the goal of changing the main processes and procedures and this shortcut to understanding was thus considered acceptable.

An approach more in line with that outlined in the literature was taken for the Decision Ladder and Information Flow Map [15]. The Decision Ladder (not shown) depicted the task of identifying the need for a corrective action (within steady state monitoring). It traces the process directly from activation of the control task through to the appropriate procedure to be implemented.

The Information Flow Map (IFM) shown in Figure 3 depicts one of the tasks described in the Decision Ladder, which is to assess whether or not monitored process parameters are within prescribed ranges. Furthermore, it describes the strategies that an operator can use to assess the appropriate control response and make sure that the system responds as intended. This describes the three primary tasks of situation assessment, reliability assessment, and response planning, as well as the six information sources that inform them. The IFM employs an adaptation of the *operator strategies* model used by Roth et al. [2], which describes how situations are assessed and then responded to (see "Situation Assessment" and "Response Planning" boxes of Figure 3). Although this IFM was designed for strategies used on CANDU 6® reactors, future work is planned to generalize it to other domains within the process industries.

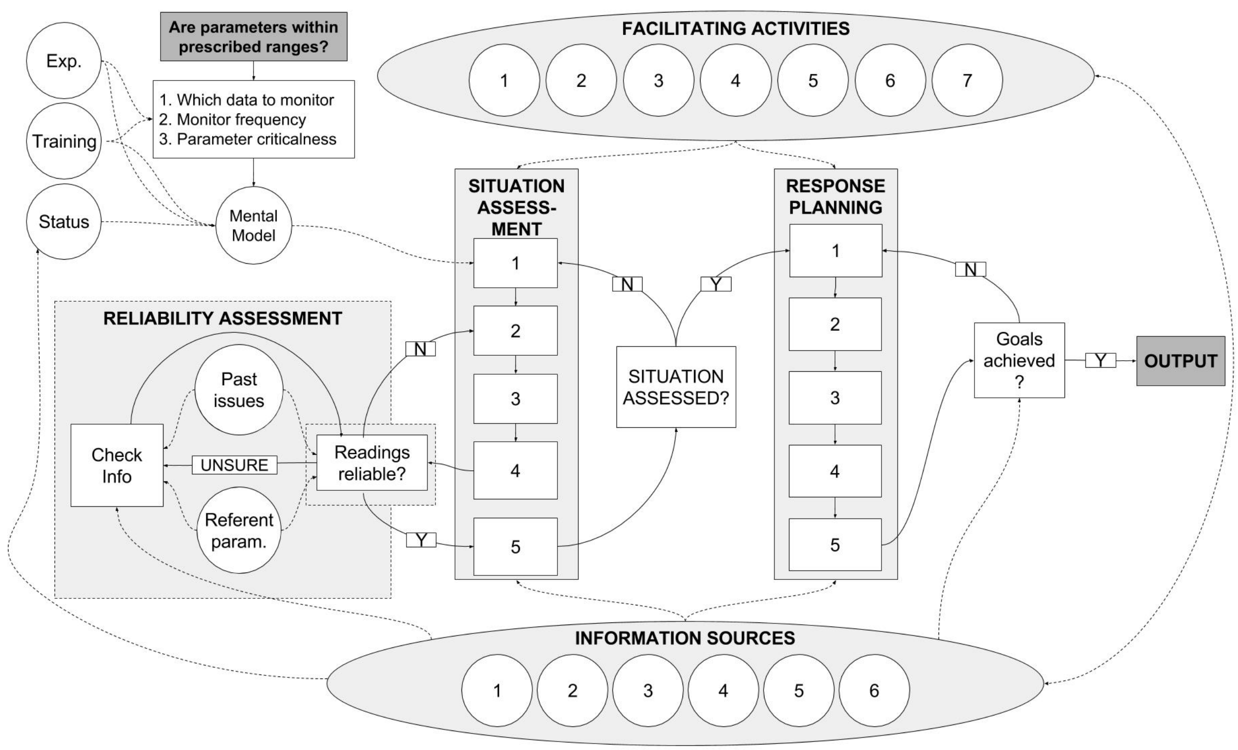

Figure 3. A simplified Information Flow Map depicting operators actively searching for unannunciated parameter deviations. The circled numbers indicate that there are seven facilitating activities and six information sources. The figure has been simplified due to size constraints (with numbers used to substitute labels).

Figure 3 takes the operator from assessing whether or not the parameters on the display are within the prescribed ranges, to the output (e.g., control response, "do nothing" response, etc.), which closes the loop back to the initial input, thereby illustrating the closed-loop nature of steady state monitoring. Although the input and output are always the same, the ways in which the operator can arrive at the output vary depending on the situation. This illustrates the different strategies that can be employed.

For the second experimental task, Shutdown System Testing (SdST), an informed choice was made to focus on the Work Domain Analysis, resulting in a single abstraction hierarchy being created to describe the system. However, defining what to include in SdST proved to be difficult. The system's goals and functions are very different during SdST than for normal operation and they rely heavily on software and display-based elements. Therefore, analyzing the entire shutdown system would have resulted in the analysis of many irrelevant components. Clearly defining the boundaries of the work domain was therefore both challenging and all the more necessary.

To address these challenges, an *Object Worlds* approach to the WDA was taken for this task. Object worlds offer a method for analyzing domains where the same objects are used in distinct ways depending on the situation [16]. Object worlds most commonly define the system with respect to a specific set of stakeholders. For the SdST, the stakeholders are the same as in regular operation but their role changes because of the task. We therefore defined our system boundary for SdST as the object world boundary of the operator while acting in the role of shutdown system tester. In addition to clarifying which entities were included in the work domain, it also allowed only the properties of these entities relevant to testing to be included. Figure 4 shows the resulting Abstraction Hierarchy.

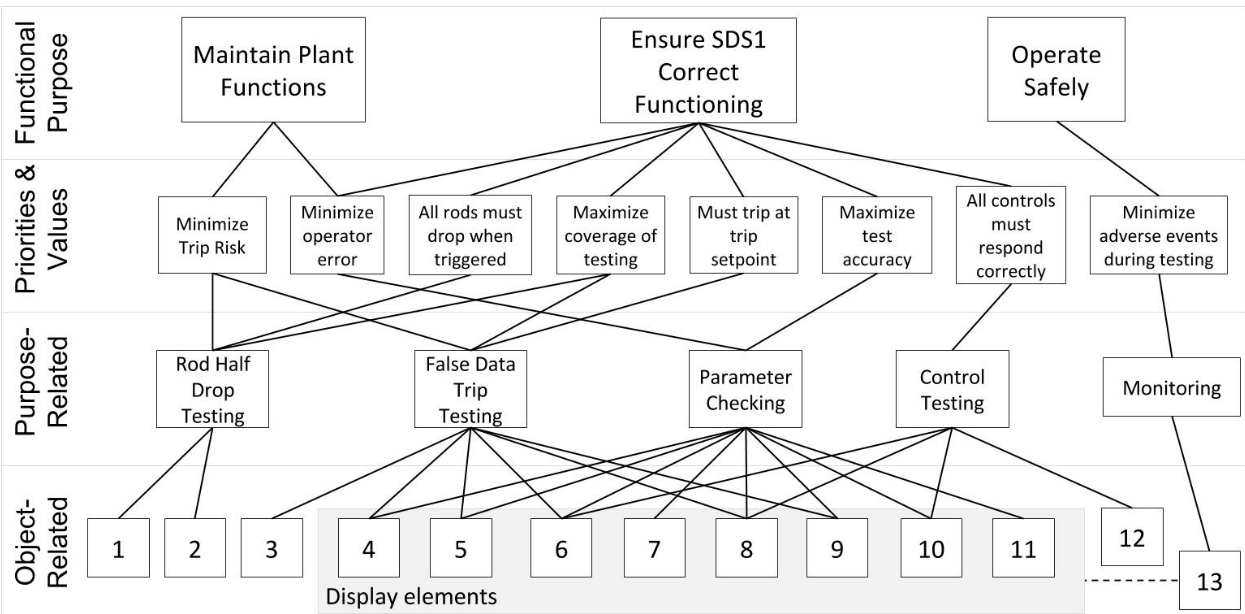

Figure 4. Abstraction Hierarchy for SdST. The figure has been simplified due to size constraints (with numbers used to substitute labels). This is done from the perspective of someone testing the shutdown system, and therefore includes the constituents necessary for that specific task.

SdST has far less random variability compared to other systems, and relies more on regulations than on natural laws. We therefore used a different set of conventions to define the four hierarchy levels. The most pronounced change is at the second level, which is defined as the *values and priorities* [17] level instead of the *abstract functions* level. This focuses on the intentional rules placed upon the system rather than the principles and laws that are appropriate for more conventionally analyzed systems.

The hierarchy in Figure 4 focuses on the components that are necessary to accomplish the specific goal of SdST. Typically, abstraction hierarchies focus primarily on the physical constituents of the system as they are the principal actors that achieve the system's goals and are therefore the components that are acted on [3]. However, SdST is an inherently different task, since it focuses on the testing of the system rather than the physical operation of it. Therefore, elements such as displays and alarms, while traditionally absent, were necessary inclusions. Since we viewed the system from an object worlds perspective, we omitted some of the shutdown system's physical elements that are not necessary for the testing of shutdown system one.

4 DISCUSSION

The objective of the analytical phase of our study was to form the foundation for a future experiment testing the claimed benefits of LSDs. The analysis supported development of experimental scenarios that will be suitable for testing these claims. Furthermore, the results of the analyses will also inform the development of a novel LSD interface employing EID principles [3].

Beyond the explicit objectives and the experimental implications of their successful achievement, the detailed documentation of the initial phases of a CWA provide a clear example for future experimenters who are doing studies wherein a novel EID interface is being compared to existing ones. If this type of comparison is their end goal, we hope that they will be able to use our methods of modeling the analytical boundaries around the needs of the end experiment, to facilitate their initial analytical phases.

5 CONCLUSIONS

The findings discussed in this paper reveal the importance of not only defining the system boundaries for work analysis, but also the analytical boundaries. Through our analysis, we have identified the various sociotechnical constraints of the system, we have developed appropriate experimental scenarios for evaluating the claimed benefits of LSDs, and we have documented the decision making processes and the strategies by which these can be achieved. By focusing our analytic efforts on the end experiment, we were able to focus these analyses on the systems and operations that are specifically relevant to our end objective.

6 REFERENCES

1. W.P. Myers, & G.A. Jamieson, "An operating experience review of large-screen displays," In NPIC-HMIT Meeting, 2015, pp. 1-15, 2015.
2. E.M. Roth et al., " Rapid prototyping and simulator evaluation of a wall panel overview display," In IEEE 6th Annu. Human Factors Meeting, Orlando, FL, 1997, pp. 14-19.
3. K.J. Vicente, *Cognitive Work Analysis: Towards safe, productive, and healthy computer-based work.* Mahwah, NJ: Lawrence Erlbaum Associates, 1999.
4. U. Ahlstrom, "Work domain analysis for air traffic controller weather displays," Journal of Safety Research, vol. 36, pp. 159-169, 2005.
5. G.A. Jamieson, C.A. Miller, W.H. Ho, & K.J. Vicente, "Integrating task-and work domain-based work analysis in ecological interface design: A process control case study," IEEE Transactions on Systems, Man And Cybernetics, vol. 37, pp. 887-905, 2007.
6. C.M. Burns, L. Garrison, & N. Dinadis, "From analysis to design: WDA for the petrochemical industry," in Proceedings of the Human Factors and Ergonomics Society Annual Meeting, vol. 56, pp. 368-372, 2003.
7. G.A. Jamieson, & K.J. Vicente, "Ecological interface design for petrochemical applications: Supporting operator adaptation, continuous learning, and distributed, collaborative work", Computers and Chemical Engineering, vol. 25, pp. 1055-1074, 2001.
8. N. Lau, O. Veland, J. Kwok, G.A. Jamieson, C.M. Burns, A.O. Braseth, & R. Welch, "Ecological Interface Design in the nuclear domain: An application to the secondary subsystems of a boiling water reactor plant simulator.," IEEE Trans. Nuclear Science, vol. 55, pp. 3579-3596, 2008.
9. G. Lintern, "Cognitive Work Analysis. Company: Cognitive Systems Design," 2013.

10. N. Lau, O. Veland, J. Kwok, G.A. Jamison, C.M. Burns, A.O. Braseth, & R. Welch, "Ecological Interface Design in the nuclear domain: An application to the secondary subsystems of a boiling water reactor plant simulator," in IEEE Trans. Nuclear Science, vol. 55, pp. 3579-3596, 2008.
11. E. Davey, "Process monitoring during normal operations at Canadian nuclear power plants," Proceedings of the Human Factors and Ergonomics Society Annual Meeting 2000, vol. 44, pp. 811-814, 2000.
12. J. Rasmussen, A. Pejtersen, & L.P. Goodstein, *Cognitive systems engineering.* New York: Wiley, 1994.
13. D.P. Jenkins, N.A. Stanton, P.M. Salmon, G.H. Walker, *Cognitive work analysis: coping with complexity.* Aldershot, UK: Ashgate, 2009
14. N. Naikar, B. Pearce, D. Drumm, & P.M. Sanderson, "Designing teams for first-of-a-kind, complex systems using the initial phases of cognitive work analysis: Case study," Human Factors: The journal of the Human Factors and Ergonomics Society, vol. 45, pp. 202-217, 2003.
15. B. Elix, & N. Naikar, "Designing safe and effective future systems: A new approach for modeling decisions in future systems with Cognitive Work Analysis," in Proceedings of the 8th International Symposium of the Australian Aviation Psychology Association, 2008.
16. G.L. Torenvliet, G.A. Jamieson, & R. Chow, "Object worlds in work domain analysis: A model of naval damage control," in IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans, vol. 38, pp. 1030-1040, 2008.
17. N. Naikar, & P.M. Sanderson, "Evaluating design proposals for complex systems with work domain analysis," in Human Factors, vol. 43, pp. 529-542, 2001.